



FÉDÉRATION SPÉLÉOLOGIQUE EUROPÉENNE a.s.b.l. (FSE)
EUROPEAN SPELEOLOGICAL FEDERATION
EUROPEAN CAVE PROTECTION COMMISSION (ECPC)



European Environmental Caves Outlook

EECO 2026

Environmental Status, Pressures, and Conservation of Cave Ecosystems in Europe

Lead Authors: Ferdinando Didonna | Philippe Fleury

Coordinating Organisation:

European Speleological Federation (FSE) – European Cave Protection Commission (ECPC)

EDITION 1 • 13th September 2026

Inspired by the UN Global Environment Outlook (GEO) – Adapted for European Subterranean Ecosystems



Foissac Cave, Aveyron, France. Photo by J.-F. Fabriol

Disclaimer

This report, the European Environmental Caves Outlook (EECO) 2026, is based on data, registries, and technical reports provided by the European Speleological Federation (FSE) and its European Cave Protection Commission (ECPC). All raw data regarding cave locations, environmental monitoring, and species occurrences are sourced from the voluntary contributions of FSE member national federations and associated scientific partners.

While every effort has been made to ensure accuracy and completeness, the FSE and ECPC provide this data "as is" without warranty of any kind. The FSE shall not be held liable for any direct, indirect, or consequential damages resulting from the interpretation or use of the data, maps, or indices (such as the E_{ka}¹ Index) presented in this outlook.

The findings and recommendations presented represent the scientific and conservationist consensus of the ECPC and the lead authors. They do not necessarily reflect the official political stance of individual national governments or the European Union.

Coordinating Organisation:

European Cave Protection Commission (ECPC).

Fédération Spéléologique Européenne a.s.b.l. - R.C.S. Luxembourg: F7846 –

Address: 2, rue du Fort Olisy L-2261 Luxembourg

Postal Address: BP. 3067 – L-1030 Luxembourg –

email: protection@eurospeleo.eu – <http://www.eurospeleo.eu/ECPC>

ECPC Commission members (2023-2027):

Jean-Claude Thies, LU – President;
 Ferdinando Didonna, IT – Secretary;
 Ruđer Novak, HR – Vice-secretary;
 Valentina Balestra, IT;
 Katharina Bürger, AT;
 Stanimira Deleva, BG;
 Philippe Fleury, FR;
 Oier Gorosabel, ES;
 Hannes Köble, DE;
 Christa Locke, DE – Media moderator;
 Ioana Meleg, RO;
 Kaloust Paragamian, GR;
 Fabio Stoch, IT;
 Jure Tičar, SI;
 Jan Urban, PL;
 Bärbel Vogel, DE;
 Alex Weigand, DE;



Býčí skála Cave, Moravia, Czech Republic.

Photo by P. Crochet

© 2026 European Speleological Federation (FSE).



European Environmental Caves Outlook © 2026 by European Speleological Federation (FSE). This work is licensed under CC BY-NC-SA 4.0. Visit

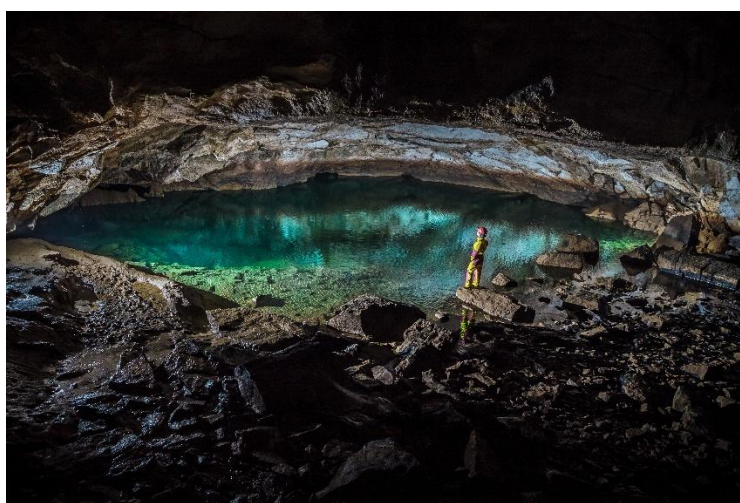
<https://creativecommons.org/licenses/by-nc-sa/4.0/>. CC BY-NC-SA 4.0 enables reusers to distribute, remix, adapt and build upon the material in any medium or format for non-commercial purposes only if attribution is given to the creator. If you remix, adapt, or build

upon the material, you must licence the modified material under the same or a compatible licence. Any commercial use or large-scale data extraction requires explicit written permission from the FSE Bureau

Contents

Disclaimer	2
Executive Summary	5
Scope and Scale	5
The Four Dimensions of Subterranean Heritage	5
Key Findings	6
Core Contributions of this Report	7
Urgent Recommendations	7
Part I: Foundations, Ecosystem Dynamics and Risk Indexing	8
1.0 <i>The Four Dimensions of Subterranean Heritage</i>	8
1.0.1 Biodiversity Heritage	8
1.0.2 Geological and Geodiversity Heritage	8
1.0.3 Hydrological Heritage	8
1.0.4 Cultural and Archaeological Heritage	9
1.0.5 Milestones in Cave Conservation in Europe	10
1.1 <i>The Karst-Aware Paradigm</i>	10
1.1.1 Speleogenesis as Infrastructure for karstic aquifers: The Triple Porosity System	11
1.2 <i>Subterranean Ecosystem Dynamics</i>	11
1.2.1 Biological Communities and Adaptive Strategies	11
1.2.2 The Microbial Foundation	11
1.2.3 Ecosystem Services	12
1.2.4 The “Cave as a Window” Paradigm	12
1.3 <i>The EECO Environmental Index (E_{ka})</i>	12
1.3.1 Index Structure and Internal Logic	13
1.3.2 Variable Definition and Weighting	13
1.3.3 Score Interpretation and Vulnerability Classes	14
Part II: Environmental Status and Current Threats	15
2.0 <i>Current Cave Environmental Status in Europe</i>	15
2.0.1 Destruction	15
2.0.2 Climate Impacts	16
2.0.3 Pollution Pathways	17
2.0.4 Uncontrolled Visitation and Vandalism	17
2.0.5 National Conservation Status Profiles	18
2.1 <i>Technical Framework: Habitat 8310 Assessment Guidelines</i>	21
The ECT Framework for Cave Assessment	22
Part III: European Comparative Analysis	23
3.0 <i>The Civil Stewardship Tradition: Speleological Organisations as Environmental Guardians</i>	23
3.0.1 The ECPC and its Mission	23
3.0.2 The EuroSpeleo Protection Label	23
3.0.3 International Reference: Cecav (Brazil)	23
3.1 <i>Multi-National Comparative Profiles</i>	24
3.2 <i>Regional Highlights and Strategic Pressures</i>	25
3.2.1 The Dinaric-Balkan Region — High Risk	25
3.2.2 The Alpine-Pyrenean Axis — Unfavourable and stable	25
3.2.3 The Central and Atlantic Platforms — Critical and Restoration Phase	25
3.2.4 Northern and Eastern Frontiers — Variable	26
3.3 <i>Multi-National Data Matrix</i>	26

Part IV: Monitoring, Research and National Data	27
4.0 Landmark European Research Projects	27
4.1 National Speleological Data Profiles	27
Croatia (HR) — Dinaric Strategic Water	27
France (FR) — Observational Excellence	27
Germany (DE) — The Systematic Registry	28
Italy (IT) — Citizen Stewardship	28
Poland (PL) — High-Altitude Monitoring	28
4.2 Scientific Critique of Prioritisation Approaches	28
Part V: Policy Recommendations	30
5.0 EU Legislative and Governance Priorities	30
5.0.1 Nature Restoration Regulation (NRR) Implementation	30
5.0.2 Water Framework Directive (WFD) Update	30
5.0.3 Geodiversity Protection	30
5.0.4 Natura 2000 Reform	30
5.0.5 Shared governance	30
5.1 Monitoring and Data Priorities	30
5.2 Citizen Science and Civil Stewardship	32
5.3 Research Priorities	32
Part VI: Selected Bibliography	33
Global Environmental Assessments	33
EU and EEA References	33
Karst Hydrology and Geomorphology	33
Climate Change	34
Subterranean Biodiversity and Ecology	34
Speleogenesis and Speleothems	34
Sulfuric Acid Speleogenesis	35
National and Regional References	35
Compliance Statement on Artificial Intelligence and Document Transparency	36
Annex: E_{ka}¹ — National calculation table	37



Underground lake, Croatia .Photo by J. Bedek.

Executive Summary

Key Message

Europe's cave and karst ecosystems are in a state of accelerating environmental decline. This outlook calls for an urgent transition from "Karst-Blind" to "Karst-Aware" governance across all EU Member States and FSE partner nations.

The European Environmental Caves Outlook (EECO) 2026 is the first systematic, continent-wide assessment of the environmental status, pressures, and conservation needs of Europe's subterranean caves and ecosystems. Led by the European Speleological Federation (FSE) through its Cave Protection Commission (ECPC), and inspired by the UN Global Environment Outlook (GEO) framework, EECO 2026 addresses a critical gap in European environmental governance: the systematic neglect of underground environments in mainstream environmental, biodiversity and water policies.

Scope and Scale

Globally, karst terrain — landscapes underlain by soluble carbonate and evaporite rocks — covers roughly 20% of the world's ice-free land surface (Ford & Williams 2025). This is a statement about surface geology, not about underground "voids", caves, fissures, and groundwater conduits. They constitute one of the largest non-marine ecosystem on Earth. These formations host karst aquifer systems that supply approximately 25% of the continent's drinking water. Karst aquifer systems contain an estimated 25 % of the world's groundwater reserves and contribute approximately 20 % of the global drinking water supply (Zupan Hajna 2025).

Yet these systems remain largely absent from national environmental restoration plans, water framework implementation, and biodiversity monitoring protocols.

The Four Dimensions of Subterranean Heritage

Cave and karst systems provide irreplaceable value across four distinct dimensions that current legislation addresses only partially, with a disproportionate focus on biodiversity (particularly bats) while geological, hydrological, and cultural values remain under-protected:

- Biodiversity: high-endemism fauna (troglonites, stygobionts), microbial communities, and bat populations of European conservation significance.
- Geological and geodiversity: unique speleothems, paleoclimatic archives, and geotopes of global scientific value threatened by extraction industries and underground uncontrolled visits and vandalism.
- Hydrological: strategic freshwater reserves and natural water purification systems serving millions of Europeans.
- Cultural and archaeological: prehistoric art, burial sites, and millennia of human interaction, including contemporary ones, with the underground environment.



Diabla Dziura w Bukowcu (Devil Hole in Mt Bukowiec), Poland, flying bat. Photo by J. Urban.

Key Findings

There are numerous threats to caves, which are linked both to human activities on the surface and to underground visitation: land disturbance, water pollution, biodiversity losses, damage to geological and archaeological heritage, over frequentation and inadequate underground visits, climate change, microplastic contamination (water and sediments). Their impacts range from small-scale, one single cave, to entire karst areas:

- The majority of EU-listed cave habitats (Habitat Type 8310, “Caves not open to the public”) are classified as “Unfavourable-Inadequate” or “Unfavourable-Bad” under the EU Habitats Directive. Belgium and the United Kingdom report over 70% “Bad” conservation status, driven by industrial and agricultural pollution; Romania and Greece show comparatively higher proportions of “Good” status. In Poland 56% of monitored caves have a “good” conservation status, however with regional differences.
- Climate change is penetrating underground. In France, underground climate trends range from +0.3 to +0.6 °C per decade (Bourges et al. 2023). In European alpine caves have increased by 0.2°C per decade since 2000 (Obleitner et al. 2024). Many Austrian and Swiss ice caves are projected to be ice-free within a decade.
- Microplastic (“plastitar”) deposits have been identified in all surveyed sea caves.
- Caves are increasingly at risk of biological crises, with the growth of micro-organisms (biofilms, fungi threatening painted caves) and the invasion of pathogens (white-nose syndrome on North American bat species). For example, pathogen pulse events — driven by extreme rainfall — have increased by 42% in the Dinaric region since 2020.



