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Extended abstracts



Karst imaging using Electrical Resistivity Tomography; A case study from West Benghazi Plain, Libya

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The Benghazi coastal plain is highly affected by karst features, including dolines, dissolution cavities, and subsurface voids, which present significant risks to infrastructure and future urban expansion. These features primarily develop within the fossiliferous limestone of the Middle Miocene Benghazi Formation. To overcome the limitation of traditional point-based borehole geotechnical investigation, this study employs two-dimensional Electrical Resistivity Tomography (ERT) at representative coastal sites along the west Benghazi plain. Data were acquired using Wenner–Schlumberger electrode configuration to resolve resistivity contrasts associated with voids, fractures, and irregular bedrock. The inverted ERT profiles successfully imaged bedrock topography, water zones, weak zones and distinct low-resistivity anomalies indicative of potential dissolution features. Results were validated against available borehole data, showing strong consistency. The study confirms that ERT is a reliable and effective tool for defining subsurface karst geometries and detecting high-risk zones. The study also recommends ERT as a critical tool for pre-construction site investigations and risk mitigation in karstic region.

Comparison of radon and CO₂ renewal dynamics in a cave with an upper opening (L-shape) – Port-Miou underground laboratory (France)

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The air in caves can have a different composition from that of the outside atmosphere, depending on the production of gases within the karst system and the renewal of air in the cave. Two gases, radon and carbon dioxide (CO₂), can be found in high concentrations in karst. Radon is produced by the natural decay of uranium present in rocks, soils and karst fillings. It can also be transported by groundwater. It is a short-lived radioactive gas (half-life 3.8 days), which accumulates in high concentrations in poorly ventilated spaces. CO₂ in epigenetic karsts is produced in the soil. It then migrates to the depths of the unsaturated zone, either as a gas or dissolved in water. The concentration of CO₂ strongly influences the processes of carbonate dissolution and precipitation; CO₂ plays a major role in karstification. In decorated caves, where prehistoric paintings and engravings are preserved, variations in the concentration of CO₂ in the air (and water) can cause the degradation of rock art, either through the deposition of calcite veils or, conversely, through the alteration of the rock supporting the artworks. CO₂ also plays a role in the formation of speleothems and influences paleoclimate records. Both gases are harmful to human health when inhaled in high concentrations. Thus, the study of radon and CO₂ in cave air (or more broadly, underground voids) is relevant to several major issues.

Gases concentrations in caves vary over time and differ between the various compartments of the karst system (i.e. within the cave itself, within the vertical distribution of karst voids). These variations depend on the shape and connectivity of each karst network. Karst networks with several openings to the outside generally promote ventilation between the cave and the outside throughout the year. Conversely, caves with a single upper opening (L-shape) generally have extremely contrasting exchanges with the outside, depending on the season. In addition to the shape of the cave, climatic and hydrological conditions control the dynamics of gases exchanges. Monitoring radon and CO₂ thus provides information on airflows and air renewal in caves, as well as on gases production rates and equilibrium times.

The goals of the study presented at Eurokarst are:

- (1) to show the measuring devices deployed at two underground sites in southern France for continuous monitoring of radon in the air, and CO₂ at one site;
- (2) to identify the processes that explain the variations in these gases over time, based on a 1.5-year time series acquired at the Port-Miou underground site (France), which is characterised by an L-shaped cave with a single opening at the top;
- (3) study the site's return to equilibrium following artificial ventilation, which allowed the entire air in the cave to be renewed.

The first part of the study aims to validate radon measurements acquired by low-cost instruments (Radon Eye Plus 2 model) by comparing them with measurements taken using the Rad7 reference instrument installed at the Laboratoire Souterrain Bas Bruit (France). Then, since December 2024, the Port-Miou site (France) has been equipped with a Radon Eye Plus 2 instrument (pulsed ion chamber) and a Vaisala GMP 251 CO₂ sensor (infrared light source; the sensor head is heated to prevent condensation), as well as monitoring by passive radon dosimeters at intervals of 2 to 4 months (Etched track detectors). The Port-Miou underground laboratory site features a 44-meter-deep vertical shaft, followed by a 50-meter-long horizontal gallery at the end of which the air measurement instruments are installed, and providing access

to a natural cave at the bottom of which the Port-Miou underground and submarine river flows to the sea within a karst conduit under pressure. Additional data includes: air temperature and pressure inside and outside the cave, as well as precipitation at a weather station (Météo-France).

The results cover a period of 18 months. Seasonal patterns are clearly identified: (1) a cold period outside, between November and March, during which concentrations of both gases are low in the cave, close to those in the outside air, and (2) a hot period outside, between April and October, which blocks air renewal, during which gases concentrations increase and then reach a plateau. The maximum values exceed 5% for CO₂ and 5,000 Bq/m³ for radon. Diurnal oscillations show natural ventilation of the cave due to the drop in outside temperature during the night, which is sufficient to partially promote air renewal at the site. Artificial ventilation events show a faster return to equilibrium for radon than for CO₂.

The simultaneous measurement of these two gases provides a better understanding of ventilation mechanisms, connections with the surface and hydro-climatic forcings, while providing essential information for assessing the radiation exposure of staff working underground.

This work has been carried out in partnership between the CNRS "Milieux Souterrains et Karsts" (MSK), French Karst National Observation Service (SNO Karst), CEREGE Laboratory, and Low noise underground laboratory (Laboratoire souterrain à Bas-Bruit LSBB).

La grotte Cosquer et le changement climatique : une grotte ornée face à la montée des eaux (Marseille, France)

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La grotte Cosquer est une grotte ornée du sud de la France, dont les parois accueillent des peintures et des gravures préhistoriques de plus de 30 000 ans. Située sur le littoral méditerranéen, elle est en partie noyée par la mer Méditerranée et accessible uniquement par plongée du fait de la montée du niveau de la mer. Pourtant un phénomène naturel exceptionnel abaisse chaque année les plans d'eau de la grotte, qui se retrouvent plus bas que le niveau de la mer, sauvant pour quelques mois l'art pariétal. Cette conférence vous propose d'accompagner une équipe de chercheurs pour comprendre pourquoi la grotte est partiellement noyée, comment l'étude du niveau d'eau est organisée par des missions sur le terrain et au laboratoire, et quelles sont les prévisions pour l'avenir. Étudier cette grotte c'est participer à préserver un trésor culturel qui s'est conservé sous terre au cours des millénaires, et aussi appliquer des méthodes interdisciplinaires pour caractériser notre environnement. Vous découvrirez qu'au cœur du fonctionnement hydroclimatique de la grotte reliée à la mer se trouve la combinaison extraordinaire de caractéristiques physiques locales qui favorisent des échanges d'air et d'eau inattendus. De l'air emprisonné par les vagues sur les falaises à l'extérieur de la grotte arrive à traverser le massif rocheux et se retrouve piégé, repoussant l'eau de la grotte. Mais certaines années peu pluvieuses, le niveau de l'eau remonte plus vite, montrant que la perméabilité de la roche joue aussi un rôle majeur. Cette conférence mêlera archéologie, géologie, hydrogéologie, océanographie, et changement climatique.

Evolution and fate of karst aquifers: from water to oil reservoirs

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The long-term (i.e., tens to hundreds of millions of years) evolution of karst aquifers is seldom researched, as studies in karst hydrogeology tend to be focused on practical issues or present and short-term (i.e., thousands of years) scenarios. Even modeling efforts rarely extend beyond a few thousand years. The decoupling of karst aquifer history from Earth's evolution leads to gaps in knowledge regarding how karst aquifers evolve through time. In a simplistic view, karst aquifers are uplifted from the phreatic zone, transition through the vadose zone, and are eventually removed by surface denudation. In this scenario, the life history of a karst aquifer could comprise timescales of c. 1–10 Ma, depending on the tectonic history of a given karst area—just a snapshot when compared to the history of carbonate sequences.

However, there are alternative scenarios in which carbonate rocks undergo subsidence/burial and become oil reservoirs. Globally, about 60% of all oil and 40% of all gas reservoirs are hosted within carbonate karst voids. The vague definition of paleokarst-related oil reservoirs, common in petroleum literature, does not reveal the long history since the inception of the original karst aquifer. In particular, the development of very high permeability zones associated with so-called “super-k” horizons—unlike what is commonly seen in karst hydrology—is of particular interest to the genesis of exploitable carbonate oil deposits. Furthermore, very little is known about how the water-to-oil/gas transition takes place and how karst aquifers behave once they become hydrocarbon deposits.

The data to be presented is based mostly on the ultra-deep (> 5 km) offshore pre-salt oil fields in Brazil but should be applicable to other sites. Some key issues and open questions include:

- What are the timescales involved in the transition from water-filled to oil-filled voids?
- Due to pressure and recrystallization, secondary (fractures) and tertiary porosity (voids) tend to decrease at depth, lowering the potential storage of the reservoir. How does this reconcile with the physical stability of oil-filled voids under pressures related to thousands of meters of depth?
- Are void geometries controlled by bedrock discontinuities, as in karst aquifers, or are there other factors (for example, geochemical fronts) at play?
- How do oil and gas interact geochemically with the bedrock, and how does this affect the geometry and evolution of oil-filled karst voids?
- Are collapse features inherited from previous shallow karst stages (i.e., paleokarst), or were they generated following the burial phase?
- Due to the presence of tufas and other subaerial features, caves are, at least in part, formed by near-surface processes. But what is the role and relative importance of hypogene karst?
- What are the sealing characteristics of karst oil reservoirs? Once depleted, are they suitable for CO₂ storage?
- Due to depth, costs, and logistics, to what extent can near-surface accessible caves be used as analogues?

Understanding the long-term evolution of karst aquifers and the subsequent transition to karst oil fields is crucial to recognizing how karst aquifers mature over million-year timescales. It can further help determine whether knowledge and concepts based on present karst aquifers can be applied to decipher the occurrence, geometry, and geo-biochemical behavior of karst oil and gas reservoirs.

Evaluation of groundwater (fissured limestone) suitability for irrigation purpose using irrigation water quality indices: case study of Tebessa plain, Algeria

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Groundwater quality is essential for meeting freshwater demands, especially in water-scare semi-arid regions, necessitating thorough evaluation. This study focuses on assessing the groundwater quality of the Tebessa aquifer system a vital source catering to diverse needs. Challenges such as water stress, urbanization, aridity and population growth increase water demand and exacerbate inherent quality issues. Intensive agricultural and industrial activities further deteriorate groundwater quality. Among the sectors reliant on this resource, irrigation stands out as the largest consumer of water. Groundwater is the only practical option for irrigation when surface water is unavailable because of inadequate precipitation or other circumstances in an agriculture dominated area. The Tebessa Plain (called Merdja) is located in northeastern Algeria and extends over 974.4 km² in a synclinal basin filled with water from the alluvial aquifer widely used for irrigation. The aim of this work is to study the hydrochemistry of these waters, and the suitability of these waters for irrigation. Indicators of water irrigation quality such the sodium absorption ratio (SAR), sodium percentage (%Na), magnesium hazard (MH), permeability index (PI) and Kelly's ratio (KR), have been used to understand and assess the results. As a result, the water of alluvial aquifer exhibits excellent to good quality for irrigation.

Reassessing karst connectivity in the Barrois Limestone: A methodological framework for multi-spectral fluorimetric data correction

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As part of the hydrogeological study of the Barrois Limestone Program conducted by Andra and BRGM, a new synthesis of previous tracing results was carried out. This synthesis highlighted numerous historical tracer tests, including several multi-restitution tracer tests conducted in the 1970s over distances going from several hundred meters to more than 20km.

Some of these tests reportedly reached karst resurgences in the lower Saulx Valley (Figure 1), as well as in the adjacent valleys of the Ornain and Marne rivers. The multiplicity of these restitutions complicates the groundwater delineation and, consequently, the operational management of these karst hydrosystems. This motivated new tracing campaigns to better delineate karst systems and refine the karst interbasin boundaries between the Ornain, the Saulx and the Marne watersheds.

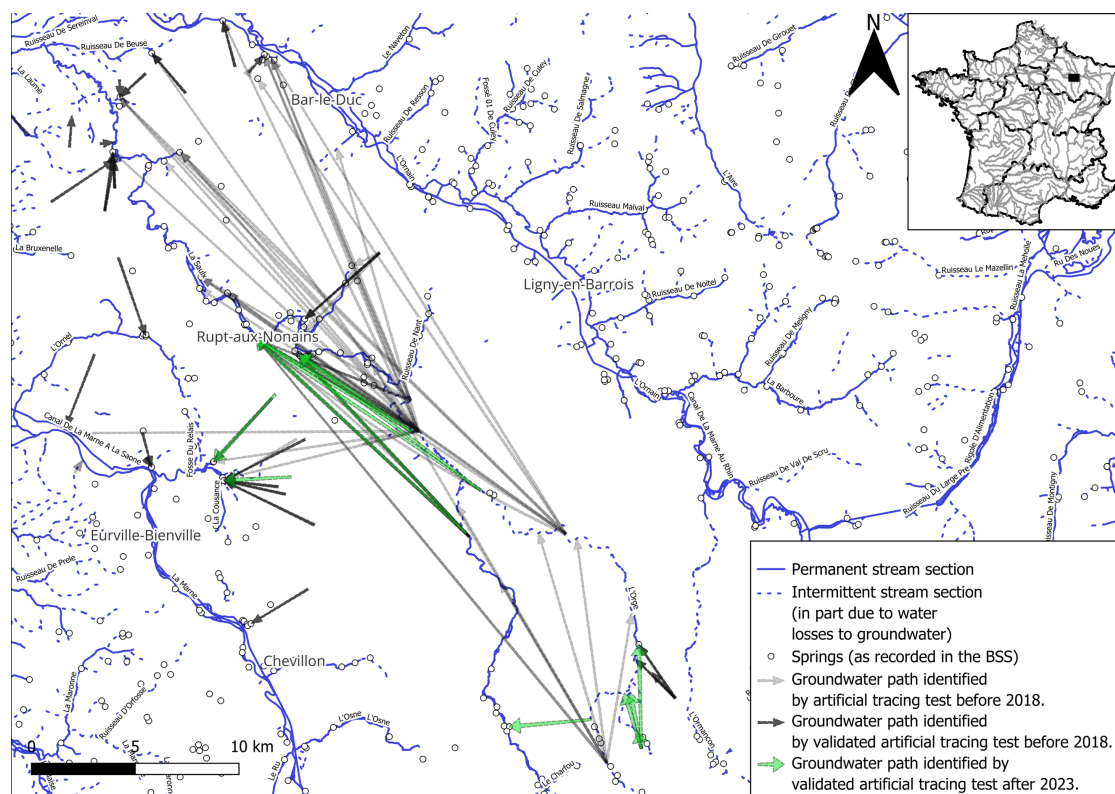


Figure 1. Saulx River watershed: Groundwater flow paths identified by tracer tests and their reliability.

The Saulx River basin exhibits eclipse karst behavior, with highly variable drying locations along its tributaries (La Bureau, L'Orge), while the main course of the Saulx River remains active most of the year. A first tracer campaign clarified the fate of infiltrated water from two sinking sections of the Orge river, in the upstream section (downstream from Saudron, and from the Bureau tributary) and near its confluence with the Saulx River. The hydrogeological

conditions observed in autumn 2025 were particularly dry, allowing for the realization of two others tracer tests from two successive total water losses in the Saulx River near Morley and Ménil-sur-Saulx. Finally, a third campaign, conducted in collaboration with ASHM (a local French speleological association), helped refine the boundaries of the Saulx/Marne interfluve, supplementing existing data in this sector (Jaillet, 2005).

This presentation builds on these results to emphasize the importance of reassessing the reliability of older tracer test data. It also demonstrates the use of an original method for correcting background noise to better describe tracer restitution dynamics using high-frequency, multi-spectral monitoring. Adapted from Bailly-Comte et al. (2018) and Schnegg and Le Doucen (2006), this method first corrects for interference caused by the presence of another tracer during multi-tracer tests, using laboratory calibration data. A multiple linear regression analysis then calculates the natural background noise captured by the other optics of the multi-spectral fluorimeter. These processes produce a corrected time series, free from natural or induced perturbations, enabling the characterization of the tracer signal even at low intensities (see Figure 2).

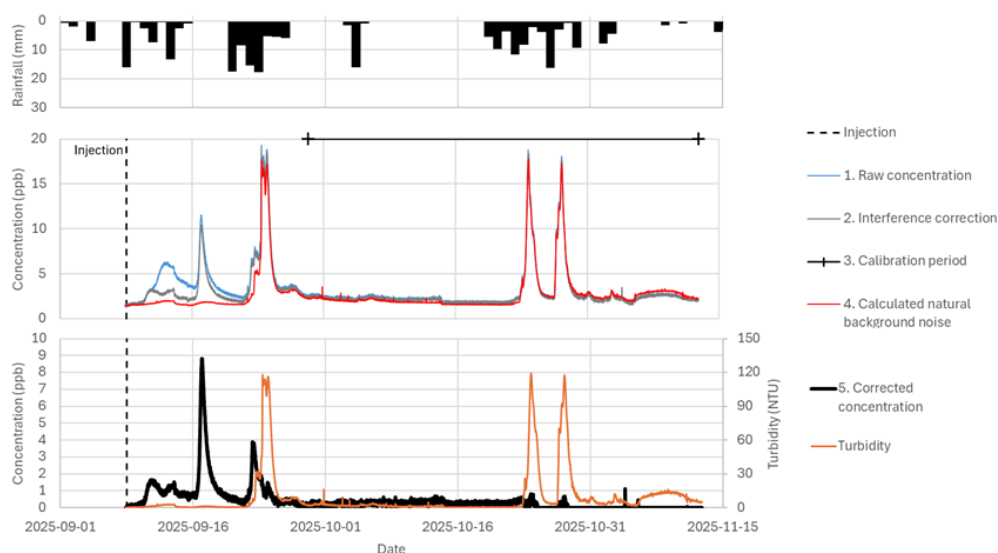


Figure 2. Workflow correction of multi-spectral fluorimetric time series at the Moulinet spring during the tracer test in the Saulx River sinking stream near Ménil-sur-Saulx (13 kg of sulfo-rhodamine B injected on 08/09/2025) – Daily rainfall data from SAFRAN database.

This correction allows for a finer characterization of the hydrodispersive properties of the karst system, including potential multi-modal restitutions. The application of this method and its findings will be discussed in this presentation.

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How does groundwater recharge relate to weather and climate? Integrating cave drip water hydrology, stalagmites, and modelling

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Since 2010, our team has been measuring the flux of drip water through several Australian cave systems using a network of automated Stalagmate © drip loggers (Figure 1). Our aim: to determine the timing of potential groundwater recharge events and relate that to weather patterns and climate drivers. At some sites, enough events have occurred to allow the analysis of the timing of recharge events and the amount of precipitation needed (e.g. Baker et al., 2020; Figure 2, site 5). However, in a water-limited continent, potential recharge events are rare and at some sites not numerous to publish yet (e.g. at Wellington, shown in Figure 1; site 5 in Figure 2).

In 2022, we expanded our monitoring network to include other underground spaces, such as mines and tunnels, across a wide range of fractured rock geologies to form Australia's National Groundwater Recharge Observing System (NGROS) (Figure 2). First results from this network, described in Baker et al (2024), show that the amount of rainfall needed to generate groundwater recharge is the same between karst and non-karst sites and that daily rainfall in the top-decile of precipitation is needed for all sites (Priestley et al., 2025a). The infrequent precipitation events that can lead to groundwater recharge can be related to specific synoptic weather patterns (Figure 3) and seasonal variations in rainfall driven by the state of climate drivers such as El Niño – Southern Oscillation. Linking groundwater recharge to precipitation amounts and specific weather events helps make groundwater more 'visible' to both the public and to policy makers.

Our NGROS network currently covers 20 sites across Australia, half of which are in karst geologies (Priestley et al 2025b). Drip water hydrology time series have been used to develop a drip water typology for karst lithologies of different geological age (sites 1-5 and 14; Figure 2; Sun et al., 2025) and investigate the role of soil moisture and vegetation in predicting recharge events at karst and non-karst sites (Kumar et al., 2025; karst sites 1-3, 5, 8 in Figure 2). Three of the sites (sites 2, 3 and 5; Figure 2) are those where monitoring started over a decade ago, and these form the foundation of a five-year project 'Caves and stalagmites: linking Climate to Groundwater recharge' (C2G). At five sites, where rainfall is sensitive to climate drivers, we are in the process of analysing stalagmite geochemistry to obtain records of past recharge for the last few hundred years (for example, Priestley et al. 2023). In our water-limited environments, stalagmite oxygen isotope time series are a good proxy for groundwater recharge in the past. Over the period of instrumental climate records, time series will be used to provide initial constraints on a karst recharge model, Var Karst-R (Hartmann et al., 2021), and over recent centuries, will help elucidate the relationship between climate drivers and groundwater recharge. The long-term drip water hydrology time series of potential recharge events will be used to further constrain the Var Karst-R model over the last ~15 years, with future recharge scenarios assessed for a range of climate projections, including different climate driver states and greenhouse warming scenarios. Our modelling approach will also allow the investigation of the impacts of fire on groundwater recharge through damage to soil cover, loss of vegetation, and associated changes in evapotranspiration and soil water storage capacity: intense fire has been observed to decrease the amount of rainfall needed for recharge to occur at one of our sites (site 4; Song et al., 2025).

Here, we present our integration of cave drip water hydrology, stalagmite geochemistry, and climate and recharge models, to improve our understanding of how groundwater recharge relates to weather and climate. Our cave hydrology and stalagmite geochemistry results from karst sites across the Australian continent show consistent patterns: for all sites, at least 20 mm of rainfall in a 48-hr period is typically needed for a groundwater recharge event to occur, which results in a strong seasonality in the occurrence of relatively infrequent recharge events. Initial results using this integrated approach to help constrain a karst recharge model will be presented.



Figure 1. Drip loggers at Cathedral Cave, Wellington (site 3)

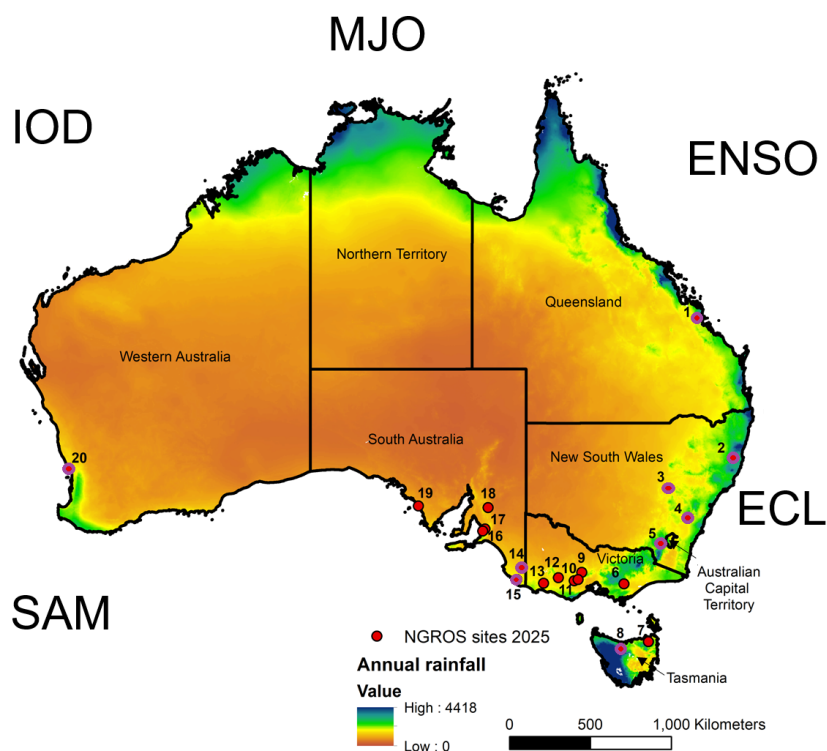


Figure 2. NGROS sites. Karst sites are shown in purple.

Wombeyan Caves, NSW



Event number	Date of recharge increase	48hr precipitation (mm)	Rain station
1	01/09/2023	17.0	063093
2	04/01/2024	30.2	063093
3	18/01/2024	18.4	063093
4	06/04/2024	166.0	063093
5	06/05/2024	43.2	063093
6	06/06/2024	135.0	063093
7	04/07/2024	14.4	063093
8	26/07/2024	23.6	063093
9	08/12/2024	24.6	063093
10	15/01/2025	60.8	063093
11	08/02/2025	45.6	063093
12	22/05/2025	76.4	070144

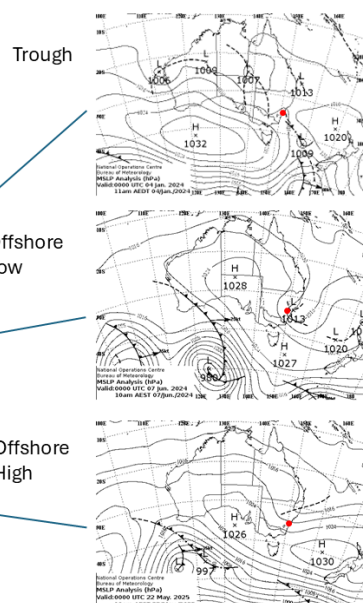


Figure 3. Recharge events at Wombeyan Caves (site 4) and associated weather patterns.

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Distributed modelling of karst aquifer accounting for heterogeneities and karst features – Preliminary results applied to the Lez aquifer.

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Karst aquifers are highly heterogeneous and exhibit significant variations in hydraulic properties throughout the system due to different porosity of each of their different media (matrix, fault and fractures, conduits). Modelling is commonly used to study karst systems with a variety of approaches (Jourde & Wang, 2023) but modelling flow through karst aquifers using a triple porosity system (karst network, fault network and a porous matrix) remains challenging.

Accordingly, a statistical modelling approach used for the generation of karst networks considering both the fault networks organization and the inception layers is proposed to simulate karst conduit networks. The model is adapted from the work of Verscheure et al. (2012) for the modelling of sub-seismic faults which organization is characterized by a fractal dimension. The generated karst network is then considered for flow modelling using an embedded model based on the work by Ricois et al. (2016). This model is applied to perform flow modelling at the scale of the Lez aquifer, a well-documented and equipped karst system in Southern France, which currently supplies drinking water to more than 300 000 people. Preliminary results will be presented, as well as planned areas of research.

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A harmonised European scale approach for mapping groundwater vulnerability in karst regions

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According to the World Karst Aquifer Map (WOKAM), carbonate terrains cover 22% of the European land surface (Chen et al. 2017). Furthermore, karst aquifers are a primary source of high-quality freshwater for human activities, with 25% of the European population living on karst (Goldscheider et al. 2020). However, karst aquifers are typically formed of solutionally-enlarged fast pathways or by-passed infiltration and so may be especially sensitive to leaching of dissolved contaminant compounds released on the Earth's surface. In Europe more than 50% of the land on carbonate terrains is used for agriculture (as identified by CORINE Land Cover 2018) and so there is a need to accurately predict the local attenuation capacity to such associated contaminant leaching in a wide range of local settings and conditions. It is therefore essential to assess and map the karst aquifer groundwater vulnerability in those regions, reliably discerning different leaching mechanisms and drivers.

A literature review highlighted that a variety of different index-rating methodologies are currently used to assess the groundwater vulnerability at catchment scale in karst areas (Iván and Mádl-Szőnyi 2017). This was initiated in 2004 by the COST action 620, a collective effort to build a European framework for vulnerability assessment (European Communities 2004), which proposed a method, called COP, focused on three main aspects: the concentration (i.e. infiltration conditions), the overlying layers (i.e. hydrogeological settings), and the precipitation (i.e. driver). This method has been complemented by the Slovene approach with a fourth factor: K for the karstification status (Ravbar and Goldscheider 2007). Since then, the COST framework has been refined and amended in different ways by different countries, focusing on different aspects of the complex karst environments. Two main examples are PaPRIKa in France (Ollivier et al. 2019) and EPIK in Switzerland (Jeannin 2025). Contrary to the COP framework, both PaPRIKa and EPIK exclude precipitation as an input. They use different approaches to evaluate the karstification factor: based on local knowledge of the karst network for EPIK, and on recession curves analysis for PaPRIKa. Different methods applied to the same catchment result in different vulnerability maps, thereby needing validation through detailed hydrogeological studies (Marín et al. 2012).