Han Cave, Belgium, giant speleothem. Photo by P. Crochet

Core Contributions of this Report

- Introduction of the EECO Environmental Index (E_{ka}^I), a composite karst-specific risk metric that quantifies subterranean environmental distress by integrating structural vulnerability, pollutant pressure, hydrological flashiness, governance capacity, and active speleogenetic processes.
- A comparative profile of 16 selected European countries — 15 FSE members plus Malta as non-member regional reference point — with illustrative E_{ka}^I pilot scores and qualitative policy-status evaluations, out of 32 FSE member nations overall.
- An inventory of landmark European research projects (PASCALIS, DarCo, KARST, eLTER, WATERWISE) and identification of critical monitoring gaps.
- A comprehensive European overview of threats to caves and key factors to handle in management strategies.
- A structured set of policy recommendations targeting the Water Framework Directive, the Nature Restoration Regulation, Natura 2000, and national cave registry systems.

Urgent Recommendations

- All EU Member States must submit their National Nature Restoration Plans to the European Commission by September 2026. They have to include in it subterranean environments (Habitat 8310 and associated karst groundwater bodies).
- Mandatory karst vulnerability mapping must be integrated into WFD Source Protection Zones across the EU.
- Geodiversity protection must be elevated to the same legal standing as biotopes, to halt the ongoing destruction of geotopes by extraction industries.
- The E_{ka}^I Index should be piloted across at least five representative European basins to enable calibration and cross-national comparison.
- Shared governance: establishment of EU level coordination body for subterranean heritage governance.



Karstic Landscape, Sicily, Italy. Photo by J.-M. Verdet

Part I: Foundations, Ecosystem Dynamics and Risk Indexing

1.0 The Four Dimensions of Subterranean Heritage

Cave and karst systems represent one of Europe's most undervalued and least-protected natural assets. Their ecological, geological, hydrological, and cultural dimensions collectively constitute an irreplaceable part of the continental heritage. A comprehensive conservation framework must recognise all four dimensions equally.

1.0.1 Biodiversity Heritage

Subterranean habitats host a disproportionately high degree of endemism relative to their surface area. Obligate cave-dwellers (troglobionts and stygobionts) exhibit extreme physiological adaptations — loss of eyes, depigmentation, metabolic slowing — that render them incapable of surviving outside their specific environment. The PASCALIS project established that crustaceans dominate groundwater biodiversity in Europe, in stark contrast to insect-dominated surface freshwaters. Numerous species of bats of European conservation significance (Annex II species under the Habitats Directive) depend on caves for hibernation and breeding.



1.0.2 Geological and Geodiversity Heritage

Speleothems — stalactites, stalagmites, cave pearls, and flowstones — are archives of past climate, rainfall, and atmospheric composition, preserving environmental records spanning hundreds of millennia. Unique geomorphological features such as blue ice glaciers in alpine caves, hypogenic sulfur cave systems (e.g. Frasassi, Italy), and gypsum karst landscapes (e.g. South Harz, Germany) are globally irreplaceable and currently threatened by industrial extraction. Geodiversity of European caves is also significantly related to non karst caves formed in siliciclastic rocks due to gravitational and weathering processes as well as by caves in modern volcanic rocks. i.e. 1 700 non karst caves in the Polish Outer Carpatians represent around 1/3 caves of Poland. Geotope protection must be elevated to the same legal standing as biotopes across EU Member States.



1.0.3 Hydrological Heritage

Karst aquifers underlie 21.6% of the European land surface and supply drinking water to approximately 25% of the population — over 100 million people.

The dissolution-driven porosity of carbonate rocks creates conduit systems capable of transmitting contaminants from surface sources to drinking water springs at speeds of several kilometres per hour. This hydrological connectivity makes karst groundwater uniquely sensitive to agricultural, industrial, and

urban pollution, and demands governance approaches fundamentally different from those applied to porous-media aquifers.

1.0.4 Cultural and Archaeological Heritage

Caves have served as places of shelter, ritual, and art from the earliest human presence in Europe. The Lascaux, Altamira, and Chauvet cave systems contain Palaeolithic art of world significance. Ongoing archaeological discoveries in European caves — including faunal remains, lithic assemblages, and burial sites — continue to revise our understanding of human prehistory. These sites are fragile, non-renewable, and increasingly threatened by uncontrolled visitation, vandalism, and climate-driven microclimate change.

Cultural heritage is diverse, ranging from prehistoric to contemporary, and from tangible to intangible, because human visitation of caves is a constant and widespread human phenomenon. Like alpinism, speleology constitutes intangible cultural heritage as it transmits technical skills, collective practices and an ethic of exploration that shape a culture shared across countries and generations. Certain caves have left their mark on the history of European speleology: the Gouffre Berger (France), Postojna Cave (Slovenia), Monte Cucco Cave (Italy), Lamprechtsofen Cave System (Austria), etc. Other caves, of more local significance, also have a strong heritage value due to the attachment that both cavers and local inhabitants have to them.



*Wonderful aragonite, Balbonne cave, France.
Photo by C. Bes*



Skeleton dating from the Copper Age, Foissac cave, France. Photo by P. Crochet

1.0.5 Milestones in Cave Conservation in Europe

The protection of subterranean environments in Europe has evolved over several decades through the combined efforts of scientific institutions, civil society, and international bodies. This takes two main forms: symbolic recognition of the significance of caves and karst (international day of caves and karst), and the inclusion of their issues within broader policies such as the Habitats Directive.:

Year	Milestone
1973	Creation of the Karst and Cave Protection Commission within the International Union of Speleology (UIS)
1975	International Year for the Protection of the Underground Environment
1992	EU Habitats Directive (92/43/EEC) — Habitat 8310 (“Caves not open to the public”) established
2020	Launch of the international Clean Up the Dark volunteer programme : https://cleanupthedark.org/
2021	International Year of Caves and Karst
2021	6 th EuroSpeleo Protection Symposium: European synopsis of cave monitoring and protecting caves through Natura 2000 and recommendations. https://riojournal.com/article/85859/
2025	UNESCO proclaims 13 september the International Day of Caves and Karst — a global recognition of the significance of the hidden world beneath our feet.
2026	Nature Restoration Regulation deadline for inclusion of subterranean environments in National Restoration Plans

1.1 The Karst-Aware Paradigm

For decades, European environmental and water management has suffered from what this report terms “Karst Blindness”: the application of porous-media (sand and gravel aquifer) models and governance frameworks to fundamentally different carbonate terrain. Standard hydrological tools — including Darcy’s Law, which relates groundwater discharge through porous media when there is a hydraulic head difference. — fail in karst environments because they assume uniform, slow flow through a homogeneous matrix. Indeed Darcy’s law is founded for laminar flow conditions and is valid when water flows on porous media hydraulic conductivity of granular or fractured media. In karst aquifers there are numerous conduits, of varying sizes with high water flow capacity. In such situations turbulent flow occurs during recharge events. This is why in karstic aquifers water flows are often non- Darcian. Karst systems feature fast, turbulent, and non-linear water flow through massive underground conduits, cracks, and caves (Lage et al., 2000 ; Kuniansky et al., 2022). Consequently, in karst systems, contaminants can travel kilometres in hours through dissolution conduits and fissures, bypassing all-natural filtration.

The Karst-Aware Paradigm recalibrates environmental risk assessment by recognising that:

- Karst aquifers are networks of high-speed conduits, not uniform sponges.
- Surface topography is often a poor predictor of actual groundwater drainage boundaries.
- Pollution events can be catastrophic, rapid, and nearly impossible to remediate once they enter the conduit network.
- Governance frameworks designed for conventional groundwater are systematically inadequate for subterranean karst environments.

1.1.1 Speleogenesis as Infrastructure for karstic aquifers: The Triple Porosity System

A Karst-Aware environmental assessment must account for three distinct flow regimes operating simultaneously in the same carbonate massif:

- **Matrix Porosity:** Water stored in microscopic rock pores, moving at millimetres per year. Provides storage but minimal transmission.
- **Fracture Porosity:** Water in joints and small cracks, moving at metres per day. Provides intermediate-speed connectivity.
- **Conduit (Cave) Porosity:** Water in large dissolution passages, moving at kilometres per hour. Provides rapid, direct transmission of contaminants from surface to spring.

Critical example: in many European karst systems, a pollution event at a sinkhole (ponor) can reach a drinking water spring 15 km away in under four hours via a cave conduit — with no filtration, no attenuation, and no warning.

1.2 Subterranean Ecosystem Dynamics

Subterranean ecosystems are complex, energy-limited environments characterised by permanent darkness, high humidity (often exceeding 95%), and strong thermal inertia — cave temperatures typically mirror the surface mean annual air temperature and remain stable across seasons. Because photosynthesis is absent, these systems depend entirely on allochthonous energy: organic matter, nutrients, and microorganisms transported from the surface by gravity, infiltrating water, and mobile organisms.

1.2.1 Biological Communities and Adaptive Strategies

Subterranean biota are categorised by their degree of dependence on the cave environment:

- **Troglobionts and Stygobionts:** obligate terrestrial and aquatic cave-dwellers exhibiting troglomorphisms — anophthalmia (eye loss), depigmentation, limb elongation, and metabolic deceleration. These organisms are highly sensitive to any alteration of their microhabitat.
- **Troglophiles:** species that utilise caves for specific life cycle stages (e.g. hibernation, breeding) but can also survive on the surface. Bats are the most ecologically significant troglophiles, providing vital nutrient inputs via guano.
- **Trogloxenes:** species that use caves opportunistically for temporary shelter.

The PASCALIS project demonstrated a fundamental divergence between subterranean and surface biodiversity patterns: crustaceans dominate groundwater biodiversity in Europe, while insects dominate surface freshwaters. European subterranean species richness peaks at mid-latitudes, forming a pattern shaped by Miocene tectonic activity and Pleistocene glacial refugia.

1.2.2 The Microbial Foundation

Cave sediments and wall biofilms are active microbial habitats where bacteria and archaea facilitate the cycling of nitrogen, sulfur, and carbon. In hypogenic systems such as the Frassasi cave complex in Italy, sulfur-oxidising microorganisms act as geochemical engines, producing sulfuric acid that dissolves the host limestone from below — driving speleogenesis independently of surface recharge. Biofilms (“snottites”) in these systems can reach pH values approaching 0–1, representing some of the most extreme microbial habitats on Earth.



Karstic landscape, Carpathians, Romania. Photo by J.-M. Verdet

1.2.3 Ecosystem Services

- Provisioning: karst aquifers contain an estimated 25 % of the world's groundwater reserves and contribute approximately 20 % of the global drinking water supply (Zupan Hajna 2025).
- Regulation: subterranean microbial communities and invertebrates function as natural water filters, degrading organic contaminants and cycling nutrients.
- Indicator function: stygofaunal richness and composition provide “lag-less” real-time indicators of groundwater quality — a decline in subterranean biodiversity often precedes the detection of pesticides or pathogens at human water extraction points.
- Palaeoclimate archives: speleothems preserve high-resolution records of past temperature, rainfall, and atmospheric composition spanning hundreds of millennia, constituting irreplaceable data for climate science.
- Cultural and ecotourism: show caves attract over 50 million visitors per year in Europe, generating significant economic value and public engagement with natural heritage. . Speleology, both science and sport, constitutes intangible cultural heritage as it transmits technical skills, collective practices and an ethic of exploration that shape a culture shared across countries and generations.