Most of the above methods were developed using local catchments on the basis of well-studied (data-rich) individual aquifers; this, however, makes it challenging to apply such methods at a wider continental scale. These methods rely on local knowledge and expert judgement, which means that they need to be adapted and harmonised to suit a more global application. It should also be noted that groundwater vulnerability in karst areas is not mapped uniformly at a European level, which prevents policy-makers and local authorities from having a useful tool for managing such territories. This work, therefore, aims to address the lack of harmonisation between the methods to develop a more suitable harmonised approach for use at a much wider scale, as a credible and uniform framework for many different karst conditions across Europe. A crucial point in this process is the availability (or extrapolation) of good-quality, reliable and harmonizable data at a sufficient resolution. Hence, all relevant data sources across Europe (such as national geological surveys) have been examined and classified uniformly, based upon a rigorous understanding of the leaching mechanisms of agricultural contaminants. A consistent framework is now being developed based on all the previous methods and newly classified indices, to be more universally applicable.

The proposed approach is based on the initial categorisation, following a few simple steps and assumptions, of two conceptually different types of karst environment, often known as “conduit” and “diffuse” karst (Ford and Williams 2007), which result in two different

behaviours and drivers in relation to vertical leaching. In *Extreme Vulnerability* conditions (conduit karst), the meteoric water promptly enters into the underground system, with little vertical attenuation only related to surficial settings and features. Alternatively, in *Mixed Vulnerability* conditions (diffuse karst), the karst system is more protected beneath a depth of soil / subsoil, so the rainwater (and any mobilised contaminants) infiltrate slowly through such porous media which act to attenuate the contaminant loading dynamics depending on their characteristics and depths.

The overall aim is to develop a harmonised approach to mapping groundwater vulnerability, integrating local knowledge of the different karst aquifers, which can be applied across the full extent of European karst areas. The resulting uniform map is expected to be a valuable tool to inform agricultural practices and policy.

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Characterising karst recharge processes using soil moisture observations across different climates and land cover types

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Previous research has shown that soil and epikarst play a key role in karst recharge processes, and that climate and vegetation strongly control hydrological processes in the shallow subsurface. In this study, recharge characterization across different climates and land-cover types was therefore investigated using soil moisture measurements collected at five karst sites representing a wide range of climatic conditions: tropical, Mediterranean, oceanic, mountainous, and semi-arid.

At each site, two plots were instrumented, one located in grassland and one in woodland. Soil moisture was monitored at hourly resolution at three depths (5 cm, 10 cm, and at the soil/epikarst interface), and daily precipitation data were used to identify hydrological events.

Vertical drainage fluxes were then simulated using a drainage model applied to soil moisture measurements at the bottom depth, where evapotranspiration effects are assumed to be minimal. These simulated fluxes were used to qualitatively assess recharge processes and to estimate annual recharge volumes.

The proportion of precipitation events leading to a soil moisture response decreased with depth, reflecting the influence of evapotranspiration. This proportion was, however, often higher under woodland, suggesting a more efficient transfer of water towards the soil despite canopy interception. Nevertheless, thinner soils and deeper vegetation water uptake in woodland must be considered when assessing recharge to the saturated zone. The ability of the drainage model to reproduce recharge events across the different sites indicates that this approach is promising at the event scale and highlights the influence of soil moisture on karst recharge.

Determination of general hydrological dynamics and spatial deviations in water level on the Cerknisko polje

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Cerkniško polje is one of the most prominent karstic areas in Slovenia and has been the subject of various scientific explorations since the 17th century. It is about 40 km² large flat depression with a complex recharge-discharge system consisting of numerous karst springs, streams, estavelles, swallow holes and ponor caves. When inflows exceed the outflow, the polje starts to flood and can generate a large lake up to 27 km² in area which can remain for up to 8 months per year.

The flooding dynamics of Cerkniško polje are under strong influences of both climate change and different human interventions over the years, which were carried out to either shorten (regulation of riverbeds and widening of swallow holes) or prolong (construction of dams, clogging of swallow holes) the floods according to changing local interests. This study aims to determine the impact of climate change and human interventions on the polje's flooding dynamics. The analysis was done on the basis of more than 70 years of continuous meteorological and hydrological observations within the Cerkniško polje recharge area. Long-term observations show changes in the meteorological dynamics which are reflected by general drop of the water level and seasonal changes with the most significant water level decreases observed during springs and summers. Over different periods human interventions also impacted the hydrological dynamics with both decreases and increases of the water level.

An important part of the study was also dedicated to detailed determination of flooded areas at various water levels, which turned out to be quite challenging. Because of the large size of the polje and its complex recharge and discharge, the lake's water surface is usually slightly tilted. For a better determination of spatial and temporal deviation in water level, we established continuous water level measurements at several places on the polje. New observations showed an almost flat water surface at the highest levels and several decimetres deviation in water level at moderate levels. Additionally, a new precise digital model of relief was made using photogrammetry when the polje was dry and most of vegetation was cut. In a combination with satellite imagery, we produced new maps showing more accurate extent of the lake surface under different hydrological conditions.

The study confirmed that long term meteorological and hydrological observations are very important to determine the general hydrological characteristics, impact of climate change and impact of human activities. A more dense network of hydrological observation is also important for analyses of specific areas. Such data and studies are crucial for a better understanding of the relationship between poljes' hydrology and ecology (ecohydrology) and for development of future management strategies, which are necessary due to constant changes of the karstic environment.



Figure 1. Partly inundated Cerknjško polje with various habitat types, land use and other human interventions.

Acknowledgement

This study is taking place within the project “Determination of ecohydrological response of karst areas to climate change and human activities – example of Cerknjško polje”, no. J7-70248 and programmes” Karst Research” (P6-0119) and “Plant Biology” (P1-0212), all financially supported by the Slovenian Research Agency, and projects “LIFE-TRŠČA” (LIFE22-NAT-SI-LIFE TRSCA - 101114184) and “eLTER - European Long-Term Ecosystem and socio-ecological Research Infrastructure”, both partly supported by the European Commission. Equipment has been supported by projects “Development of research infrastructure for the international competitiveness of the Slovenian RRI space – RI-SI-EPOS and RI-SI-LifeWatch”, supported by the European Regional Development Fund.

Modeling the development of keyhole passage morphology

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Cave passage morphology is an important indicator of the paleohydrological conditions under which a cave passage was formed. Keyhole passages are a commonly occurring type of passage morphology that consists of a round, wide top with a smaller canyon incised into the bottom of the passage. These passages typically indicate a shift from phreatic to vadose conditions. However, there are multiple mechanisms by which such a transition can occur, and little is understood about which of these mechanisms is most common, or whether aspects of keyhole morphology may indicate the primary formation mechanism. We tested several hypothesized ways to model keyhole passage formation using caveCHAMP, a physically based cave evolution model that can simulate the evolution of passage shape along an extended conduit including effects of ventilation and CO₂ dynamics in the air-filled portion of the conduit.

We have identified three main mechanisms that can form a keyhole: a sharp decrease in discharge, base level fall, and epiphreatic processes. Each mechanism produces a keyhole shape, with a unique geometry dependent on the process. We have simulated the change to keyhole morphology along a conduit and shown that the cross section maintains consistent geometry throughout the passage when created by a sudden decrease in discharge. In contrast, the keyhole widens and becomes less distinct upstream when created by base level fall or epiphreatic processes. For a keyhole to be created through epiphreatic processes, the system must be in a vadose regime for the majority of the time it is being eroded.

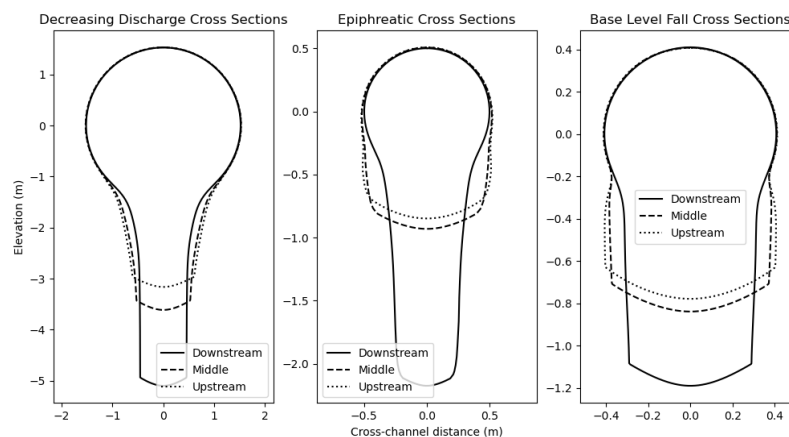


Figure 1: Cross section diagrams of keyholes formed by the three mechanisms.

We have discovered that a difference in the depth of the slot in the keyhole over the length of the passage reveals the original slope of the feature that formed the passage. The slot is entirely formed in a vadose regime, indicating that this may be a trend which can be applied to understanding non-keyhole vadose passages. We have also discovered that the distinctiveness of a keyhole shape, specifically the ‘corner’ formed by the transition from phreatic to vadose, is controlled by the timescale during which the phreatic-to-vadose transition occurs. To quantify changes in cross section shape, we have developed a set of parameters to describe the shape of the cross section. These parameters compare the widths of several parts of the keyhole, the depths of the different components of the keyhole, and the radius of curvature on the ‘corner’ of the keyhole. By measuring these differences in morphology in the field, we may be able to ascertain the primary formation mechanism responsible for the formation of the keyhole, as well as some of the paleohydrological conditions under which it formed.

Hydrodynamic modeling of fault zone impacts: Compartmentalization and preferential recharge in a semi-distributed lumped karst aquifer model

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Fault zones can influence groundwater flow in contrasting ways and are often described as structures acting either as conduits or as hydraulic barriers. However, their influence remains poorly understood, particularly in karstified carbonate aquifers, where the heterogeneity of the environment, the organization of karst networks, and the high rate of exchange between surface water and groundwater increase both system complexity and vulnerability. The interaction between karstification and fault structures generates localized hydrogeological behaviors. At the aquifer scale, these interactions constitute preferential zones of exchange between surface and subsurface, playing a key role in preferential infiltration processes and in the vulnerability of water resources.

In this context, this study proposes an adapted model structure and flow formulation that simultaneously integrates the effects of compartmentalization and the areas of rapid and concentrated recharge induced by tectonic structures. The model is based on a semi-distributed discretization based on current knowledge of the organization of flows within the Lez karst system. Spatialization is based on a representation in reservoirs, weighted both by their surface area and by the spatial distribution of precipitation.

This approach provides an operational framework for analyzing the impact of faults on aquifer dynamics and resource vulnerability, while reproducing the rapid hydrodynamic responses characteristic of karst systems. The simulated volumes associated with rapid flows linked to preferential infiltration within fault zones are consistent with existing estimates for the study site validating the ability of the model to represent these processes.

Finally, the model enables the estimation of parameters directly related to aquifer structure, which can be adjusted according to the availability of observations. It is therefore a relevant tool for integrated and forward-looking groundwater management, taking into account the combined effects of geology, tectonic structure, and karst, while offering the possibility of defining predictive performance criteria consistent with the modeling objectives.

Insights on speleogenesis through multi-scale observations

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Karst systems are highly heterogeneous formations, shaped by the dissolution of soluble rocks by acid fluids. Their heterogeneity is not only due to large-scale structures (faults, fractures), but also to strong variability within the rock matrix itself (Bakalowicz, 2005). Variations in petrophysical properties (porosity, permeability), and pore structure (pore-size distribution, specific surface area, pore connectivity) create sharp contrasts in the flow properties and reactivity of the rock matrix (Abdullah, 2021). These small-scale heterogeneities can therefore strongly control speleogenetic pathways and the long-term evolution of karst networks.

To better understand the interplay between transport and mineral reactivity in carbonate karst environments, we descend to the scales of the matrix and grains to investigate reactive transport processes. We compare two different outcrop carbonate formations, Euville and Lavoux limestones, and perform flow-through dissolution experiments on both bulk samples and powders of different particle sizes.

For bulk samples, significantly different dissolution patterns are obtained for Euville and Lavoux limestones under similar hydrodynamical conditions (Figure 1). In the case of Euville limestone, dissolution is distributed throughout the entire volume of the sample, while in the case of Lavoux limestone, it is much more localized, with dissolution channels concentrating most of the dissolution. The origin of these different dissolution patterns is attributed to differences in microstructures (pore connectivity mostly): intragranular microporosity is more accessible in the case of Lavoux limestone, thus offering a larger mineral surface area to react with the fluid, whereas flow is mostly constrained to the macroporous network in the case of Euville limestone (Briolet *et al.*, 2025). When changing the hydrodynamic conditions (lower flow rate), similar localized dissolution patterns are observed for both Euville and Lavoux limestones. This result suggests that, under conditions more favorable to diffusion, larger reactive surface areas can also be accessed for Euville limestone. This interpretation, implying significant control of microstructural properties and transport regime on dissolution processes, is validated numerically through transport simulations (Lattice-Boltzmann method) (Figure 2).

Powder samples of different grain sizes are obtained by grinding bulk samples. The differences in microstructural properties are thus eliminated to preserve only differences in grain structure. Column dissolution experiments reveal that, for both Euville and Lavoux limestones, the reactive solution reaches conditions close to equilibrium regardless of grain size and flow rate. This result can be explained by the much larger mineral surface area accessible to the reactive fluid for experiments on powders compared to experiments on bulk samples. This result questions the representativeness of grain-scale experiments for the study of reactive transport at larger scales.

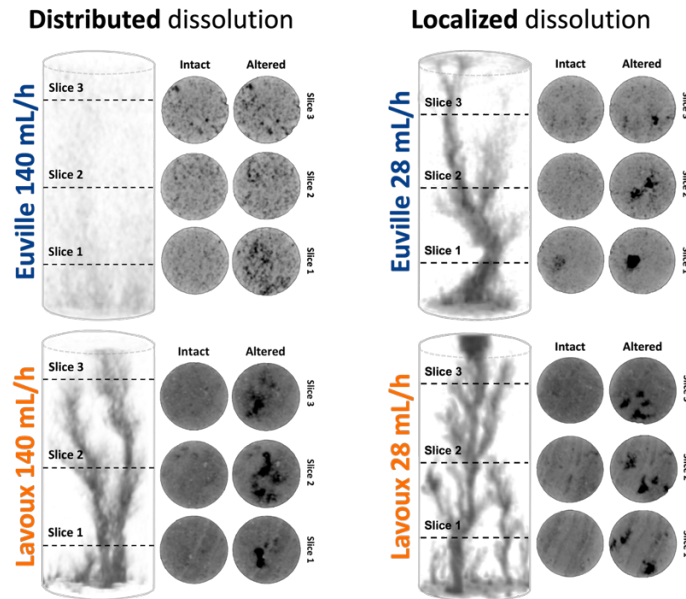


Figure 1. Dissolution patterns on bulk samples obtained under different flow rate conditions for Euville and Lavoux limestones. Dissolution is distributed in the case of Euville limestone altered at high flow rate and localized at lower flow rate, while dissolution remains localized for Lavoux limestone under both hydrodynamic conditions.

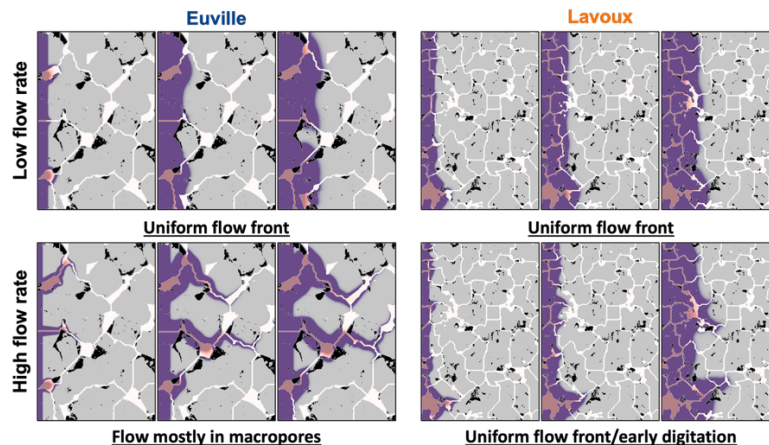


Figure 2. Transport simulations at low and high flow rates for Euville (left) and Lavoux (right) limestones. At low flow rates, the fluid can access the entire porous volume (and associated reactive surface) for both Euville and Lavoux limestones. For high flow rates, the entire porous volume remains accessible for Lavoux limestone, while the flow is mostly constrained to the macropore network in the case of Euville limestone.

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Characterization of a large database of karst cave networks using graph-based metrics

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Karst aquifers exhibit conduit networks shaped by complex speleogenetic processes acting over geological timescales. These networks control groundwater flow, storage, and vulnerability, yet their internal geometry remains difficult to characterize systematically, particularly at large spatial scales. Graph-based approaches provide a powerful framework to represent cave networks as mathematical objects and to quantify their topology and geometry using reproducible metrics (Collon et al., 2017, Jouvès et al., 2017). In this study, we apply this graph analysis workflow on a large worldwide database of clean cave survey datasets (Trunz et al., 2026). The objective of this work is to characterize the geometry and topology of those caves in relation to their environment and provide a framework to simulate or constrain the simulation of karst networks in inaccessible locations.

The cave survey database is composed of 370 clean individual cave networks originating from multiple countries and exploration contexts. Raw survey data were collected by cavers with different caving software and were homogenized, cleaned, and converted into undirected spatial graphs (Trunz et al., 2026). In these graphs, nodes represent survey stations, and edges represent surveyed segments. Additional information, such as geometric attributes or survey annotations, is stored on the nodes or segments. The dataset includes caves spanning several orders of magnitude in size and complexity. In addition, for each cave, we collected contextual metadata from scientific literature, speleological reports, and global geospatial datasets to support interpretation of structural patterns. Those metadata include the description of geological settings, deformation and fracturing intensity, climate regimes, and speleogenetic context.

Each individual cave (or connected component) is characterized using a set of geometric, topological, and scaling metrics derived from previous studies (Collon et al. 2017, Jouvès et al. 2017, Hendrick and Renard 2016). We calculate those topology and geometry metrics with the Karstnet Python toolbox (<https://github.com/karstnet/karstnet>) complemented by individual Python scripts.

Violins of the selected statistical metrics for clean connected components of caves

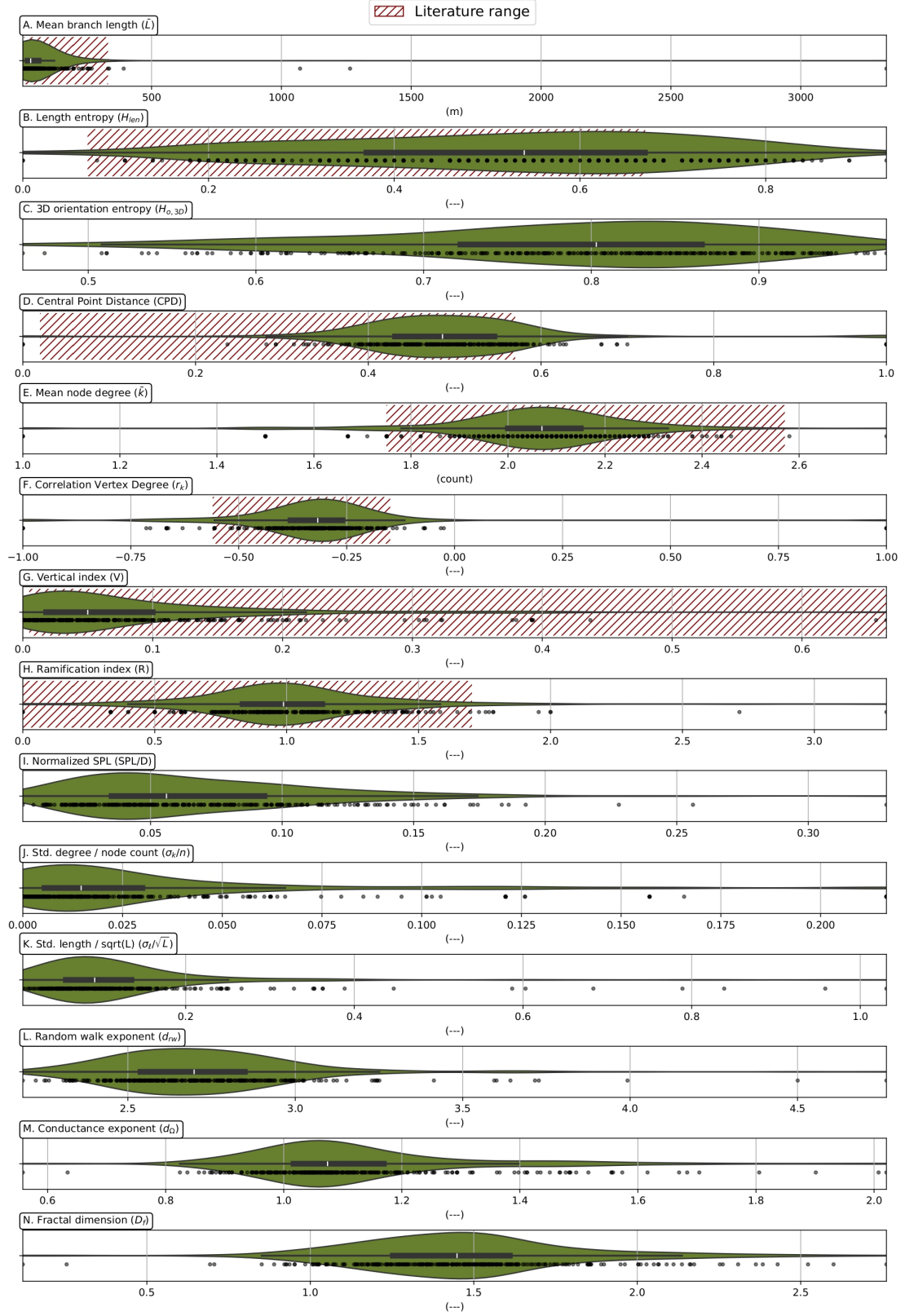


Figure 1. Violin plots of the distribution of statistical metrics results for all the datasets. The literature ranges are taken from Collon et al. (2017) and Jouvès et al. (2017).

First, we evaluated the results for the clean database with the metrics calculated on the raw dataset to evaluate the impact of cleaning over the metrics results. Results (Figure 1) demonstrate that cleaning is a prerequisite for meaningful characterization of karst networks. Removal of survey artifacts significantly reduces variability in metric distributions and eliminates extreme values. Degree-related metrics and ramification indices increase after reconnection of legitimate links, while path-length descriptors decrease following removal of redundant segments, highlighting the strong influence of survey practices on connectivity indicators. The new results show, as expected, a broader range of statistical metrics than previously observed (Hendrick and Renard 2016, Collon et al. 2017, Jouvès et al. 2017).

Thirdly, we used rank-based correlation analysis to identify redundant descriptors and highlight independent structural signatures. Fourthly, we used single, bi-variate, and multi-variate analysis between the metrics to identify patterns in topology or geometry based on the metadata we collected.

Correlation analysis between the statistical metrics reveals strong associations among degree-based and geometric descriptors, whereas diffusion-related metrics capture complementary aspects of network organization.

Finally, we attempted an empirical classification of the cave networks based on the classification proposed by Palmer (1991) using a combination of the statistical results and structural geology metadata (Figure 2). This analysis shows that branchwork and maze-type networks can be partially distinguished using graph metrics, but unsupervised clustering fails to clearly isolate karstic systems with complex morphologies. This highlights both the potential and current limitations of global graph descriptors for cave classification.

Repartition of connected components by cave morphology

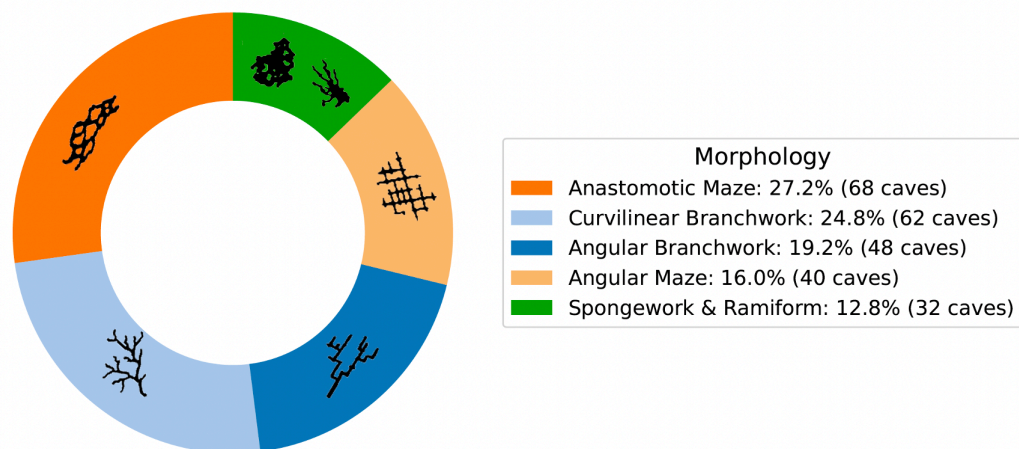


Figure 2. Rule-based classification of the processed datasets derived from Palmer's classification (Palmer, 1991). This classification is based on a mix of statistical tools and structural metadata information.

Finally, results show that graph metrics efficiently capture rather simple geometric and topological organization but remain limited in describing the internal variability of complex or multi-phase cave systems. This highlights the need for additional developments, such as local-scale descriptors, network segmentation approaches, and refined diffusion-related metrics, to better represent structural heterogeneity and improve morphogenetic interpretation.

Acknowledgments

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To what extent does karst control the water system of the MIKAS Gihon Spring and Hezekiah's (Siloam) Tunnel?

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The Gihon Spring is the principal natural freshwater source of ancient Jerusalem, and was probably the motive for settlement some 4,000 years ago. It is a perennial karstic spring issuing from Turonian limestones and dolomites on the eastern slope of the “City of David” hill. The spring drains a perched aquifer; its average discharge and salinity are 0.6 MCM/year and 220 mg Cl/L, respectively (Amiel et al., 2010; Sneh et al., 2010). Until the last century, the spring was characterized by a pulsating behavior. The chemical composition of the water indicates circulation through carbonate rocks, with significant impact from urban anthropogenic activity in the catchment area (e.g., high nitrate concentrations and the presence of fecal coliforms). The spring was reliable enough to sustain urban life; however, its location outside the earliest city walls necessitated the construction of artificial systems to secure the water supply.

The Gihon spring is one of four MIKAS springs in Israel. In consultation with the MIKAS project manager, Zoran Stevanović, it was chosen to be on the list not because of its aesthetic/ ecological/ economic uniqueness, but due to its outstanding historical importance. The Spring is mentioned in the Bible as the site of King Solomon's inauguration (I Kings 1: 33-45), and later became known in Christianity as the 'Virgin Fountain'. Its most prominent biblical narrative concerns King Hezekiah, who ordered the diversion of the spring's waters into a reservoir within the city walls in preparation for the imminent Assyrian siege in 701 BC. A new tunnel was constructed to convey the spring's water to the Siloam Pool via a protected underground route (II Kings 20:20; II Chronicles 32: 2-4, 30). The tunnel named Hezekiah's or the Siloam, which still functions today, is renowned for its sinuous course, its near-horizontal gradient (a gentle slope of 0.05%, or 32 cm between entrance and exit), the absence of vertical man-made ventilation shafts to the surface (except for one natural shaft), and the fact that it was excavated simultaneously from two opposite ends, as commemorated in the 2,800-year-old Siloam Inscription. It is widely accepted that the tunnel is man-made; however, the techniques employed by the diggers remain under debate – whether the tunnel followed a natural, karst-guided route or is entirely a primary human-engineered design. At the core of the debate, three key arguments must be addressed: (1) Why did the two tunneling teams follow such a long and winding route (533 m; Fig. 1) instead of a much shorter, straight-line course (318 m)? (2) How did the two teams, working simultaneously from opposite ends, manage to meet? (3) How was the problem of ventilation overcome - an indispensable requirement for miners at the blind end of a narrow passage and for the oil-burning lamps?