1.2.4 The “Cave as a Window” Paradigm

A major outcome of the 6th EuroSpeleo Protection Symposium (2021, Vilm, Germany, organized by ECPC FSE) was the formal recommendation to view caves not as isolated units but as “windows into the subterranean realm”. Conservation must therefore extend beyond the visible cave to the connected aquifer system and the surface exchanges (recharge catchment, flows of water, energy, various materials, species, ...). Monitoring must evaluate biodiversity and geodiversity elements with equal rigour, and environmental DNA methods offer a promising path to standardised, non-invasive biodiversity assessment across the 23 EU Member States where Habitat 8310 is present.

1.3 The EECO Environmental Index (E_{ka}^I)

The EECO Environmental Index (E_{ka}^I - European Karst & Cave Environmental Index) is introduced as a composite framework for quantifying subterranean environmental distress in karst groundwater basins. It is designed to function as a “health score” for European karst systems: not a substitute for detailed

hydrogeological investigation, but a structured screening and prioritisation tool that integrates multiple dimensions of environmental risk into a single, policy-interpretable metric.

The EECO Environmental Index, E_{ka}^I provides a synthetic, comparable, and methodologically transparent assessment of the level of vulnerability, anthropogenic pressure, and protection status of the karst and subterranean heritage across the 32 member countries of the Fédération Spéléologique Européenne (FSE).

1.3.1 Index Structure and Internal Logic

The EECO Environmental Index (E_{ka}^I) evaluates relative karst and subterranean hydrogeological vulnerability based on physical exposure, cave density, anthropogenic pressure, and governance readiness. The core vulnerability score combines a 4-component weighted base sum (E_{base}) with a non-linear policy risk multiplier (Ω_a):

$$E_{ka}^I = E_{base} \times \Omega_a = (0.35 \times K_{dens} + 0.25 \times C_{dens} + 0.20 \times P_{anthrop} + 0.20 \times (100 - G_{prot})) \times \Omega_a$$

The Index is based on a Macro-Level Formula relevant at national or regional level. This option ensures maximum simplicity in application, avoids the introduction of complex composite variables lacking uniform calibration and guarantees robust comparative stability among national indices.

Index Formula (Conceptual Structure)

$$E_{ka}^I = E_{base} \times \Omega_a$$

$$E_{base} = (0.35 \times K_{dens}) + (0.25 \times C_{dens}) + (0.20 \times P_{anthrop}) + (0.20 \times (100 - G_{prot}))$$

Where:

- K_{dens} = Density and sensitivity of outcropping karst rocks.
- C_{dens} = Density of hypogean systems and caves with high ecological or hydrogeological value.
- $P_{anthrop}$ = Combined anthropogenic pressure resulting from land uses, agriculture, subterranean tourism, recharge water pollution.
- G_{prot} = Percentage of karst territory under legal protection (Natura 2000, National Parks, ...).
- Ω_a = Multiplicative factor of environmental governance and management.

The national index E_{ka}^I is obtained by multiplying a weighted base index (E_{base}) by an amplification/territorial governance factor (Ω_a).

Note: The final score is dimensionless and intended for comparative screening, not absolute diagnosis.

1.3.2 Variable Definition and Weighting

Variable	Symbol	Description	Scale	Weight (ω)
Karst density	K_{dens}	Density and sensitivity of outcropping karst rocks (percentage extent of karst territory and degree of solubility).	0 - 100	35% (0.35)
Caves density	C_{dens}	Density of hypogean systems and caves with high ecological/hydrogeological value.	0 - 100	25% (0.25)
Anthropogenic pressure	$P_{anthrop}$	Combined anthropogenic pressure (land use, agricultural intensity, subterranean tourism, recharge water pollution, ...).	0 - 100	20% (0.20)
Protected karst territory	G_{prot}	Percentage of karst territory under legal protection (Natura 2000, National Parks, ...). The formula uses (100 - G_{prot}) to measure the share of unprotected area.	0 - 100 (%)	20% (0.20)
Governance factor	Ω_a	Multiplicative factor of environmental governance and management (accounts for monitoring effectiveness and regional regulations).	0.75 - 1.25	Multiplier

1.3.3 Score Interpretation and Vulnerability Classes

Score Range E_{ka}^I	Class	Interpretation	Recommended Action
< 40.0	Low	Contained anthropogenic pressure and/or high coverage of legal protection.	Routine monitoring
40.0 - 59.9	Moderate	Hydrogeological and ecological balance under moderate pressure.	Preventive planning measures required.
60.0 - 74.9	High / Vulnerable	High level of anthropogenic impacts and/or gaps in protection.	Priority interventions needed.
75-100	Very High/Critical	High subterranean exposure, weak resilience and gaps in management and protection	Requires immediate National Restoration Plans.

Important caveat: The interpretation bands are provisional and require more calibration through pilot applications of the Index. The index should be used as a decision-support and comparative screening tool, complemented by site-specific hydrogeological investigation.



*Before and after cleaning, Jaskinia Lubańska, Lubania Cave, Świętokrzyskie Mts, Poland.
Photo by J. Urban*

Part II: Environmental Status and Current Threats

2.0 Current Cave Environmental Status in Europe

Recent assessments from the 6th EuroSpeleo Protection Symposium, the European Environment Agency (EEA), and the technical guidelines for Habitat 8310 (2025) converge on a consistent finding: Europe's cave and karst habitats are in a precarious and deteriorating state.

EEA State of Nature in the EU (2020) — Key Finding

81% of protected habitats in the EU, including cave habitats, are in poor or bad conservation status.

The majority of cave habitats (Habitat Type 8310) are classified as “Unfavourable-Inadequate” or “Unfavourable-Bad”.

While the Natura 2000 network provides some coverage, current protection is insufficient to reverse negative trends.

There are numerous threats to caves, which are linked both to human activities on the surface and to underground visitation: land disturbance, water pollution, biodiversity losses, damage to geological and archeological heritage, over frequentation and inadequate underground visits, climate change, microplastic contamination (water and sediments). Their impacts range from small-scale, one single cave, to entire karst areas:

2.0.1 Destruction

- Quarries and mines, flooding (dam), backfilling (urban development)



Marble quarries, Custonaci, Sicily, Italy. Photo by J.-M. Verdet

2.0.2 Climate Impacts

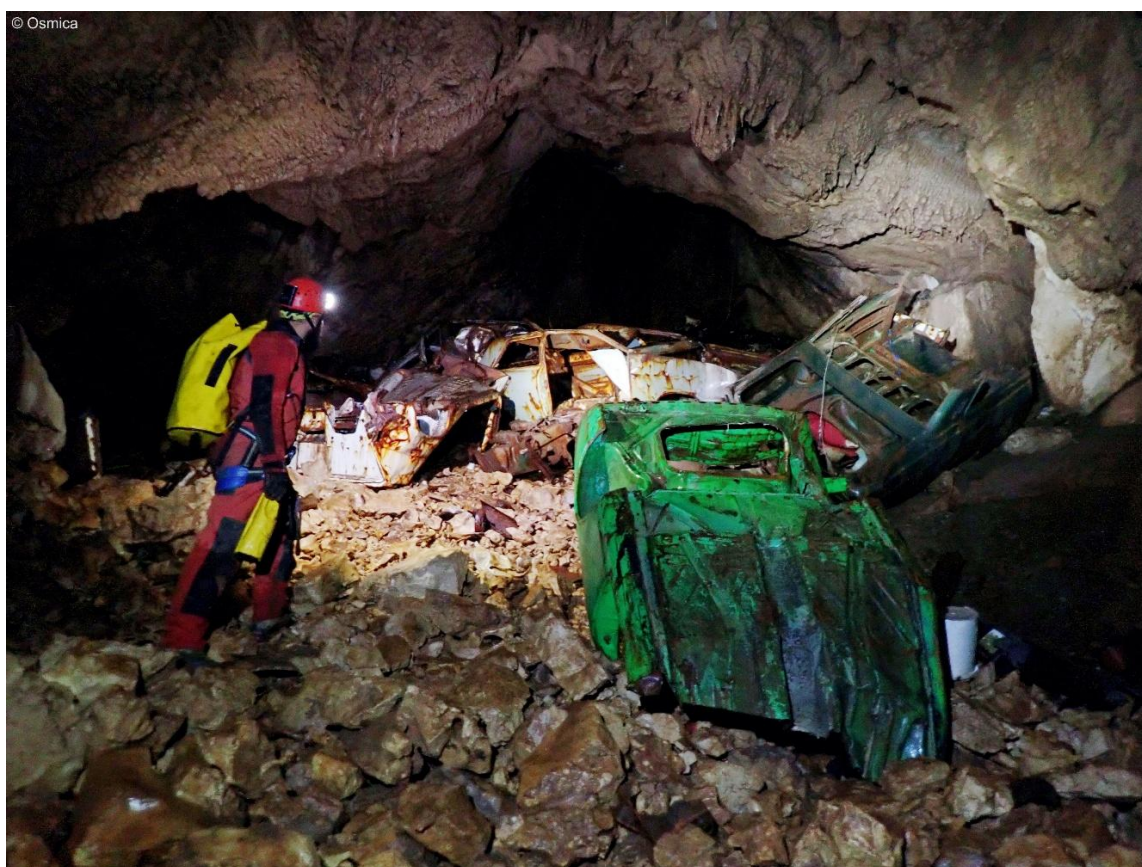
- Climate change is penetrating underground:
 - In France, underground climate trends range from +0.3 to +0.6 °C per decade (Bourges et al. 2023).
 - Subsurface temperatures in European alpine caves have increased by approximately 0.2°C per decade since 2000 (Obleitner et al. 2024).
 - Perennial ice in many Austrian and Swiss caves is retreating rapidly; some caves are projected to become ice-free within the next decade, with irreversible consequences for microhabitat and palaeoclimatic archives.
- Temperature is not the sole factor affected; reduced rainfall, increased frequency of extreme weather events (droughts, heatwaves, floods) and rising CO₂ levels in caves are also affected:
 - The decline in rainfall will affect several parameters of the underground environment: reduction in water flow rates and infiltration; decrease in relative humidity; drying out of the walls or, in other places, increase in the thickness of the water film; and changes in the physico-chemical and biological properties of the water. Water has a temperature-stabilising effect and even helps to cool the cavities, and this effect will diminish.
 - Extreme precipitation events are increasing, driving more frequent and severe “Pathogen Pulse” episodes: drought concentrates pollutants in deep cave storage, which are then mobilised explosively by the first autumn rains (“First Flush Effect”), reaching drinking water springs with minimal warning.
 - Climate change affects all speleogenic processes: dissolution and precipitation of carbonates, erosion, deposits, shifts in frost-thaw zones and rockfall zones, and biocorrosion caused by living organisms.
 - Speleothems – stalactites, stalagmites, draperies and excentrics – are particularly accurate climate archives. Recent publications show that they have already started to record climate change. However, climate change is not expected to cause them any major damage.
- The main concerns related to climate change do not relate to speleogenetic processes but to the conservation of painted caves, the preservation of underground ecosystems and species, human access (CO₂) and the declining water levels in aquifers.



***Underground ice and cave glaciers are threatened by climate change
Ice cave, Arolla Glacier, Valais, Switzerland. Photo by P. Crochet***

2.0.3 Pollution Pathways

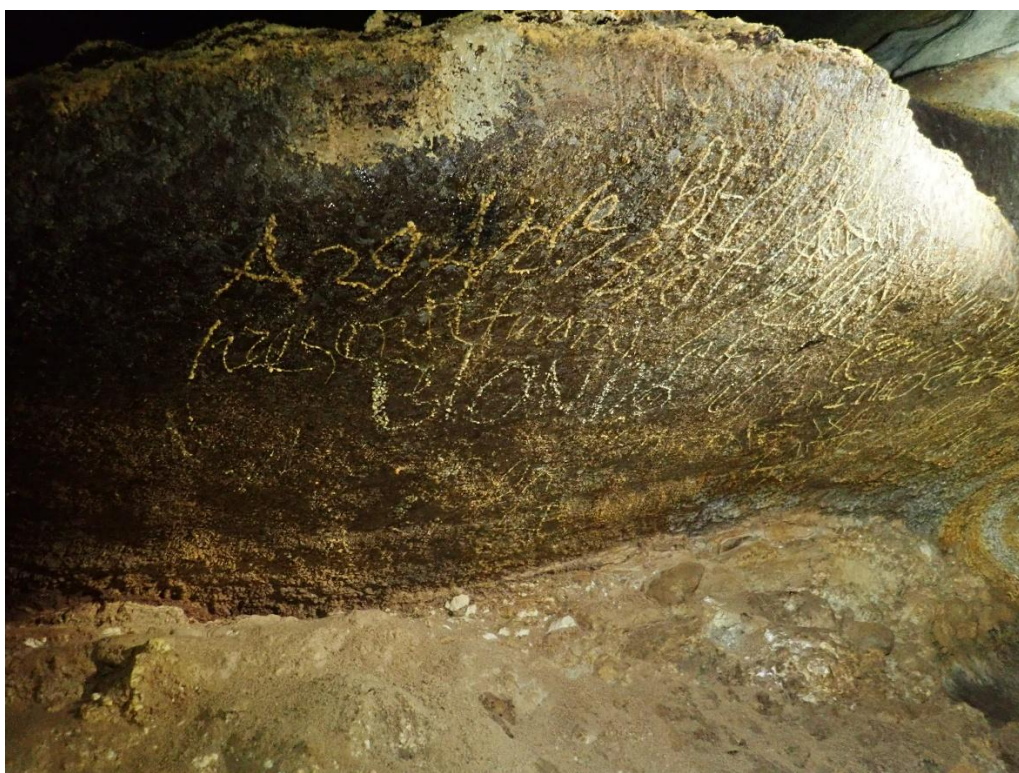
- Agriculture (nutrients, pesticides, pathogens) and urban sprawl are the primary drivers of cave habitat degradation across Europe.
- Marine debris — particularly fragmented plastics (“plastitar” deposits) — has been identified in all surveyed sea caves.
- Microplastics ingested through karst swallow holes abrade into micro-particles within cave conduits, creating a permanent internal contamination source.
- Caves are increasingly at risk of biological crises, with the growth of micro-organisms (biofilms, fungi threatening painted caves) and the invasion of pathogens (white-nose syndrome on North American bat species). For example, pathogen pulse events — driven by extreme rainfall — have increased by 42% in the Dinaric region since 2020.
- Major changes in land use or in the surface hydrogeological regime also have an impact on water quality and quantity and on underground microclimates: deforestation, clearing of grassland for cultivation, water use, urbanisation, mining and quarrying, waste disposal.



Various waste. Gvozdenica cave, Croatia. Photo by D. Basara

2.0.4 Uncontrolled Visitation and Vandalism

Mass tourism and uncontrolled access remain significant drivers of cave habitat destruction in many European countries. The relevant threat is not caving as a discipline — speleological organisations are among the most effective stewards of cave environments — but specifically uncontrolled visitation, vandalism, waste dumping, and the disturbance of sensitive bat colonies and fragile speleothem formations. Dedicated cave management and access regulation, in partnership with national caving federations, is essential.



Graffiti. Sant Ninfa cave, Sicilia, Italy. Photo by J.-M. Verdet

2.0.5 National Conservation Status Profiles

Under the EU Habitats Directive Article 17 reporting cycle (<https://nature-art17.eionet.europa.eu/article17/>), Member States submit conservation status assessments for Habitat 8310 every six years. Based on the 2013-2018 cycle, the results in progress for the cycle 2019-2024 and available FSE data, the following national profiles emerge:

Country	Overall Status	Primary Pressures	Notes
Austria (AT)	Moderate / Stable	Alpine denudation shifts	Strong monitoring; E _{ka} ^I score 46
Belgium (BE)	Unfavourable-Bad (>70%)	Industrial & agricultural pollution	Operation Dépollution active
Croatia (HR)	Unfavourable	Hydropower, industrial legacy	78% water from karst; 1,000 polluted sites
France (FR)	Unfavourable-Inadequate/declining or stable	Agricultural nitrates	SNO KARST national observatory
Greece (EL)	Mixed/Improving	Salinity management challenges	E _{ka} ^I score 81 (Critical)
Italy (IT)	Unfavourable-Inadequate/Bad	Agricultural nitrates, seawater intrusion	Puliamo il Buio citizen programme
Poland (PL)	Favorable and stable .	Human disturbance inside caves, destruction by quarrying, waste and pollution.	56% of caves favorable, the rest are unfavorable
Romania (RO)	Relatively Favourable	Limited industrial pressure	High biodiversity in Peștera Vântului

Country	Overall Status	Primary Pressures	Notes
Slovenia (SI)	Favourable	Tourism pressure (Postojna)	Karst-specific legislation; E _{ka} ¹ score 54
Spain (ES)	Mixed/Critical (S regions)	Saline intrusion, aridification	22 of world's 100 deepest caves
United Kingdom (UK)	Unfavourable-Bad (>70%)	Agricultural runoff, urban leaching	BGS karst monitoring active



Lava Tube, Timanfaya National Park, Lanzarote Island, Spain, Photo by L. Thierry

Figure: Habitat 8310 conservation status (reporting period 2013-2018)

<https://nature-art17.eionet.europa.eu/article17/>

Legend	Favorable	Unfavorable Inadequate	Unfavorable Bad	Unknown
--------	-----------	---------------------------	--------------------	---------

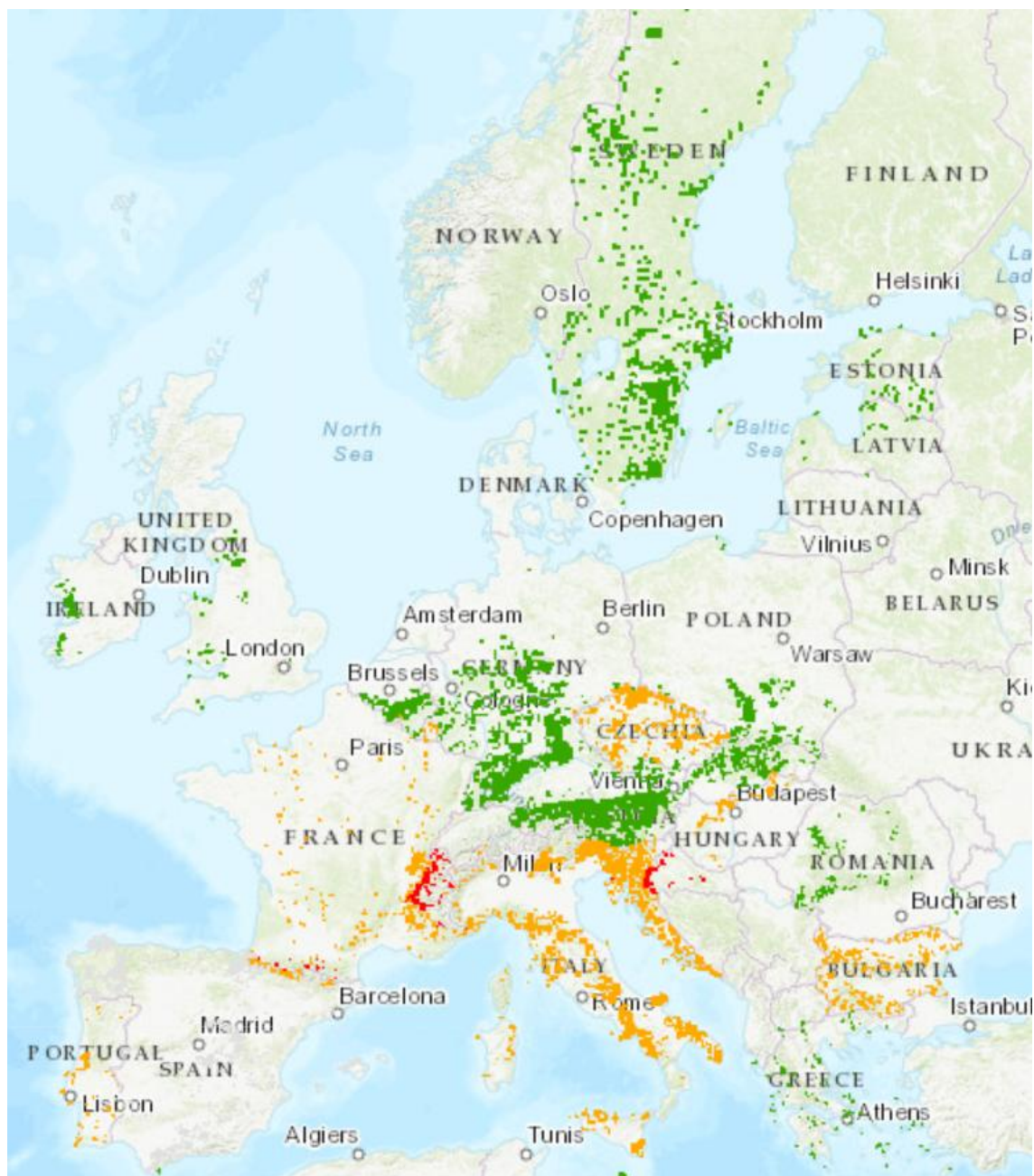
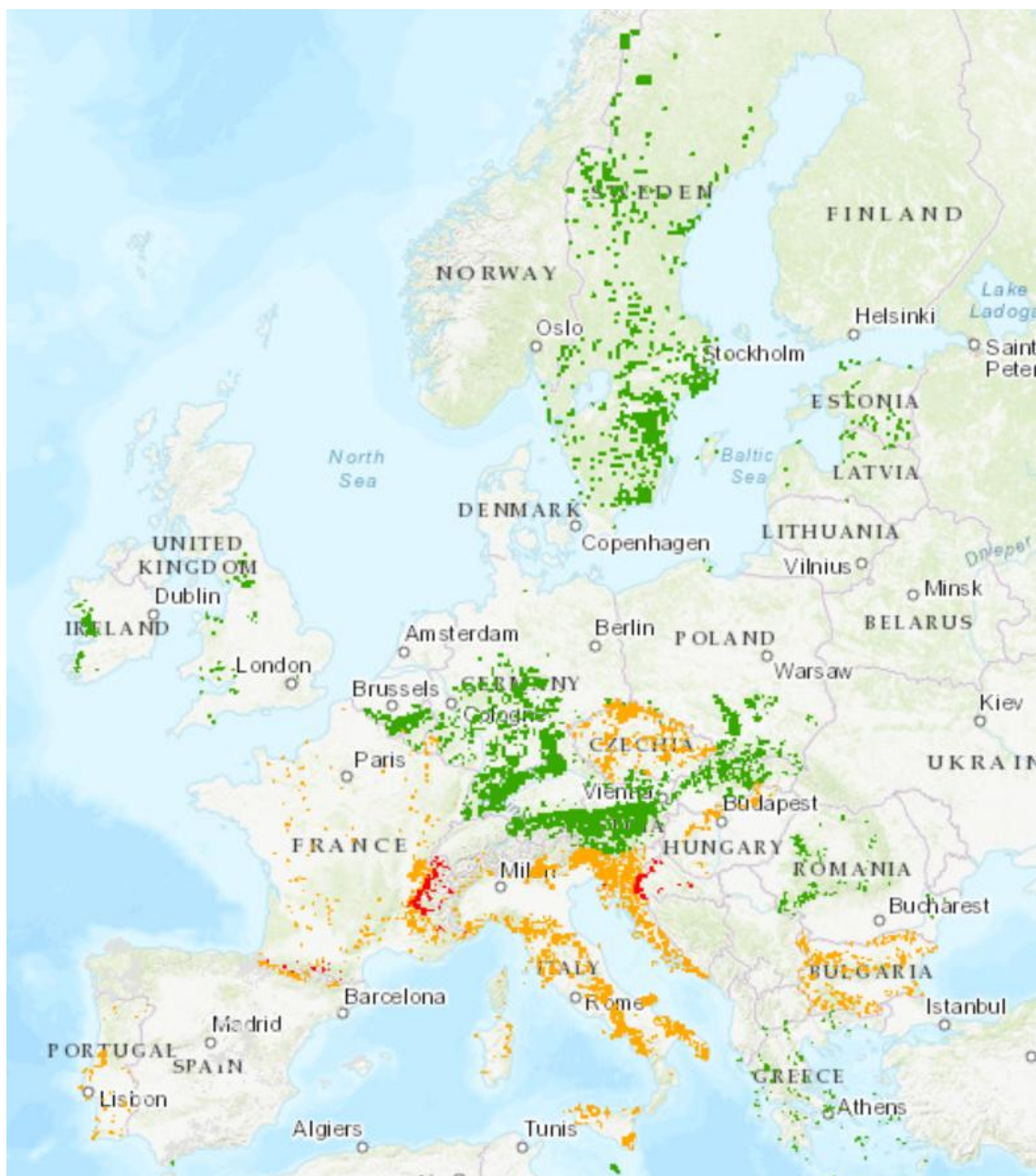