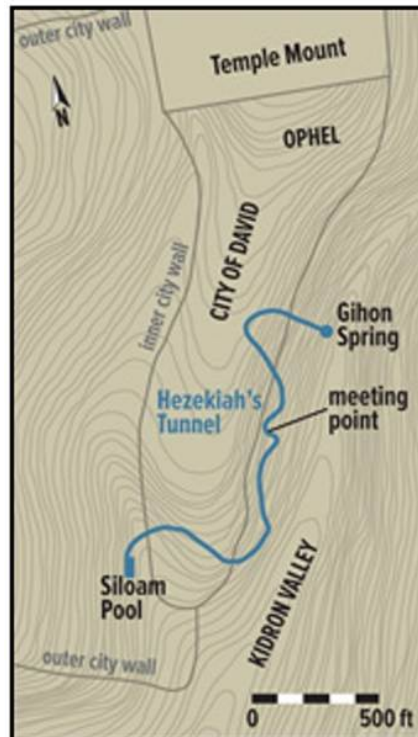


Figure 1. Map of ancient Jerusalem at the end of the eighth century BC (from Shanks, 2013).

According to the proposed karst-guided model, the quarrymen exploited and widened a pre-existing natural karstic conduit or a chain of interconnected dissolution cavities developed along fissures (Gill, 1991; Gill and Burg, 2013, and also Sneh et al., 2010, with some modifications). The hewing of the tunnel obliterated most of the original karst dissolution features; however, some features that exceeded the dimensions of the original karstic conduit are still visible in the form of dissolution cavities and small vertical shafts in the ceiling. Gill (1991) and Gill and Burg (2013) emphasize that only the karst-guided model adequately addresses the three major challenges noted above, namely the winding route, underground orientation, and essential ventilation. This model also explains the absence of man-made ventilation shafts and the extremely low gradient tunnel, interpreted as the result of a sub-horizontal karstic pathway.

The alternative interpretation attributes the tunnel entirely to intentional human decision-making, assuming it was hewn according to a predesigned engineering plan. Proponents of the “no-karst” scenario proposed three methods by which the quarrymen could have been guided from the surface: (1) acoustic communication, whereby sound waves produced by knocking on the bedrock above the tunnel were used for routing (Frumkin and Shimron, 2006); (2) charting the route on the surface by identification of intersections of prominent joints, which could supposedly also be recognized in the subsurface, and instructing the quarrymen to reach these nodal points (Reich and Shukron, 2007); (3) exchanging directional and distance information between the hewers and surface planners, who plotted a chart on the ground that mimicked the progress of excavation and enabled them to direct the quarrymen accordingly (Rosenberg, 1998).

This abstract is dedicated in memory of my colleague, Dr. Dan Gill, who, more than anyone else, revealed the karst phenomena of the Gihon Spring system.

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Linking fracture and karst network orientations in the Tsanfleuron aquifer system, Swiss Alps

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The influence of structural geology on karst development has been extensively described, with particular emphasis on the role of fractures in generating preferential dissolution pathways. Alignments between fractures and conduits are commonly observed in regions where the tectonic history imprints fracture patterns that enhance dissolution. To test the hypothesis that fractures play a major role in karst development, we test whether the orientation of fractures and karst features are similar by statistically comparing their azimuths in the karst system of Tsanfleuron, in the Helvetic domain of the western Swiss Alps. We interpret fracture alignments on a scale of 1:2.500, using an open dataset of a high-resolution digital elevation model (DEM) and an orthomosaic from a drone acquisition. The fracture interpretation was validated through field observations. The karst dataset was acquired by the Groupe de Spéléologie Rhodanien, the Société Spéléologique Genevoise, the Spéléo-Club Jura, and the Groupe Spéléo Lausanne. We calculate the azimuths from the fracture interpretation and karst surveys. We identify dolines as circular to elliptical depressions on the DEM. To identify doline alignments, edge detection was first applied to a binary image of mapped dolines, followed by Hough Transform. The Hough Transform converts each point in the image space into a family of possible lines in the Hough space, where collinear points produce intersections corresponding to dominant alignment parameters. These intersections define the equations of continuous lines that pass through the dolines in image space. The superposition of structural and karstic features on maps and the plot of their direction in rose diagrams show that some fracture sets coincide with the orientation of most of the conduits in the study area. A quantitative approach is proposed to verify how similar the distributions of fractures, conduit and doline alignments are by applying statistical tests such as the chi-squared test. The analysis consists of 1) binning azimuths according to the selected angular interval, 2) computing expected frequencies from the observed distributions, 3) calculating the chi-squared statistics to evaluate whether the distributions differ significantly. The null hypothesis assumes that both distributions are statistically similar, meaning that any observed differences are due to random variations, and the alternative hypothesis is that the distributions are significantly different. If the chi-squared test yields a value under the significance level of 5%, we reject the null hypothesis, suggesting that the two distributions are significantly different. When considering the complete azimuth range, from 0° to 180°, the null hypothesis cannot be rejected, indicating that fracture and conduit orientations are statistically similar. In addition, analyses of specific directional intervals reveal no statistically significant differences, with high significance values, particularly in the NE-SW, ENE-WSW, and E-W directions. Although based on fewer observations, doline alignments also show a preferential NE-SW orientation. We conclude that the fracture and karst conduit azimuth distributions are similar. These results suggest that fracture networks together with stratigraphy and the gentle dip of the bedding, act as the primary structural controls on karst development, mainly along the NE-SW, ENE-WSW, and E-W directions.

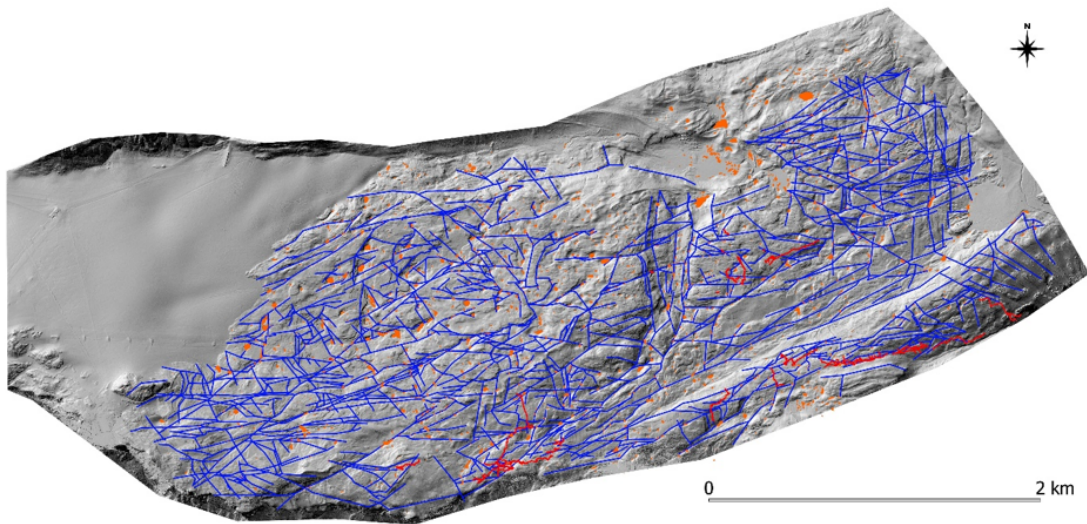


Figure 1. Fracture network interpretation (blue), karst networks from mapped caves (red) and dolines (orange). Base map: Hillshaded DEM from UAV at 10 cm/px resolution.

Where does the water come from? Recharge source contributions to the Manavgat karst system, Central Taurus, Türkiye

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The Manavgat River is one of the major rivers in southern Türkiye, discharging into the Mediterranean Sea. Its catchment is located within the Central Taurus karst belt, where previous studies have demonstrated a strong contribution of karst groundwater to river discharge. Consequently, hydrological models that consider only the surface-water catchment fail to close the water balance of the Manavgat River, a limitation widely recognized in national-scale studies. Discharge records from two gauging stations along the river—Şahapköprü in the upstream section and Sinanhoca downstream—reveal a substantial increase in flow between the two stations, indicating significant groundwater inputs along the river course. Most of the karst springs contributing to the river are fed from the western karst system, and investigations conducted under the UNDP program in the 1950s already suggested that these springs are recharged from areas located outside the surface-water catchment.

In this study, potential recharge areas contributing to the Manavgat River were delineated by considering the spatial extent of Jurassic and Upper Cretaceous limestone formations together with regional tectonic and geomorphological characteristics. Based on these criteria, the karst system was divided into three sub-systems. Each sub-system was simulated using the VarKarst model, and model outputs were jointly calibrated against the baseflow component of discharge observed at the Sinanhoca gauging station. Model results indicate a total contributing recharge area of approximately 2,500 km² and suggest characteristic groundwater travel times of about 30, 70, and 90 days for the three sub-systems. The findings highlight the dominant role of regional karst groundwater flow in sustaining the Manavgat River and underline the necessity of explicitly accounting for external karst recharge in hydrological assessments of large karst-fed river systems.

Typology of karst-river interactions, implications on groundwater transfers and water quality (Loue riv., French Jura Mountains)

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Karst aquifers are characterized by highly heterogeneous permeable formations that can promote interactions between surface water and groundwater (SW/GW). Evaluating these karst-river interactions can enhance understanding of groundwater recharge and discharge processes, as well as pollutant transport. Accordingly, this study aims to propose a typology of SW/GW interactions in karst catchments, and to discuss the implications on groundwater transfers and quality.

The study site is located in the upper karstic section of the Loue River, within the French Jura Mountains. The Loue catchment covers an area of approximately 1,000 km² and is dominated by a deep canyon incising limestone plateaux. These plateaux are extensively drained by major karst springs, including three springs with mean annual discharges exceeding 5 m³/s. To investigate surface water-groundwater (SW/GW) interactions, two physico-chemical surveys were conducted along a 55 km river profile during contrasting seasonal conditions (e.g., high/low flow periods). High-resolution measurements (2-minute intervals) were collected using multi-parameter probes mounted on sealed boats, enabling the detection of fine-scale spatial variations. The monitored parameters included water temperature, electrical conductivity, and nitrate (NO₃⁻) concentrations. Concurrently, differential gauging campaigns were conducted to quantify water exchanges (inflows / outflows) between the river and surrounding karst aquifers. Complementary, hydrogeological and hydrochemical analyses were also conducted using multi-environmental tracers (major elements, $\delta^{18}\text{O}/\delta^2\text{H}$, strontium isotopes ⁸⁷Sr/⁸⁶Sr), and dissolved gases (SF₆, CFCs). These tracers were used to characterize interaction processes in specific reaches including water flux estimations and groundwater residence times.

Based on the physico-chemical data, nine distinct types of SW/GW interactions in the Loue catchment were identified and classified. These types include: loss-spring system, localised spring inflows to the river, river losses (e.g., infiltration into the aquifer), diffuse inflows from extensive saturated zones drained by the river, inversacs (flow reversals, involving alternating phases of aquifer recharge and discharge). Along the river's longitudinal profile, from upstream to downstream, the dominant SW/GW interactions types are described and characterized using hydrogeochemical indicators. Results are interpreted in light of the regional hydrogeological setting, describing and quantifying recharge and discharge dynamics in karst systems. Additionally, the NO₃ data provide insights into the dynamics of nitrogen transfers between karst aquifers and the river.

A network-scale approach to estimate equivalent friction factors in karst conduit networks

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Flow in fully saturated karst conduits is commonly modeled using the Darcy–Weisbach equation, where head losses are controlled by a friction factor. This formulation is widely used to represent turbulent and transitional flow in karst conduit models, including recent large-scale simulation frameworks such as OpenKARST (Kordilla et al., 2025). While the Darcy–Weisbach equation is well established for single conduits of constant diameter, real karst systems consist of complex networks with strong diameter heterogeneity and nontrivial connectivity. Explicitly resolving this heterogeneity at the scale of a catchment leads to high computational costs and limits the applicability of detailed models under extreme flow conditions. There is therefore a need to define effective hydraulic parameters, in particular a friction factor, directly at the scale of conduit networks.

In this work, we develop a network-scale framework to define an effective Reynolds number and an effective friction factor for karst conduit networks. Steady-state Darcy–Weisbach flow simulations are performed on synthetic networks generated following percolation-based backbone models for karst systems (Hendrick & Renard, 2016), with controlled structural properties including mean degree, connectivity, and diameter disorder. Effective network-scale quantities are derived from global pressure drops and total fluxes, with the objective of characterizing asymptotic behavior in the turbulent regime and describing the transition from laminar to turbulent flow.

Preliminary analyses indicate that network structure and diameter heterogeneity play a central role in controlling flow redistribution and the emergence of dominant flow paths, which in turn affect effective hydraulic behavior. Based on this observation, we propose a practical strategy to estimate an equivalent network-scale friction factor from a limited number of steady-state simulations, by combining global pressure–flux responses with statistical descriptors of the flow field. This approach aims to capture the behavior of the network across laminar, transitional, and turbulent regimes while substantially reducing the computational effort required to characterize frictional losses at the network scale.

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Numerical representations of karsts: integrating geological knowledge

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Numerical representations of karsts serve multiple purposes, ranging from simple visualization (e.g., Paris *et al.*, 2021) and exploration to flow simulation (e.g., Duran *et al.*, 2021) and the evaluation of speleogenetic hypotheses (e.g., Fandel *et al.*, 2023). Depending on the objectives, the scale of interest can vary from pluri-metric (*i.e.* detailing the shape of some karstic conduits, e.g., Rongier *et al.*, 2014) to kilometric (*i.e.* concerning the karstic network as a whole, e.g., Pardo-Iguzquiza *et al.*, 2012). Since the 2010s, various approaches have been developed to numerically reproduce these geometries. After a brief overview, this presentation will focus on strategies that have permitted to integrate geological knowledge into simulations of the karstic objects (networks and conduits), and will discuss perspectives opened by evolving technologies.

Reproducing natural objects first requires accurate tools to analyse them objectively. We have proposed converting speleological exploration data into a unified mathematical graph representation, with properties describing the conduit geometry (Vuilleumier *et al.*, 2012; Collon *et al.*, 2016). For conduits dimensions, analyses have demonstrated that most approximations done for flow simulations were inaccurate, inspiring the development of alternative property simulations (Frantz *et al.*, 2021). For 3D karstic networks, new metrics were tested to characterize not only their geometry but also their topology. Reference values were proposed, but their representativity is limited by the scarcity and heterogeneity of the speleological data used (Collon *et al.*, 2017&2021, Jouves *et al.*, 2017). Thus, these pioneering works highlight the need for a unified and organized data acquisition process. Recent advances in LiDAR and lightweight photogrammetric methods offer new facilities to extend and improve the quantitative knowledge of karstic systems (Cazes *et al.*, 2025; Racine *et al.*, 2025;).

In parallel, graph simulation technics combined with “best-path” algorithms have been proposed to simulate 3D karstic networks (e.g., Henrion *et al.*, 2008; Collon-Drouaillet *et al.*, 2012, Borghi *et al.*, 2012). Recent developments now allow us to globally control the 3D topological karstic patterns, to differentiate between phreatic and vadose zones, to account for geological structuration, fracture orientations, inception features, ghost-rock karstification processes, and polyphasic speleogenesis (Gouy *et al.*, 2024). Tracer tests can serve as an input constraints, but the approach can also be diverted to test our current understanding of the controlling factors in conduit development. Further improvements are still needed to reproduce the full diversity observed in real systems, particularly the specificities of hypogenic karsts, and to adapt to the multi-scale nature of these complex objects.

Capable of generating highly detailed graphs with attached dimensional properties, these tools now face the challenges of their integration into modelling software. Beyond technical feasibility, this question must consider a reasonable use of energy and resources in relation to the scientific questions these tools aim to address. As such, research still has many paths to explore.

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Understanding the variability in gas concentrations of Carlsbad Cavern

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Cave air circulation provides an important control of the cave environment through its influence on gas, dust, and aerosol transport. Gas concentrations heavily depend on cave airflow as ventilation transports gases out of caves (CIGNA, 2005; GOMELL & PFLITSCH, 2022). Without cave air circulation, gases such as carbon dioxide, can build up inside these underground enclosed spaces. Cave airflow is heavily influenced by surface temperatures and pressure, as the cave atmosphere constantly tries to equalize with the surface atmosphere. Differences between surface air and cave air temperatures produce density differences that cause air to circulate from the surface into the cave (CIGNA, 1968).

Carlsbad Caverns National Park is a UNESCO World Heritage Site located in the Guadalupe Mountain range of Southeast New Mexico, USA that attracts over 300,000 annual visitors worldwide. Carlsbad Cavern is over 30 miles long and has the largest cave chamber by volume in North America, the Big Room (HILL, 1990). Carlsbad Cavern has two main airflow mechanisms, barometric airflow, which occurs year round in many passages, and circulating convective airflow (KILLING-HEINZE et al., 2017).

Circulating convective airflow starts at the Natural Entrance and penetrates about a mile into the cave (KILLING-HEINZE et al., 2017). Circulating convection occurs in Carlsbad Cavern during late October to March, when cold air sinks into the cave along the floor, warms up inside the cave, rises to the ceiling, and flows out the same entrance near the ceiling (AHLSTAND, 1980; COVINGTON & PERNE, 2015). In April to early October, the surface temperatures are much higher than the cave temperatures, stagnating the cave air by shutting down the circulating convective airflow cell and allowing CO₂ and radon concentrations to stay high (CHENG et al., 1997).

Continuous atmospheric characteristics including temperature, relative humidity, barometric pressure, wind speed and direction, CO₂ and radon concentrations were monitored by six speleometeorological stations in Carlsbad Caverns from September 15, 2024 to December 20, 2025. Overall, both gas concentrations follow a seasonal trend with high concentrations in the summer months and low concentrations in the winter months. For CO₂, the lowest levels detected are around 400 ppm during cooler months, which is close to the average surface atmospheric CO₂ concentration, suggesting maximum cave air ventilation during the winter. The Big Room has higher CO₂ than the other locations due to heavy visitation, producing additional anthropogenic CO₂. The measurement site furthest from the entrance, Lefthand Tunnel, has frequent spikes in both gas concentrations. The radon spikes are higher than the CO₂ spikes, indicating there may be a localized radon source.

Elevated CO₂ levels during hotter surface temperatures drop notably following a decrease in surface temperatures, leading to rapid CO₂ reductions that resemble exponential curves. A simple exponential gas transfer model (MILANO & GABROVŠEK, 2009) produces a good fit to two significant CO₂ reduction events at the end of October and early November, 2024. Two of the sites display rapid gas transfer, on a timescale of days, indicating a shift in air ventilation (Fig 1), while one site displays much slower gas transfer, on the timescale of a month (Fig 2).

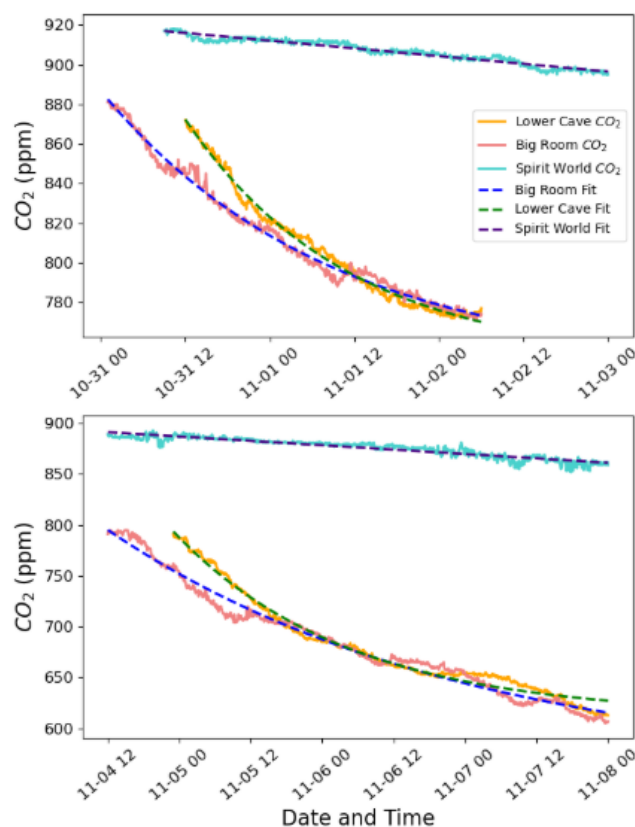


Figure 1. The fit of the exponential function to the two rapid decreases in CO₂ concentrations at the Lower Cave, Big Room, and Spirit World stations. While both Lower Cave and Big Room display clear concave upward curvature, the Spirit World curve is nearly linear over this period.

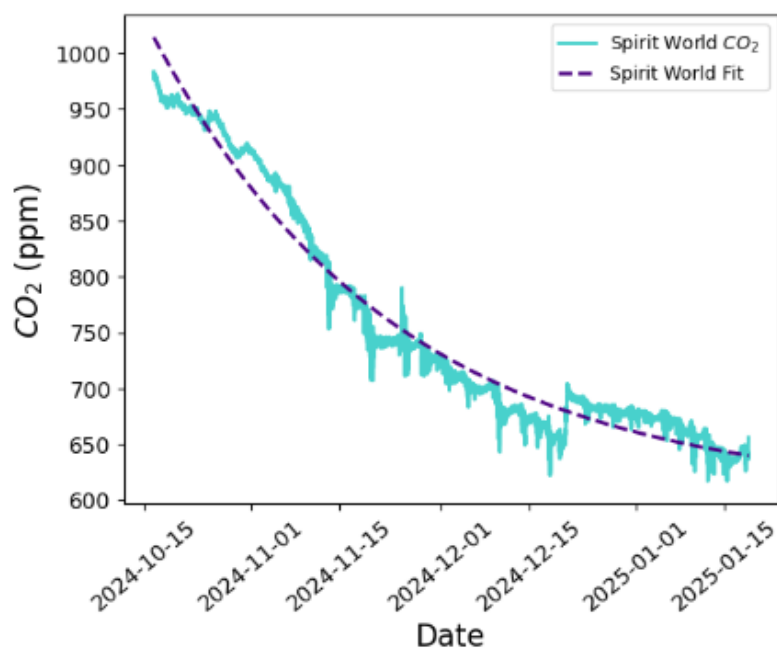


Figure 2. The fit of the exponential function to the long-term decrease in CO₂ concentrations at Spirit World from October 15 – January 15, where concave upward curvature is clearly visible.

Parameter values determined from fitting the exponential function are physically plausible given estimated cave volume, observed airflow, and approximate CO₂ production rates of tourists. The fact that CO₂ production rates estimated in the model are similar to those estimated from tourists suggests that tourists may be the primary source of CO₂ during the study period. The third site, Spirit World, appears to be isolated from the main convection cell and exhibits much slower gas exchange. Spirit World may act as a warm air trap during convection cell periods.

The simple exponential gas transfer model was modified to account for the radioactive decay of radon. This model was also applied to the rapid exponential decrease in measured radon concentrations in Lower Cave, suggesting rapid gas transfer during this period. Ongoing analyses explore the deviations in behavior at Lefthand Tunnel in more detail to determine if they are driven by barometric airflow, and analyzing surface weather data in conjunction with cave atmospheric data to further understand the interactions between the cave atmosphere and the surface atmosphere.

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Modeling interactions between speleogenesis and cave airflow

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A variety of field-based studies have indicated important interactions between cave ventilation, CO₂ dynamics, and the saturation state of cave streams. However, the long-term implications of these interactions on the morphology of karst systems remains unclear. To explore how such processes influence cave evolution, we develop a speleogenesis model that tracks cross-sectional passage shape and simulates transport of CO₂, including ventilation within the air-filled portion of the passage and exchange between the air and water. Paired simulations with and without CO₂ exchange show that this process can profoundly influence the rates of speleogenesis and the morphology of the resulting cave passages. We demonstrate that air-water CO₂ exchange produces feedback that impacts dissolution rates and channel morphology. Within stream channels, steep zones (knickpoints) are often interpreted as indicating changes in tectonic forcing or rock erodibility. The model suggests that internal CO₂ dynamics can produce knickpoints in cave streams without changes in external forcing. Such knickpoint morphologies can develop at an equilibrium state, where channel incision matches tectonic uplift along the entire channel. For knickpoints that are migrating, we find that knickpoint celerity is a function of stream chemistry, following a scaling relationship that can be derived analytically. Cave passages often record long histories of changing channel width and passage shape, providing records of paleohydrological conditions and cave evolution. Comparing our physically based model for the evolution of cave passage shapes against observed morphologies in the field may enable more detailed understanding of the information recorded in cave passage walls as caves evolve over time.

Sequence-stratigraphic control on karst development and connectivity in the Malm geothermal reservoir, greater Munich area (South German Molasse Basin, Germany)

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The Upper Jurassic to Lower Cretaceous (Purbeck) succession of the South German Molasse Basin, referred to here as the Malm Reservoir, forms part of the North Alpine Foreland Basin and hosts one of the largest geothermal resources currently exploited in continental Europe, forming the backbone of geothermal development in the greater Munich area. This laterally extensive carbonate system is characterised by pronounced heterogeneity in depositional facies, structural deformation, and extensive karst development. Within this complex geological framework, the present study investigates the stratigraphic control on karst distribution, geometry, and hydraulic behaviour in a deeply buried setting.

The analysis integrates data from 45 wells, including geophysical logs, mud-log descriptions, borehole image logs, and available production data. Karst features are classified into five categories: (1) epi-karst related to subaerial exposure, (2) stratiform dissolution along bedding and facies contrasts, (3) paleowater-table karst with cross-cutting geometries, (4) localised biogenic dissolution, and (5) fracture-related karst. For each type, thickness, stratigraphic position, and hydraulic significance are assessed.

Karst bodies are heterogeneously distributed and preferentially occur at exposure-related sequence boundaries. A regional sequence-stratigraphic framework (Wolpert et al., 2022; Wolpert, 2020) links relative sea-level fluctuations to facies organisation within the Jurassic carbonate ramp system. Whereas facies associations largely determine matrix storage properties, exposure duration at sequence boundaries governs karst intensity, lateral continuity, and hydraulic connectivity.

Although karstification initiated at multiple exposure surfaces, the most laterally continuous and hydraulically effective systems formed during prolonged Cretaceous subaerial conditions. These regionally extensive horizons locally cross-cut depositional facies and now act as principal conduits for fluid circulation. Hydraulically active zones in the most productive geothermal wells commonly coincide with such karstified intervals (Hörbrand et al., 2025; Schölderle et al., 2023), highlighting their dominant role in reservoir performance. Faults and fractures are presently interpreted as hydraulically minor relative to stratigraphically controlled dissolution zones. Given remaining uncertainties, their permeability and structural control are being examined in a parallel study and are not treated here.

Normalised vertical sequence analysis reveals systematic stacking patterns of karst types and demonstrates that sequence boundaries differ markedly in karst potential. Exposure time emerges as the primary control on karst thickness and connectivity. This stratigraphic organisation supports prediction of karst-dominated versus matrix-dominated intervals and improves assessment of reservoir compartmentalisation.

Conducted within the GIGA-M project, this well-based study establishes a predictive model for karst development that will be calibrated against existing and forthcoming 3D seismic data and incorporated into a regional 3D geological model, forming the basis for subsequent dynamic reservoir simulations. The project integrates well observations and large-scale seismic interpretation to characterise the deep geothermal system of the greater Munich area. The resulting framework enables construction of karst-probability maps and upscaling of well-scale observations to the seismic domain, supporting prediction of high-permeability pathways, evaluation of flow connectivity and well interference, and optimisation of geothermal

management at regional scale. These findings demonstrate that stratigraphic control on karst connectivity is fundamental for sustainable production and long-term resource management in geothermal carbonate systems developed in foreland basin settings worldwide.