Figure: Habitat 8310 conservation status (reporting period 2019-2024, results in progress)

<https://nature-art17.eionet.europa.eu/article17/>

Legend	Favorable	Unfavorable Inadequate	Unfavorable Bad	Unknown
--------	-----------	---------------------------	--------------------	---------



2.1 Technical Framework: Habitat 8310 Assessment Guidelines

In 2025, the European Commission published the first EU-wide Technical Guidelines for assessing and monitoring the condition of Annex I Habitat Type 8310 (Caves not open to the public) under the Habitats Directive. Authored by Jozef Šibík (Slovak Academy of Sciences), Augusto Pérez Alberti (ATECMA), and Ana Zuazu Bermejo (ATECMA), and published by the Publications Office of the European Union (DOI: <https://doi.org/10.2779/7667114>), this document provides the most authoritative current framework for national monitoring programs.

The ECT Framework for Cave Assessment

The guidelines structure cave condition assessment into six thematic classes aligned with the UN System of Environmental-Economic Accounting (SEEA-EA) Ecosystem Condition Typology (ECT):

- Abiotic Physical: microclimate stability (temperature, humidity, ventilation patterns).
- Abiotic Chemical: water quality, CO₂ composition, absence of pollutants and heavy metals.
- Biotic Compositional: troglobitic and stygobitic fauna, Annex II species (bats), microbial communities.
- Biotic Structural/Functional: biofilms, nutrient cycling, energy flow from surface to cave.
- Landscape: integrity of the surface recharge catchment and connectivity of the hydrogeological network.
- Other variables : disturbances, presence of human disturbances, habitat alterations, pollution indicators

To have a holistic view we propose to incorporate Cultural and Archaeological characteristics: presence and condition of prehistoric art, archaeological deposits, and cultural heritage both material and immaterial, including contemporary ones, within cave systems.



Jaskinia Mylna, Confusing Cave, Tatra Mts, Inner Carpathians, Poland. Photo by J. Urban

Part III: European Comparative Analysis

3.0 The Civil Stewardship Tradition: Speleological Organisations as Environmental Guardians

The European Speleological Federation (FSE), founded in 1990, is the central coordinating body for scientific and sport speleology in Europe, encompassing 32 member nations following the accession of the Czech Speleological Society at the FSE General Assembly of 16 April 2026. Beyond their exploration mandate, national caving federations across Europe represent a unique and irreplaceable environmental monitoring and stewardship resource: trained, geographically distributed, and deeply familiar with local cave systems.

FSE member nations include Albania, Armenia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Georgia, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Switzerland, Turkey and the United Kingdom.

3.0.1 The ECPC and its Mission

The European Cave Protection Commission (ECPC), the FSE's dedicated conservation body, operates under the IUCN Guidelines for Cave and Karst Protection (2022) and the EU Habitats Directive. Its six core objectives are:

- To position cave and karst protection at the priority level within European natural and cultural heritage conservation, including bio- and geodiversity, habitats, species, geotopes, and geosites.
- To develop and implement common European good practices of cave and karst protection across national federations.
- To support speleologists in their engagement with public authorities and regulatory bodies.
- To develop collaboration with EU specialised structures and international institutions in the field of cave and karst protection.
- To build a political lobby for cave and karst protection in Europe and to influence regulations, guidelines, and directives.
- To generate and disseminate scientific knowledge about the values of caves and karst, and to promote effective methods of their preservation.

3.0.2 The EuroSpeleo Protection Label

The ECPC's annual EuroSpeleo Protection Label (ESPL) recognises exemplary cave conservation projects by European caving clubs. Recent laureates include the CaveLife app for standardised digital faunal data entry (winner), a microplastic monitoring project in karst aquifers (2022), and the Vjosa River Basin caves conservation initiative (2025). These awards highlight the practical conservation capacity of civil speleology.

3.0.3 International Reference: Cecav (Brazil)

Brazil's Centro Nacional de Pesquisa e Conservação de Cavernas (Cecav) (<https://www.gov.br/icmbio/pt-br/assuntos/centros-de-pesquisa/cavernas>), operating within the Chico Mendes Institute for Biodiversity Conservation under the Brazilian Ministry of Environment, provides a compelling international reference model for institutional cave protection. Cecav manages the National Speleological Patrimony register, conducts systematic cave inventories, and advises on environmental licensing for infrastructure projects in karst areas. ICMBio/Cecav has an institutional mission to carry out scientific research and management actions for the conservation of cave environments and associated species, as well as to assist in the management of federal Conservation Units with cave [environments](#).

The establishment of a comparable EU-level coordination body for subterranean heritage governance — drawing on the Cecav model — merits serious consideration in the context of the Nature Restoration Regulation implementation.

3.1 Multi-National Comparative Profiles

The following table provides an overview of cave and karst governance across 16 key European nations, based on data compiled from FSE newsletters, national registries, and WOKAM coverage datasets (<https://data.europa.eu/data/datasets/473d851c-4694-4050-a37f-ee421170eca8?locale=en>).

(Data consolidation in progress and may contain minor provisional inaccuracies)

Country	Karst km ²	Caves (n)	Cavers (est.)	Primary Legislation	E _{ka} ^I Score*	Policy Status of karst and caves**
Armenia (AM)	~4 400	<500	<100	Water Code	49 (moderate)	n/a
Austria (AT)	~16 700	~20 000	~2 500	Geotope Protection	46 (moderate)	Karst-Aware
Belgium (BE)	~3 600	>5 000	~1 200	Regional Monument Law	60 (high)	Karst-Blind
Croatia (HR)	29 400	4 979	~800	Nature Protection Law	70 (high)	Karst-Blind
France (FR)	~193 000	>50 000	~8 000	Conservatory Model (historic monuments, landscapes and nature)	56 (moderate)	Transitioning towards Karst-Aware
Germany (DE)	~42 800	14 991	~2 400	Federal Nature Act	38 (low)	Fragmented (depending on Länder)
Greece (EL)	~39 500	>10 000	~1 200	Salinity Management	81 (critical)	n/a
Italy (IT)	~66 300	>44,362	~5 000	Regional Planning	83 (critical)	n/a
Malta (MT)***	100% karst	n/a	n/a	WSC Desalination	79 (critical)	n/a
Poland (PL)	~60 000	5 800	~1 500	Nature Protection Law, Water Law	n/a	n/a
Romania (RO)	n/a	n/a	n/a	Nature Protection Law	n/a	n/a
Slovenia (SI)	~8 700	>14 000	~1 200	Specific Karst Law	54 (moderate)	Karst-Aware
Spain (ES)	~175 900	>40 000	~3 500	River Protection	77 (critical)	n/a
Switzerland (CH)	7 900	~7 500	~2 000	Waters Protection Act	46 (moderate)	Karst-Aware
Turkey (TR)	~313 000	>40 000	~3 000	Coastal Management	66 (high)	Fragmented
United Kingdom (UK)	~23 400	~2 500	~4 000	GW Regulations	52 (moderate)	Emerging

* E_{ka}^I figures shown are provisional and should not be used as validated risk assessments.

** **Policy Status of karst and caves:** this column refers to the “Karst-Aware Paradigm” (Part 1 1.1) and provides a qualitative assessment of the importance attached to karstic aquifers, landscapes and to caves in public policies.

*** **Malta** is not on the FSE's member roster (see Section 3.0) — it is included here as non-member regional reference/comparator country.

3.2 Regional Highlights and Strategic Pressures

3.2.1 The Dinaric-Balkan Region — High Risk

This region faces high-risk status due to rapid hydropower expansion and legacy industrial pollution. Geodiversity is world-class — Slovenia has more than 14 000 documented caves in 20,273 km² of territory — but legislative protection often lags behind infrastructure development.

- Croatia: 78% of the nation's renewable freshwater is stored in karst aquifers; over 900 polluted cave sites have been identified through the Clean Underground initiative, with 140 locations cleaned.
- Albania: vulnerable to massive water abstraction in the Vjosa basin (up to 50% flow diversion in dry months).
- Bosnia and Herzegovina: conflict between hydropower development in Upper Horizons areas and the integrity of karst poljes.
- Slovenia: the Postojna-Planina cave system operates as the world's first real-time karst laboratory (eLTER site), serving as a global reference for integrated monitoring.

3.2.2 The Alpine-Pyrenean Axis — Unfavourable and stable

These countries possess the most advanced monitoring networks in Europe (e.g. SNO KARST in France, Visual KARSYS in Switzerland), but climate change is destabilising hydrological stationarity assumptions that underpin current governance frameworks.

- Austria: Vienna's primary water supply relies on Alpine karst aquifers delivering 400 000 m³ daily, but climate warming triggers shifts in cationic denudation—the process where acidic, carbon dioxide rich water dissolves and leaches essential mineral cations like calcium (Ca^{2+}) and magnesium (Mg^{2+}) from the carbonate bedrock—ultimately altering spring flow dynamics and water quality.
- France: operates the SNO KARST national observatory network (9 stations); the PaPRIKa method manages karst catchments including the Fontaine-de-Vaucluse system; website dedicated to knowledge of the underground environment, Karsteau, created and maintained by the French Speleological Federation. more than 50 000 caves documented.
- Poland (Carpathians): large bat colonies are present and non-cavers entering caves are the most significant threats. Bat monitoring is carried out each winter in majority of Polish caves. Agricultural nitrates runoff impact cave water quality.
- Slovakia: state-owned caves are 99% preserved in original natural condition — a benchmark for institutional management.
- Spain: houses 22 of the world's 100 deepest caves; uses the COP method for karst vulnerability mapping; E_{ka}^I score 77 (Critical) reflects saline intrusion and aridification pressure in southern regions.
- Switzerland: employs Visual KARSYS for 3D hydrogeological modelling; glacial retreat is impacting stationarity assumptions for karst spring discharge.

3.2.3 The Central and Atlantic Platforms — Critical and Restoration Phase

Historically high pollution from agriculture and industry is now being managed through remediation programmes, but recovery is slow and many systems remain functionally degraded.

- Belgium: high cave density in Wallonia; Opération Dépollution manages legacy waste contamination; E_{ka}^I score 60 (Karst-Blind policy status).
- Germany: 14 991 documented caves; 685 officially recorded as destroyed; gypsum extraction in the South Harz constitutes an ongoing geodiversity emergency.
- Hungary: Aggtelek World Heritage site (712 caves) provides an internationally recognised reference for karst conservation.
- Poland (Krakow- Częstochowa Upland) : large bat colonies are present and non-cavers entering caves are the most significant threats. Bat monitoring is carried out each winter in majority of Polish caves. Agricultural nitrates runoff impact cave water quality.

3.2.4 Northern and Eastern Frontiers — Variable

Eastern frontiers face emergency-level pressures from resource over-extraction, while northern frontiers generally show good preservation status.

- Armenia: the Ararat Artesian Basin is in critical failure, with a 0.5 billion m³ annual extraction deficit; E_{ka}^I score 49 (Moderate).
- Georgia: hosting Hypogea 2026 (International Congress on Speleology in Artificial Cavities); 513 caves revealed in recent national inventory.
- Romania: Peștera Vântului hosts one of the highest levels of subterranean biodiversity recorded in the EU.
- Slovakia: state-owned caves are 99% preserved in original natural condition — a benchmark for institutional management.

3.3 Multi-National Data Matrix

(Data consolidation in progress and may contain minor provisional inaccuracies)

Cluster	Member States	Karst Coverage	Dominant Threat	E_{ka}^I Avg*
Alpine-Dinaric	SI, AT, IT, HR, RO, PL (South)	22–46%	Flash flooding / Pathogens	Moderate to High
Mediterranean	ES, EL, CY, MT, FR (S), PT	15–30%	Saline intrusion / Aridification	Critical
Central Platform	DE, FR (N), PL, CZ, BE, HU	10–25%	Agricultural nitrates	Moderate
Baltic / Northern	EE, LV, LT, SE, FI, DK	5–15%	Silicate vs. carbonate mix	Low
Atlantic / Island	IE, UK (England)	10–20%	Urban runoff / Leaching	Variable

* E_{ka}^I figures shown are provisional and should not be used as validated risk assessments.



Krizna Jama (Krizna cave), Slovenia. Photo by P. Crochet

Part IV: Monitoring, Research and National Data

4.0 Landmark European Research Projects

Long-term monitoring is essential to understanding change in cave ecosystems. Recent advances have transitioned from local exploratory surveys to integrated digital and genomic monitoring frameworks.

Project	Focus	Countries / Scale	Link
PASCALIS	Groundwater biodiversity mapping; protocols for subsurface species assessment	BE, FR, IT, PT, SI, ES	pascalis-project.org
DarCo	Subterranean biodiversity; climate change scenarios; vertical dimension of conservation	EU-wide	n/a
KARST (ERC Synergy)	LiDAR 3D cave models; flood prediction and pollution modelling	16 European caves	idaea.csic.es
eLTER (Postojna-Planina)	Real-time karst critical zone monitoring; soil-cave water dynamics	Slovenia	izrk.zrc-sazu.si
WATERWISE	Digital toolboxes for sustainable Alpine karst water management (2021–2027)	Alpine Space	alpine-space.eu
WOKAM	Global karst aquifer map; vulnerability to urbanisation and climate change	Global / UNESCO	whymap.org
DIKTAS	Transboundary Dinaric karst; equitable water use and ecosystem protection	HR, BA, ME, AL	diktas.iwlearn.org
KARMA	Mediterranean karst groundwater; contamination early warning systems	Mediterranean	karma-project.org
SNO KARST	French national karst observatory network; long-term hydro-geochemical data	France (9 stations)	sno-karst.fr
Sub-BioMon	Standardised eDNA methods for karst biodiversity monitoring	EU-wide (proposed)	n/a
DECACLIM	Decorated caves under climate changes : Redefining an effective conservation strategy	France	https://anr.fr/Projet-ANR-22-CE27-0027

4.1 National Speleological Data Profiles

Croatia (HR) — Dinaric Strategic Water

- Karst coverage: 52% of national territory (29,400 km²).
- Caves: 4 979 documented; 39% are vertical systems.
- Groundwater: 78% of total renewable underground water stored in karst aquifers.
- Biodiversity: 520 new taxa described from Croatian cave localities — a global hotspot for subterranean science.
- Clean Underground citizen programme started in 2015: over 900 polluted sites identified; 140 locations cleaned <https://cistopodzemlje.info/en/o-nama/>.

France (FR) — Observational Excellence

- Karst coverage: 35% of land area.
- Caves: more than 50 000 documented.
- SNO KARST: national network of 9 observatories providing long-term hydro-meteorological and geochemical data.
- Conservatoire du milieu souterrain: land acquisition or agreement for active cave management.
- Development of regulatory protections (strong protection areas) mainly for bat protection.

Germany (DE) — The Systematic Registry

- Karst coverage: 12% of land area; carbonate aquifers present in 21% of territory.
- Caves: 14 991 documented; 685 officially recorded as destroyed or lost.
- Biodiversity: 766 known cave species; biokataster.de tracks 280 000 individual records.
- Critical issue: aggressive natural gypsum extraction in the South Harz region threatens unique global geodiversity heritage.

Italy (IT) — Citizen Stewardship

- Karst coverage: 22% of land area.
- Caves: more than 44,362 documented.
- Puliamo il Buio: since 2005, volunteers have removed 148 tons of waste and contributed 2.9 million hours of conservation work.
- Seawater intrusion: regions such as Puglia face extreme coastal aquifer contamination; more than 96% of coastal monitoring samples show marine influence.

Poland (PL) — High-Altitude Monitoring

- Karst coverage: approximately 20% of total land area.
- Caves: 5 800. The Carpathians is a very diverse region with 1 600 non-karst caves and around 1 000 karst caves.
- Stygobiont fauna: more than 80 species.
- Trogllobiont fauna: about 30 species or subspecies.
- Number of speleologists: approximately 1 500.
- Monitoring focus: Carpathian and Kraków-Częstochowa karst systems.
- Key indicators: bat population trends and agricultural nitrates runoff impacts on cave water quality.

4.2 Scientific Critique of Prioritisation Approaches

Current conservation prioritisation frameworks for cave systems suffer from several methodological limitations that undermine their effectiveness:

- Inventory bias: richness-based protection lists systematically favour well-studied caves (which accumulate more species records) while ignoring poorly documented systems that may harbour equal or greater biodiversity.
- The troglophile problem: international rankings frequently include troglophile species (not restricted to caves), diluting protection for genuinely endemic trogllobionts.
- Legislative redundancy: in nations such as Romania, species-specific cave prioritisation is partially redundant because Habitat 8310 under the EU Habitats Directive already covers almost all natural subterranean voids.
- Biodiversity focus bias: current frameworks prioritise biodiversity (especially bats) to the systematic exclusion of geodiversity, hydrological, and cultural heritage values. A holistic approach encompassing all four dimensions of subterranean heritage is essential.



Lava Tube, Mount Etna, Sicily, Italia. Photo by J.-M. Verdet

Part V: Policy Recommendations

The following recommendations are addressed to the European Commission, EU Member State governments, national environmental agencies, and FSE member federations. They are structured in order of urgency and institutional level.

5.0 EU Legislative and Governance Priorities

5.0.1 Nature Restoration Regulation (NRR) Implementation

- All EU Member States must submit their National Nature Restoration Plans to the European Commission by September 2026. For the 23 States where it is present they have to include subterranean environments (Habitat 8310 and associated karst groundwater bodies).
- Restoration targets for cave habitats should be aligned with the ECT framework conditions defined in the 2025 Technical Guidelines.

5.0.2 Water Framework Directive (WFD) Update

- Mandatory karst vulnerability mapping must be integrated into WFD Source Protection Zone delineation for all identified karst groundwater bodies.
- The Karst-Aware Paradigm — recognising conduit-dominated flow, rapid contaminant transport, and the failure of Darcy-based models in carbonate terrain — must be formally incorporated into WFD technical guidance.

5.0.3 Geodiversity Protection

- EU Member States should elevate geotopes to the legal protection status currently afforded to biotopes, halting the ongoing destruction of karst geodiversity heritage by extraction industries (gypsum, limestone, dolomite).
- An EU-wide recycling mandate for construction gypsum should be explored to reduce pressure on natural karst gypsum landscapes.

5.0.4 Natura 2000 Reform

- The current disproportionate focus on biodiversity (especially bats) within cave Natura 2000 management plans must be addressed.
- Management plans for cave Natura 2000 sites should explicitly incorporate geological heritage, groundwater quality, and cultural/archaeological heritage dimensions alongside biodiversity objectives.

5.0.5 Shared governance

- Establishment of EU-level coordination body for subterranean heritage governance. The concept for such a task force could draw inspiration from CECAV (Brazil, <https://www.gov.br/icmbio/pt-br/assuntos/centros-de-pesquisa/cavernas>) and seek to bring a European coherence to issues such as: scientific research, management actions and assistance for the conservation of cave environments and associated species. This request merits serious consideration in the context of the Nature Restoration Regulation implementation.

5.1 Monitoring and Data Priorities

- Implement the Ecosystem Condition Typology (ECT) framework for Habitat 8310 (DOI: <https://doi.org/10.2779/7667114>), monitoring across all 23 EU Member States where this habitat is present, ensuring harmonisation of assessment variables and methods.
- Develop and fund the Sub-BioMon eDNA programme as a standardised, non-invasive tool for subterranean biodiversity monitoring, overcoming physical accessibility barriers.
- Support national cave registry development: at minimum, all Member States should achieve Cave Registry Indicator (CRI) Level 2 (centralised national database) within the current legislative cycle.

- Require mandatory national federation of speleology data submission to ECPC as a condition of FSE membership, ensuring EECO data quality for future editions.



Waste removal at a phosphatière, Quercy, France. Photo by P. Tyssandier

5.2 Citizen Science and Civil Stewardship

- Formally recognise national speleological federations as authorised environmental monitoring partners in the context of WFD and Habitats Directive reporting.
- Integrate the CaveLife app as the recommended standardised digital data-entry tool for citizen science contributions to national cave monitoring databases.
- Scale up citizen-led cave clean-up initiatives modelled on Italy's Puliamo il Buio, Croatian Clean Underground citizen programme and the Clean Up the Dark programme to all FSE member nations: <https://cleanupthedark.org/>.
- Explore EU LIFE or Horizon funding mechanisms for national federation monitoring activities.
- Clean Underground citizen programme started in 2015: over 900 polluted sites identified; 140 locations cleaned <https://cistopodzemlje.info/en/o-nama/>.



Waymarking to protect sensitive areas, Quercy, France. Photo by B. Piaudel

5.3 Research Priorities

- Commission at least two pilot basins per Member State for full E_{ka}^I calibration studies, with tracer-informed validation and comparison against contamination event histories.
- Develop a European research project focusing on the cultural heritage – both tangible and intangible, historical and contemporary – of caves and karst features.
- Fund the DarCo and Sub-BioMon projects to completion to establish cost-effective subterranean biodiversity baselines across European biogeographical regions.
- Develop an EU-coordinated speleoclimate network to track subsurface micro-climate changes in diverse subterranean contexts feeding into IPCC climate assessment processes. Establish formal collaboration with Cecav (Brazil) and equivalent institutions in non-EU karst nations to exchange methodologies and build the EECO into a global reference framework.

Part VI: Selected Bibliography

A full bibliography of approximately 120 references is maintained in the FSE Digital Archives. The following represents the principal sources consulted for EECO 2026.