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Epukarst - in situ monitoring of nitrate behavior in 5 karst watershed used for drinkable water production in Wallonia (South Belgium)

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The EPU-Karst project, financed by the Société Publique de Gestion de l'Eau (Belgium) between 2024 and 2027, aims at assessing the nitrate behavior in various compartments of karstified limestone aquifers used for drinkable production in Belgium. Five karst watersheds used for drinkable production by 5 local water-producers are studied in south of Belgium. Those basins have problematic qualitative status regarding nitrogen (close to 50 mg/liter). During 2024-2027 we apply a high temporal resolution measurement of nitrogen at the karst outlets, while keeping the focus on variable compartments behavior across the karst aquifer. In addition, dedicated measurement into agricultural lands at the surface are used to inform about the nitrate input with a more refined approach. The aim is to be able to evaluate more precisely the correlation between agro-environmental actions and the response of the karst aquifer outlet. The quick reaction of karst aquifer and the knowledge about its quantitative behavior allow to precise the effect of the actions, their efficiency at short time scale and to objectify their implementation towards local stakeholders and decision-makers.

Coupled deep-seated processes in karst cave system formation: models and field evidence

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The upper crust evolves through tightly coupled thermal, fluid-flow, mechanical, and geochemical processes, often termed thermo-hydro-mechano-chemical (THMC) interactions. These processes involve multiple nonlinear feedbacks operating across wide spatial and temporal scales, making their interpretation challenging. The integrated outcome of these hidden processes is often recorded in water-rock interactions and alteration patterns, providing valuable clues. In particular, morphologies of hypogene karst and cave systems formed by deep-seated ascending fluids are of great importance. This type of karst is distinct from the shallower, commonly more evident epigenic karst formed by surface infiltration of CO₂-rich meteoric water. Despite being often less visible, it is globally extensive and in many regions dominant, producing voluminous and structurally complex cave systems. As such, hypogene karst offers a unique natural laboratory for investigating coupled upper-crustal dynamics [1–2].

Here, we consolidate field observations of different components into a THMC conceptual scenario for hypogene cave system formation, which is explored using numerical and theoretical modelling. The results reproduce and help clarify hypogene cave morphologies that have been difficult to explain. Several global case studies demonstrate systematic relationships between cave development and structural-tectonic context, supporting the proposed scenario. This work improves understanding of obscured coupled subsurface processes, with relevance to geothermal systems, critical-mineral exploration, and geohazard assessment.

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Flow and transport modeling in karst from conduit to network scale

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The flow and transport behaviors of karst aquifers are determined by a broad range of spatial scales from the pore scale to the network scale, and the corresponding range of hydrodynamic flow modes from laminar to turbulent. They are important for the understanding of how karst is formed on the one hand, and how karst aquifers transmit and store water and solutes on the other, which are key items in view of water resources management and preservation. The disparity of scales and variety of hydrodynamic behaviors make the quantification of karst processes a challenging task. This talks wants to give an overview of approaches and concepts for the modeling of karst from the conduit to the network scales, and report on recent advances in the framework of the ERC-SYG project KARST.

On the karst conduit scale, we discuss the impact of wall geometry on flow parameterization in terms of the Darcy friction factor, the transition from laminar to turbulent flow, and the validity of correlations for rough pipes. We explore classical transport description in terms of hydrodynamic (turbulent) dispersion and its limitations for strong wall fluctuations. We then discuss the quantification of laminar and turbulent network-scale flow and transport in synthetic and real network topologies. The upscaling of flow and transport are discussed in the light of network topology and heterogeneity in the framework of stochastic modeling using a continuous time random walk approach.

Characterizing functioning of the Dyr Karst (Tebessa, Algeria) by correlative and spectral analysis of hydro-pluviometric chronicles

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In this paper, we present the study results of the hydraulic behavior of the Maastrichtian karst system of the Dyr perched syncline that is situated in the north of the Algerian territory and constitutes the north horst of the Tebessa subsidence basin. Processing and analyzing the hydro-pluviometric chronicles registered for 3134 days, between September 01, 2002 and March 31, 2011 at the hydropluviometric station of Ain Zerga, by means of the correlative and spectral analysis method, allowed us, at first, to describe and to compare the structures of both chronological series:

The chronological series of rainfall in the syncline of Dyr, considered as input (the cause) of the karst system,

The chronological series of flow rate of the spring Ain Zerga, considered as its output (the effect).

On the basis of signal processing, determining the signal components allowed us to demonstrate clearly the effect of the temporal variability of pluviometry on the hydraulic functioning of this karst system in a big aquifer potentiality. Indeed, this work of analysis revealed that the karst system is characterized by a weakly inertial behavior and possesses a well-developed drainage structure which constitutes a functional karstification.

Karst network geometry and groundwater flow in the Aulp du Seuil catchment (Chartreuse, France)

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Groundwater flow in karstic aquifers is highly dependent on the geometry of the conduit network. Not integrating the conduits explicitly leads to inaccurate predictions of the aquifer's behavior. Even on a small (250 m * 250 m) and very well characterized site such as the Hydrogeological Experimental Site of Poitiers (France), flow models have difficulties predicting the aquifer's response to pumping-injection test (Bodin et al., 2012). Conversely, the addition of discrete conduits can improve the hydraulic head estimations as shown by Saller et al. (2013) in the Madison aquifer (South Dakota, USA).

Models that explicitly represent the spatial distribution of cave conduits require a lot of data that is rarely available and these models are therefore limited to synthetic cases or extensively studied sites. A possible approach for overcoming this difficulty is to generate discrete karst networks in a stochastic way. This means generating a large number of karst networks constrained by the same geological and hydrological settings. These simulated networks can then be used as inputs for distributed flow models.

We combine in a single workflow a karst network simulator and flow modelling in the conduits. We propose using two open-source and Python-based tools: pyKasso for the karst network generation (Miville et al., 2025) and openKARST for modeling flow in conduits (Kordilla et al., 2026). PyKasso is a pseudo-genetic karst network generator, it is based on conceptual knowledge of speleogenesis. OpenKARST handles turbulent, laminar and transient flow in complex karst network. The simulated networks and their respective hydrographs constitute a database to explore the relationship between hydrological properties and the network organization.

This poster presents our first results on a small (~10 km²) karstic catchment in the Chartreuse Mountains, France (Fig.1). The Aulp du Seuil was chosen due to its 16-years record of discharge measures at the outlet (Fig. 2), and the 25 kilometers of conduits explored and mapped by speleologists (Collectif de l'Aulp du Seuil et al., 2024). Large parts of the network are probably unknown because it does not extend over the entire catchment area and it is small in comparison with the Granier (55 km), the Alpe-Alpette (72 km) and the Dent de Crolles (>60 km) networks, also located in the eastern syncline of the Chartreuse. Being able to compare the simulated networks and the modeled hydrographs with real life data is important to test the value of the tools.

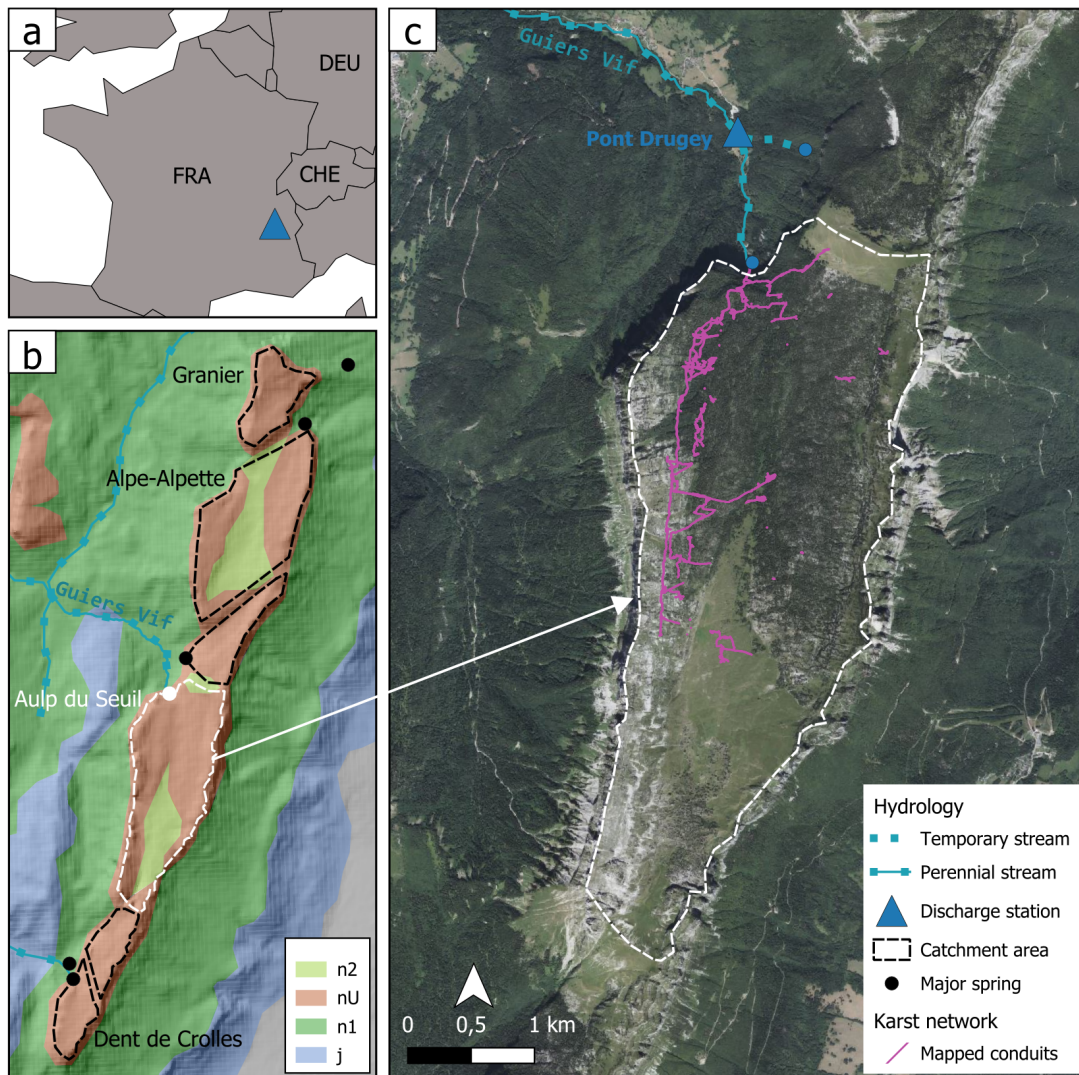


Figure 1. (a) Location of the Chartreuse Mountains in France. (b) The eastern syncline of the Chartreuse with the karstic catchments and the major springs. Background colors are based on geological units (*n2*: Upper and Middle Cretaceous-limestones and chalk; *nU*: Urgonian facies-limestones, *n1*: Lower Cretaceous-alternance of marls and limestones; *j*: Jurassic-alternance of marls and limestones). (c) Map of the Aulp du Seuil catchment with Pont Drugey discharge station on the Guiers Vif river and the karst network.

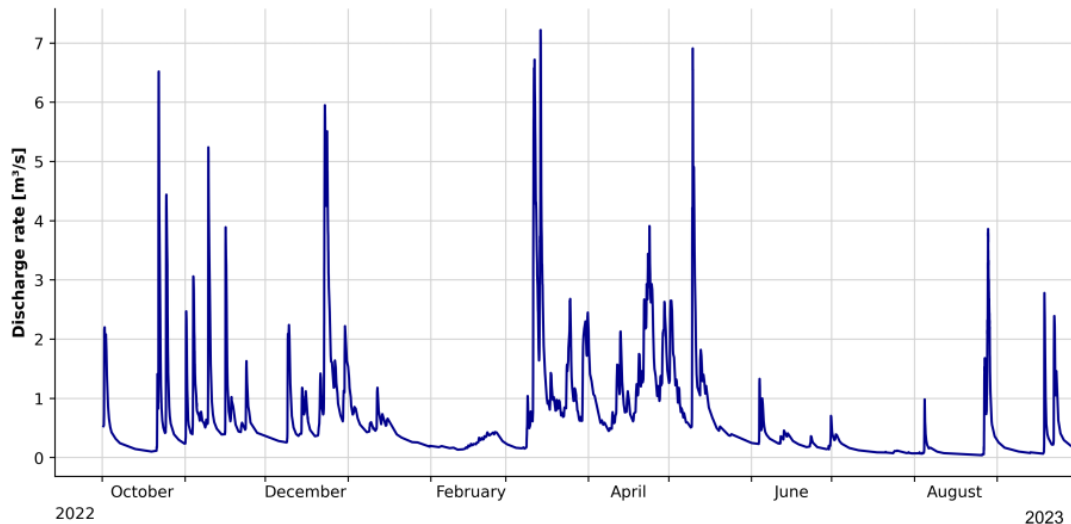


Figure 2. Discharge rate of the Guiers Vif river recorded at Pont Drugey during the hydrological year 2022-2023.

Acknowledgments

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Hydrogeological response of a karst aquifer using a multi-scale spatio-temporal approach to the unsaturated zone: application to Durzon spring aquifer, Larzac, France.

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The unsaturated zone is both the largest part of karst hydrosystems and the most heterogeneous, with horizontal and vertical transfer processes associated with transfer times ranging from daily to seasonal cycles. However, this heterogeneity of the karst unsaturated zone remains poorly documented as it is difficult to observe directly or indirectly.

The objective of this work is to identify the compartments and the associated transfer processes in the hydrogeological responses of a karst spring under a Mediterranean climate. To address this issue, a multi-scale and multidisciplinary approach is used, including more than twenty years of hydrodynamic, hydrogeochemical, and geophysical time series. The study site is located on the Larzac plateau in southern France, in the recharge area of the Durzon spring largely composed by weathered dolomite and limestone.

The spring flow is studied at several spatial and time scales, separating periods of low flow, small floods, and major floods to understand the variations in the contribution of the compartments according to hydrological conditions. The contribution of the unsaturated dolomitic zone is estimated through a transfer model (Tempo ©BRGM) allowing to combine various input datasets (hydrodynamic: discharge and water levels at various depths, geophysical: gravity) in order to simulate the output (spring flow).