Global Environmental Assessments

- United Nations Environment Programme. (2019). *Global environment outlook 6: Healthy planet, healthy people*. Cambridge University Press. <https://www.unep.org/resources/global-environment-outlook-6>
- United Nations Environment Programme. (2024). *Global environment outlook 7: Summary for policymakers*. <https://www.unep.org/resources/global-environment-outlook-7>
- United Nations Environment Programme. (2025). *Global Environment Outlook 7: A future we choose – Why investing in Earth now can lead to a trillion-dollar benefit for all*. Nairobi. <https://wedocs.unep.org/handle/20.500.11822/49014>
- Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. <https://www.ipcc.ch/report/ar6/wg2/>
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). *Global assessment report on biodiversity and ecosystem services*. <https://ipbes.net/global-assessment>
- Slay M. E. (2019). *Protecting caves*. Encyclopedia of caves, Chapter 100, 830-835, Elsevier, Amsterdam.
- Zupan Hajna N., (2025). Caves and karst in global sustainability: The case for an international day, Nature-Based Solutions, Vol. 8, <https://doi.org/10.1016/j.nbsj.2025.100282>.

EU and EEA References

- European Environment Agency. (2020). *State of nature in the EU* (EEA Report No 10/2020). <https://www.eea.europa.eu/en/analysis/publications/state-of-nature-in-the-eu-2020>
- Šibík, J., Pérez Alberti, A., & Zuazu Bermejo, A. (2025). *Technical guidelines for assessing and monitoring the condition of Annex I habitat types: Caves not open to the public (8310)*. Publications Office of the European Union. <https://doi.org/10.2779/7667114>
- European Environment Agency. *Conservation status of habitats under the EU Habitats Directive [Article 17 Dashboard]*. <https://www.eea.europa.eu/en/analysis/indicators/conservation-status-of-habitats-under>

Karst Hydrology and Geomorphology

- De Filippi, F.M.; Sappa, G. (2025). *Recent Advances in Karstic Hydrogeology*, 2nd Edition. Water, 17, 2180. <https://doi.org/10.3390/w17152180>
- Ford, D. C., & Williams, P. W. (2025). *Karst hydrogeology and geomorphology: 21st century revision*. Wiley-Blackwell.
- Goldscheider, N., et al. (2020). *Global distribution of carbonate rocks and karst water resources*. Hydrogeology Journal, 28(5), 1661–1677. <https://doi.org/10.1007/s10040-020-02139-5>
- Goldscheider, N. (2010). *A holistic approach to groundwater protection zoning in karst areas*. Groundwater, 48(4), 501–510. <https://doi.org/10.1111/j.1745-6584.2009.00632.x>
- Kuniansky, E. L., Taylor C. J., Williams J.H., & Paillet F. (2022). *Introduction to karst aquifers*. The Groundwater Project. <https://doi.org/10.21083/978-1-77470-040-2>
- Lage, J.L. & Antohe B. V. (2000). *Darcy's experiments and the deviation to nonlinear flow regime*. American Society of Mechanical Engineers, Journal of Fluids Engineering, 122(3), pp. 619-625, <https://doi.org/10.1115/1.1287722>
- Ravbar, N., et al. (2026). *Integrated multi-scale ecohydrogeological monitoring of spatio-temporal dynamics in karst critical zones*. Journal of Hydrology, 669(Part A), <https://doi.org/10.1016/j.jhydrol.2026.135027>.

Climate Change

- Badino G. (2004). *Cave temperatures and global climatic change*. Int. J. Speleol., 33 (1/4), pp. 103-114. <https://doi.org/10.5038/1827-806X.33.1.10>
- Bartolomé, M., Moreno, A., Sancho, C. et al. (2024). *Reconstructing hydroclimate changes over the past 2500 years using speleothems from Pyrenean caves (NE Spain)*, Clim. Past, 20, pp. 467–494. <https://doi.org/10.5194/cp-20-467-2024>, 2024.
- Bourges, F., Lartiges, B., Perrier, F., Genty D., et al. (2023). *Global warming evidence in long-term temperature monitoring of heritage karstic caves*, EGU General Assembly, Vienna, Austria, 24–28 Apr 2023, EGU23-13666, <https://doi.org/10.5194/egusphere-egu23-13666>.
- Culver D. C. & Pipan T. (2010). *Climate, abiotic factors and the evolution of subterranean life*. Acta Carsologica, 39(3):577-586, <https://doi.org/10.3986/ac.v39i3.85>
- Di Lorenzo T., Avramov M., Galassi D. M. P. et al. (2023). *Chapter 20 - Physiological tolerance and ecotoxicological constraints of groundwater fauna*, Editor(s): Malard F., Griebler C., Rétaux S., Groundwater Ecology and Evolution (Second Edition), Academic Press, pp. 457-479, <https://doi.org/10.1016/B978-0-12-819119-4.15004-8>.
- Domínguez-Villar, D., Lojen, S., Krklec, K. et al. (2015). *Is global warming affecting cave temperatures? Experimental and model data from a paradigmatic case study*. Clim Dyn, 569–581 (2015). <https://doi.org/10.1007/s00382-014-2226-1>
- Festa F., Ancillotto L., Santini L., Pacifici M., Rocha R., Toshkova N., et al. (2023). *Bat responses to climate change: a systematic review*. Biol Rev, 98: 19-33. <https://doi.org/10.1111/brv.12893>
- Mammola S., Piano E., Cardoso P., Vernon P., Domínguez-Villar D., et al. (2019). *Climate change going deep: The effects of global climatic alterations on cave ecosystems*. Anthropocene Review, 6 (1-2), pp.98-116 , <https://doi.org/10.1177/2053019619851594>
- Obleitner, F., Trüssel, M. Spötl, C.,(2024). *Climate warming detected in caves of the European Alps*. Sci Rep 14, 27435. <https://doi.org/10.1038/s41598-024-78658-y>
- Vaccarelli I., Colado R., Pallarés S., Galassi D. et al. (2023). *A global meta-analysis reveals multilevel and context-dependent effects of climate change on subterranean ecosystems*, One Earth, Volume 6, Issue 11, Pages 1510-1522, <https://doi.org/10.1016/j.oneear.2023.09.001>.

Subterranean Biodiversity and Ecology

- Culver D. C. & Pipan T. (2019). *The Biology of Caves and Other Subterranean Habitats*, 2nd edition. Oxford, Oxford University Press, 301p.
- Deharveng L., Bedos A., Pipan T., Culver D.C. (2024). *Global Subterranean Biodiversity: A Unique Pattern*. Diversity, 16, 157. <https://doi.org/10.3390/d16030157>
- Deharveng, L., Stoch, F., et al. (2009). *Groundwater biodiversity in Europe (PASCALIS project)*. Freshwater Biology / Faunaltalia. <https://www.faunaltalia.it/fstoch/pdf/Deharveng%20et%20al.,%202009.pdf>
- Furey N.M. & Racey P.A. (2016). *Conservation Ecology of Cave Bats*. In: Voigt, C., Kingston, T. (eds) Bats in the Anthropocene: Conservation of Bats in a Changing World. Springer, Cham. https://doi.org/10.1007/978-3-319-25220-9_15
- Gibert, J., & Culver, D. (2009). *PASCALIS: Overview and main results*. In D. Culver & W. White (Eds.), World subterranean biodiversity.
- Meleg, I. N., & Moldovan, O. T. (2016). *Conservation of European cave fauna: A critique of the prioritizing system*. International Journal of Speleology, 45(3), 203–208. <https://doi.org/10.5038/1827-806X.45.3.1970>

Speleogenesis and Speleothems

- Audra P. & Palmer A.N. (2015). *Research frontiers in speleogenesis. Dominant processes, hydrogeologic conditions and resulting cave pattern*. Acta Carsologica, 44(3), pp. 315-348, <https://doi.org/10.3986/ac.v44i3.1960>
- Baker A. & Fairchild I. J. (2012). *Drip Water Hydrology and Speleothems*. Nature Education Knowledge, 3(10):16. <https://www.nature.com/scitable/knowledge/library/drip-water-hydrology-and->

[speleothems-26394838/](#)

Honiat, A., Bourges, F., Skali-Lami, S., Lartiges, B. (2025). *Measurements of water film thickness on cave walls and speleothems*. International Journal of Speleology, 54(3), ijs2568.

<https://doi.org/10.5038/1827-806X.ijs2568>

Jaillet S., Audra P., Barriquand L., Bruxelles L., Camus H., Dandurand G. (2025). *Temporalités spéléo-génétiques. Karst et grotte ne sont pas des synonymes*, Dynamiques environnementales, 54-55,

<http://journals.openedition.org/dynenviron/9135>

Sulfuric Acid Speleogenesis

Galdenzi, S., Cocchioni, M., Morichetti, L., Amici, V., & Scuri, S. (2015). *Fate of sulfide in the Frasassi cave system*. Chemical Geology, 410, 21–27, <https://doi.org/10.1016/j.chemgeo.2015.06.002>

Jones, D. S., et al. (2012). *Community genomic analysis of an extremely acidophilic sulfur-oxidizing biofilm*. The ISME Journal, 6(1), 158–170, <https://doi.org/10.1038/ismej.2011.75>

De Waele, J., et al. (2024). *Sulfuric acid caves of the world: A review*. Earth-Science Reviews, 250, 104693, <https://doi.org/10.1016/j.earscirev.2024.104693>

National and Regional References

Audra, P., et al. (2010). *Geomorphological Map of French Karsts and Subterranean Heritage*. Fédération Française de Spéléologie (FFS).

Buzjak, N., et al. (2023). *Waste in the karst: Results of the Clean Underground initiative*. Zagreb: Speleological Society.

Didonna, F., Balestra, V., & Stoch, F. (2025). *Environmental Outlook Status of Caves in Italy (EECO Italy - V2025)*. European Cave Protection Commission (ECPC) / Società Speleologica Italiana (SSI).

<https://www.eurospeleo.eu/ECPC>

Didonna, F., & Fleury, P. (2026). *European Environmental Caves Outlook (EECO 2026): Environmental Status, Pressures, and Conservation of Cave Ecosystems in Europe (Edition 1)*. Fédération Spéléologique Européenne (FSE) / European Cave Protection Commission (ECPC), Luxembourg, 36 pp.

<http://www.eurospeleo.eu/ECPC>

Fédération Spéléologique Européenne (FSE). (2026). *Official Directory of FSE Member National Federations*. <https://www.eurospeleo.eu/members/>

Fleury, P. (2025). *Clean Up the Dark in France 2025 — FFS National Report for World Cleanup Day*. Fédération Française de Spéléologie (FFS) / ECPC.

Fleury P. & Lankester M.-C. (2025). *Les engagements des spéléologues dans la protection du monde souterrain*, Dynamiques environnementales, 54-55, <http://journals.openedition.org/dynenviron/8958> ; DOI: <https://doi.org/10.4000/14y1b>

Maurice, L.D.; Farrant, A.R.; Mathewson, E.(2023). *Karst in the Chalk of East Anglia. BGS Karst Report Series : C3*. Nottingham, UK, British Geological Survey, 66p. <https://nora.nerc.ac.uk/id/eprint/536313>

Novak, R. (2025). *Clean Underground (Čisto podzemlje): Ten Years of Subterranean Waste Remediation in Croatian Karst (2015-2025)*. EECO Fact Sheet Croatia, Croatian Speleological Federation / ECPC.

Ollivier, C., et al. (2019). *PaPRIKa method for large karst aquifers*. Environments. <https://doi.org/10.3390/environments6030039>

Plan, L., & Decker, K. (2006). *Quantitative historical karst hydrology of the Northern Limestone Alps*. Journal of Hydrology, 329(1-2), 172–184. <https://doi.org/10.1016/j.jhydrol.2006.02.011>

Polish Geological Institute (PGI). (2024). *Jaskinie Polski (Caves of Poland National Database)*. PGI Internet Database. <https://jaskiniepolski.pgi.gov.pl/>

Urban, J., Dumnicka, E., Piksa, K., & Kicińska, D. (2024). *Environmental Outlook Status of Caves in Poland (EECO-Poland-1-fin)*. Polish Geological Institute & ECPC.

Verband der deutschen Höhlen- und Karstforscher (VdHK). (2021). *CaveLife App: Digital Assessment Tool for Cave Habitats (EuroSpeleo Protection Label Winner 2021)*. European Cave Protection Commission (ECPC). <https://www.eurospeleo.eu/ECPC/espl/>

Vogel, B., Köble, H., & Weigand, A. (2025). *Environmental Cave and Karst Outlook Germany (ECKO Germany)*. Verband der deutschen Höhlen- und Karstforscher (VdHK) / ECPC / UIS Repository. <https://www.caveprotection.org/country-reports>



Cleaning operation in a cave, Croatia. Photo by R. Novak

Compliance Statement on Artificial Intelligence and Document Transparency

Methodological & Technological Transparency

This research document and its underlying technical synthesis were compiled and structured with the collaborative assistance of advanced Artificial Intelligence systems (including Google Gemini and Anthropic Claude). AI models were utilized strictly as supportive tools for linguistic harmonization, data structuring, mathematical layout formatting, and source reference verification.

Data Protection & Ethical Compliance

All input datasets, hydrogeological indicators, and speleological inventories used in this document derive exclusively from publicly available academic literature, official institutional archives, and published national reporting frameworks. No proprietary, sensitive, or confidential personal data were exposed or processed. This methodology strictly adheres to the provisions of the **European Union Artificial Intelligence Act (EU AI Act - Regulation 2024/1689)** regarding transparency, oversight, and traceability, as well as the **EU Public Access to Documents Regulations (Regulation EC 1049/2001)** and general European standards on document open-access and scientific integrity.

Purpose & Institutional Intent

This document is published under the auspices of the European Speleological Federation (FSE) and the European Cave Protection Commission (ECPC) as an educational, screening, and awareness-building instrument. Its primary intent is to raise public, institutional, and scientific awareness regarding the environmental vulnerability of subterranean karst ecosystems, to promote rigorous cross-border research, and to encourage proactive cave conservation policies across all member nations of the European Speleological Federation.

Annex: E_{ka}^I — National calculation table

The following table presents the homogeneous application of the macro-level formula to a sample of FSE member countries, calculated based on inventory data and bibliographic research consolidated in the EECO 2026 report.

For calibration and data inquiries, contact the ECPC through the European Speleological Federation:

www.eurospeleo.eu

Index E_{ka}^I : short reminder

$$E_{ka}^I = E_{base} \times \Omega_a$$

$$E_{base} = (0.35 \times K_{dens}) + (0.25 \times C_{dens}) + (0.20 \times P_{anthrop}) + (0.20 \times (100 - G_{prot}))$$

Where:

- K_{dens} = Density and sensitivity of outcropping karst rocks.
- C_{dens} = Density of hypogean systems and caves with high ecological or hydrogeological value.
- $P_{anthrop}$ = Combined anthropogenic pressure resulting from land uses, agriculture, subterranean tourism, recharge water pollution.
- G_{prot} = Percentage of karst territory under legal protection (Natura 2000, National Parks, ...).
- Ω_a = Multiplicative factor of environmental governance and management.

The national index E_{ka}^I is obtained by multiplying a weighted base index (E_{base}) by an amplification/territorial governance factor (Ω_a).

Multi-National Comparative Data Matrix

The following table presents the homogeneous application of the macro-level formula for all 16 nations listed in Section 3.1. The data were obtained by an inventory data and bibliographic research consolidated in the EECO 2026 report.

Country (Code)	Karst Density Sub-score (K_{dens})	Cave Density Sub-score (C_{dens})	Pressure Sub-score ($P_{anthrop}$)	Protection Sub-score ($100 - G_{prot}$)	Base Sum (E_{base})	Multiplier (Ω_a)	E_{ka}^I Score*
Armenia (AM)	42.0	25.0	18.0	75.0	39.6	1.25	49 (moderate)
Austria (AT)	68.0	85.0	32.0	15.0	54.50	0.85	46 (moderate)
Belgium (BE)	35.0	72.0	60.0	45.0	51.3	1.18	60 (high)
Croatia (HR)	88.0	50.0	42.0	40.0	59.7	1.18	70 (high)
France (FR)	72.0	78.0	45.0	35.0	60.7	0.93	56 (moderate)
Germany (DE)	40.0	55.0	38.0	50.0	45.4	0.83	38 (low)
Greece (EL)	82.0	65.0	30.0	70.0	65.0	1.25	81 (critical)
Italy (IT)	75.0	82.0	52.0	60.0	69.1	1.20	83 (critical)
Malta (MT)	100.0	30.0	20.0	85.0	63.5	1.25	79 (critical)
Poland (PL)	30.0	42.0	50.0	50.0	41	—	n/a

Country (Code)	Karst Density Sub-score (K_{dens})	Cave Density Sub-score (C_{dens})	Pressure Sub-score ($P_{anthrop}$)	Protection Sub-score ($100 - G_{prot}$)	Base Sum (E_{base})	Multiplier (Ω_a)	E_{ka} Score*
Romania (RO)	n/a	n/a	n/a	n/a	—	—	n/a
Slovenia (SI)	92.0	95.0	28.0	10.0	63.6	0.85	54 (moderate)
Spain (ES)	80.0	48.0	55.0	70.0	65.0	1.18	77 (critical)
Switzerland (CH)	62.0	80.0	48.0	15.0	54.3	0.85	46 (moderate)
Turkey (TR)	78.0	45.0	22.0	65.0	56.0	1.18	66 (high)
United Kingdom (UK)	48.0	40.0	65.0	50.0	49.8	1.05	52 (moderate)

Step-by-Step Calculation Examples

Example 1: Calculation for France

- **Input Data:** $K_{dens} = 72.0$, $C_{dens} = 78.0$, $P_{anthrop} = 45.0$, $G_{prot} = 35.0\% \Rightarrow (100 - G_{prot}) = 65.0$. $\Omega_a = 0.93$.
- **Step 1 (Calculating E_{base}):**

$$E_{base} = (0.35 \times 72.0) + (0.25 \times 78.0) + (0.20 \times 45.0) + (0.20 \times 65.0)$$

$$E_{base} = 60.7$$
- **Step 2 (Multiplying by Ω_a):**

$$E_{kal} = 60.7 \times 0.93 = 56.4$$
- **Interpretation:** France falls into the **Moderate** vulnerability class. By adopting the macro-level formula, the national index benefits from a better weighting of legal protection coverage, while keeping open the possibility of calculating disaggregated regional sub-indices (e.g., Atlantic zone vs. Alpine/Pyrenean zone).

Example 2: Calculation for Italy

- **Input Data:** $K_{dens} = 75.0$, $C_{dens} = 82.0$, $P_{anthrop} = 52.0$, $G_{prot} = 40.0\% \Rightarrow (100 - G_{prot}) = 60.0$. $\Omega_a = 1.20$.
- **Step 1 (Calculating E_{base}):**

$$E_{base} = (0.35 \times 75.0) + (0.25 \times 82.0) + (0.20 \times 52.0) + (0.20 \times 60.0)$$

$$E_{base} = 69.1$$
- **Step 2 (Multiplying by Ω_a):**

$$E_{kal} = 69.1 \times 1.20 = 83.0$$
- **Interpretation:** Italy falls into the **Critical** vulnerability class. The elevated score is driven by the wide distribution of karst complexes (Prealps, Apennines, Apuan Alps, and islands) combined with intense anthropogenic pressure and a significant percentage of karst hydrostructures not included in formal protected areas.

Country Profiles Synthesis

EECO Italy (Italy)

- **Lead Authors/Contributors:** Ferdinando Didonna, Valentina Balestra, Fabio Stoch (Società Speleologica Italiana - SSI).
- **Key Data:** Karst covers ~50,000 km² (one-sixth of Italy). Over 100 years of exploration have documented **44,362 natural caves** and 5,155 artificial cavity systems across 20 regions. Major systems include Codula Ilune (>70 km, Sardinia), Pian del Tivano (>60 km, Lombardy), Monte Corchia (>56 km, Tuscany), Col delle Erbe (>45 km, Friuli Venezia Giulia), and Piaggia Bella (>40 km, Piedmont).
- **Conservation & Stewardship:** Protected under EU Habitat Type 8310 and Habitat 8330 (marine caves). Civil stewardship includes the SSI campaign "*Puliamo il Buio*" (Clean Up the Dark), which has extracted over 148 tons of waste from caves since 2005.
- **Index Value:** E_{kal} Score=83 (Critical Risk).

EECO France (France)

- **Lead Authors/Contributors:** Philippe Fleury (Fédération Française de Spéléologie - FFS).
- **Key Data:** Major karst regions across the Pyrenees, Alps, Massif Central, and Jura. High observational standards for hydrogeological monitoring.
- **Conservation Projects:** Active involvement in transnational species conservation via *LIFE MinioPtère* (targeting *Miniopterus schreibersii*) and annual World Cleanup Day subterranean operations.
- **Index Value:** E_{kal} Score=56 (Moderate Risk).

EECO Croatia (Croatia)

- **Lead Authors/Contributors:** Ruđer Novak (Croatian Speleological Federation).
- **Key Data:** Dinaric karst underlies over 88% of the country, containing vital strategic freshwater aquifers.
- **Stewardship Highlight:** The national program "**Clean Underground**" (*Čisto podzemlje*), launched in 2015, maps, catalogs, and physically remediates illegal waste dumps in karst caves and sinkholes.
- **Index Value:** E_{kal} Score=70 (High Risk).

EECO Poland (Poland)

- **Lead Authors/Contributors:** Jan Urban, Elżbieta Dumnicka, Krzysztof Piksa, Ditta Kicińska (Polish Geological Institute & Polish Speleological Societies).
- **Key Data:** Over 5,800 caves recorded (total length >234 km). Key areas include the Tatra Mts. (Inner Carpathians, with Jaskinia Wielka Śnieżna at ~24 km), Outer Carpathians (non-karst flysch caves), Silesian-Kraków Upland (Upper Jurassic limestone), Nida Basin (gypsum karst), and Sudetes.
- **Protection Status:** Database managed online by PGI (jaskiniepolski.pgi.gov.pl). Strict protection within National Parks (e.g., Tatra NP), with variable protection levels in external regions.
- **Index Value:** E_{kal} Score= Data Pending.

EECO Germany (Germany)

- **Lead Authors/Contributors:** Bärbel Vogel, Hannes Köble, Alex Weigand (Verband der deutschen Höhlen- und Karstforscher - VdHK).
- **Report Designation:** Officially designated as **ECKO Germany** (*Environmental Cave and Karst Outlook Germany*) in national documentation and deposited in the UIS repository.
- **Key Data:** Comprehensive cave inventories across Franconian/Swabian Alb, South German Mesozoic limestone, and Alpine karst, with strong regulatory integration for groundwater and bat hibernacula protection. Developer of the *CaveLife App* for standardized habitat condition recording.
- **Index Value:** E_{kal} Score=38 (Low Risk).



Ice river, Eiskogel Cave, Tennengebirge, Austria. Photo by P. Crochet

— EECO 2026 Edition 1 —

© 13th September 2026

European Speleological Federation (FSE) – European Cave Protection Commission (ECPC)
email : protection@eurospeleo.eu – <http://www.eurospeleo.eu/ECPC>