Multi-scale hydrogeochemical analysis from both in-situ and outlet sampling allow to detail the contribution of the limestone and dolomite compartments and the associated transfer processes. Major Mediterranean floods induced pressure and mass transfer in the limestone and dolomite compartments. Small floods are characterized by a transfer of pressure only, essentially in the limestone part. During low flow, the spring flow originates from the saturated zone, but also from the unsaturated dolomitic zone due to pressure transfer.

The “inertial” characterization of the Durzon spring – compared to other karst systems - is thus associated with transfer times in the unsaturated zone ranging from a few days to several months. The variability in transfer times is linked to the heterogeneity of the dolomitic rock, in particular variations in porosity due to the presence of weathered zones (ghost rock). Regarding long-term response of the karst aquifer, the dolomite and its weathered zones in the unsaturated zone constitute a storage reservoir that may have an impact on the hydrogeological and hydrochemical variations at the spring, linked to climate change.

Environmental tracer-based characterisation of the karst Oum Er Rbia springs (Middle Atlas, Morocco)

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In the Mediterranean basin, observations and climate change scenarios point out an increase in aridity especially in the southern regions like Morocco. In such a context, the availability in fresh groundwater resources is critical for water supply and socio-economic activities. Consequently, a deeper insight into the functioning of karst hydrogeological systems is required. The Oum Er Rbia (OER) spring system is one of the most important karst springs of Morocco, located in the semi-arid Middle Atlas Mountains. The OER system exhibits a striking contrast in water quality, ranging from freshwater (800 $\mu\text{S}/\text{cm}$) to saltwater springs (up to 35 000 $\mu\text{S}/\text{cm}$) accounting for 95% and 5% of the total discharge, respectively. The total flow was estimated at 6 m^3/s in April 2025, and the analysis of historic surveys has revealed a decline by 1,5 m^3/s per decade since the mid-twentieth century. Despite its importance for water supply, the geological structures and lithological facies that respectively control groundwater circulation and salinity within the OER system remain poorly understood.

In 2024-2025, hydro-geochemical investigations were conducted in the OER watershed to improve the understanding of this hydrogeological system. The research integrated chemical, water stable isotope and radioisotope dating approaches at multiple sampling points across the basin, during different hydrological seasons.

Water quality is mainly controlled by lithology; freshwater springs show a Ca-HCO_3 facies and are associated with the Lias dolomitic rocks. In contrast, salty springs show Na-Cl facies linked to Triassic evaporitic clays. This heterogeneity is also reflected in distinct groundwater recharge areas: freshwater springs show depleted $\delta^{18}\text{O}$ values (-8, 58 ‰ vs SMOW) corresponding to a mean recharge elevation at about 2000 m a.s.l., while saltwater springs exhibit more enriched $\delta^{18}\text{O}$ values (-7,61 ‰ vs SMOW), with a mean recharge elevation at 1400-1600 m a.s.l.

Preliminary results from the geological field survey show a dominant trend of karstified joint sets, oriented N°130E, controlling the main freshwater spring. The saline spring reservoir is also karstified, especially along fracture corridors trending N°60E and NS, favoring water flow toward the springs. In this reservoir, karst features were observed in Liassic carbonates as well as in Triassic evaporites.

Radio isotopes ^3H and ^{14}C also highlight the heterogeneity of the system with the main fresh spring water notably older than the saline springs.

These new results modify the overall understanding of this hydrogeological system's functioning.

Climate-change impacts on the discharge of strategic karst springs in the region of Neuchâtel, Switzerland

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Karst aquifers are a key component of drinking-water supply in the Canton of Neuchâtel, especially during low-flow periods. Because these systems have complex and strongly contrasted dynamics, their spring and gallery discharges can respond very differently to changes in recharge. Under ongoing warming and a projected seasonal redistribution of precipitation, this project assesses how observed and future hydroclimatic changes may affect discharge dynamics and resource reliability in four representative and strategic karst catchments: the Areuse spring at St-Sulpice, the Noiraigue spring, the Bossy gallery (Areuse gorges), and the Vigner overflow springs (St-Blaise area) (Fig. 1).



These sites cover diverse hydrogeological settings (e.g., Malm vs. Dogger aquifers, perennial springs vs. threshold-controlled overflow outlets, selective drainage vs. potential interactions with superficial storages). The methodology combines (i) compilation, quality control, and harmonization of hydrological time series (mainly discharge) with climatic forcings (precipitation, air temperature, potential evapotranspiration), (ii) hydroclimatic and trend analyses to characterize seasonality, interannual variability, and recent changes in regimes, and (iii) conceptual karst hydrological modelling for hindcasting and future-scenario runs. For future conditions modelling, SSP pathways (e.g., SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) are used, for being the most up-to-date and more plausible trajectories. Expected outcomes include: (1) a classification of site responses (e.g., in terms of activation thresholds, drought sensitivity, inertia), (2) a quantified assessment of recent regime changes with associated uncertainties, and (3) realistic discharge predictions highlighting critical periods (e.g., prolonged low flows, intermittent recharge) and uncertainty ranges, delivered in a technically robust synthesis suitable for scientific discussion and for supporting cantonal water management.

From pipe to karst conduit flow - Experimental investigation of flow in realistic, three-dimensional karst conduits

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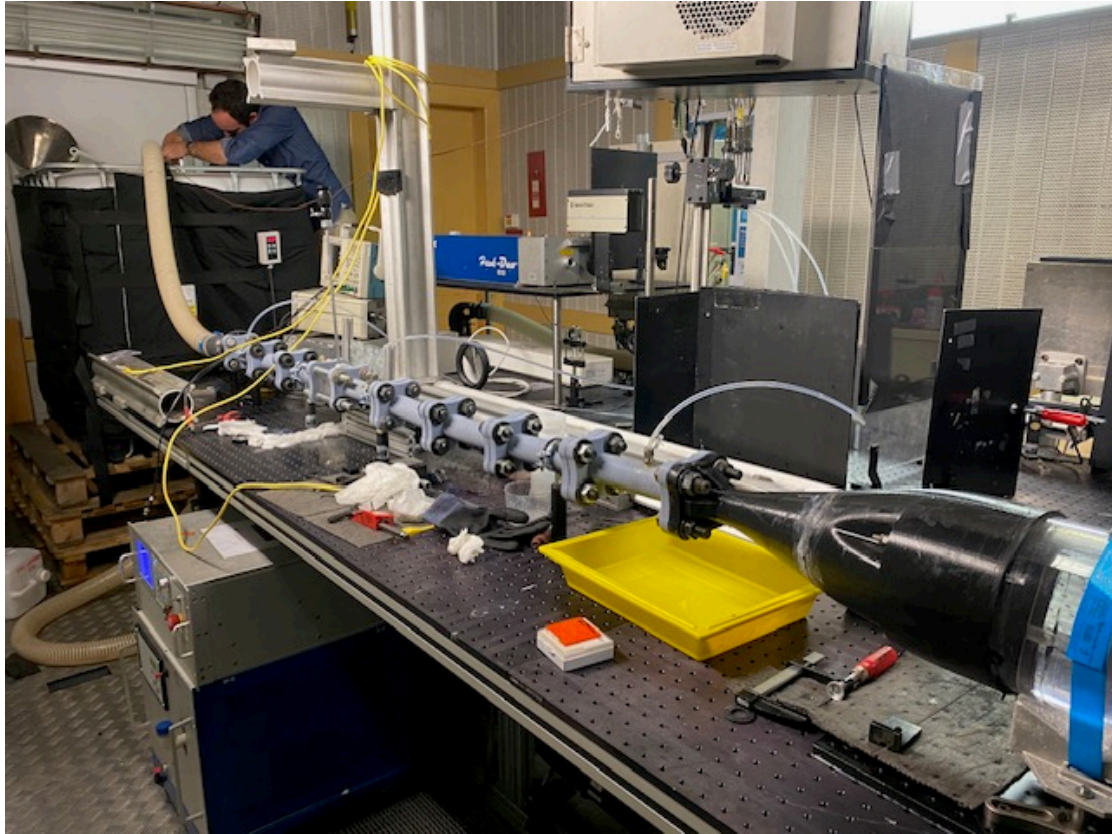
Karst systems are of major importance as they provide a substantial portion of the global population with safe drinking water (Stevanović, 2019). However, the heterogeneous nature of karst systems poses a challenge for their characterization and management as flow velocities cover a wide range. Karst conduits may only contribute little to the overall porosity of a system but offer pathways for rapid flow and transport. Therefore, an accurate risk assessment for potential contamination requires a sound understanding of flow in karst conduits which are characterized by complex wall geometries.

Hence, in karst system modeling, dual-domain models are typically employed to account for the hydraulic duality of such systems. Flow within conduits is commonly approximated by the empirical Darcy-Weisbach equation. The dimensionless Darcy friction factor accounts for any pressure losses along a pipe as a function of the Reynolds number Re .

Numerous relations, such as the Colebrook-White equation, exist to relate the friction factor for laminar and turbulent flow to a range of Re and relative surface roughnesses. However, these relations have been derived from pipe flow investigations in which the full range of geometric features offered by karst conduits was neither tested nor discussed due to their focus on industrial applications. In particular within the transitional regime the friction factor is often not accurately recovered and deviates from observations for both smooth and rough surfaces. The predictive accuracy of karst models consequently may be questioned where flow and transport within conduits is considerable.

We present an experimental methodology for the laboratory-scale investigation of flow within karst conduits with impermeable walls. The experimental setup provides a constant mass flux via a pump and a water-glycerin solution is moved through a test section where observations of the pressure are recorded at several distances. Hence, the Darcy friction factor can be obtained for a given setup over a range of Re covering laminar, transitional, and turbulent flow. Our investigation focuses on the impact of geometric characteristics such as surface roughness and tortuosity on the pressure development. To this end we consider straight, wavy, and rough pipes in addition to conduit geometries that are derived from LIDAR images of real caves. The experimental setup is validated against literature values of friction factor for smooth and rough pipes.

This investigation goes beyond the scope of previous pipe-flow studies and aims to obtain friction factor relations that account for laminar, transitional, and turbulent flow within geometrically complex structures such as karst conduits. We find that common parametrizations of the friction factor (e.g., Colebrook-White) are not able to describe the observed data. The onset of turbulence can be both at lower or higher Re than for smooth and rough pipes depending on the wall geometry. This can be traced back to the coexistence of different flow modes along the conduit due to strong wall modulations. Hence, our results suggest that common methodologies and roughness concepts used in karst system modeling may be lacklustre for a conceptually sound characterization of flow and highlight the need for further systematic investigations.



The role of roughness in karst conduit flow

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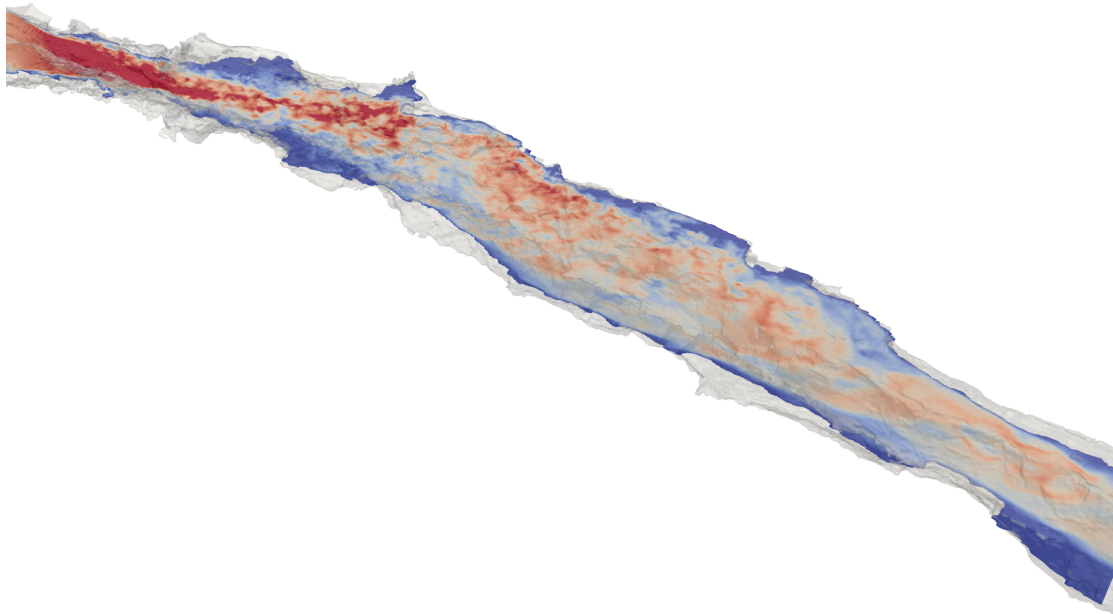
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Karst aquifers consist of complex conduit networks in which geometric variability plays a key role in controlling groundwater flow and transport. At the conduit scale, strong wall roughness ($k/D \sim 10^{-1}$), non-uniform cross-sections, and tortuous centrelines challenge classical hydraulic descriptions derived from smooth or idealised pipes.

In this study, we investigate flow dynamics in natural karst conduits using numerical simulations over a broad range of Reynolds numbers ($Re = 1-10^4$). The aim is to quantify relevant geometric and hydraulic descriptors, including effective cross-sectional areas, conduit centrelines, velocity fields, and friction factors. Wall roughness is characterised through Fourier-based spectral analysis of the conduit geometry, enabling separation of roughness across spatial scales and a consistent roughness description in karst conduits.

The conduit geometries are directly derived from high-resolution scans of karst formations and retain the dominant geometric features resolved at the available measurement and meshing resolution. Simulations are performed without additional geometric idealisation, allowing roughness-induced disturbances and wall effects to be resolved within these limits.

The results reveal clear departures from smooth-conduit behaviour, with geometry-driven heterogeneity strongly influencing velocity distributions and friction losses across all flow regimes. Flow dispersion is found to be dominated by large-scale roughness, indicating that simplified conduit geometries preserving these features can reproduce the main hydraulic response of the fully resolved cases.



Characterization and generalization of recharge dynamics with vadose zones of karstified aquifers using statistical analysis of a multi-parameter subsurface monitoring network

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Within the BMBF-funded GRaCCE project, we established a multi-parameter monitoring network consisting of seven Thomson–weir boxes installed in a limestone quarry to statistically characterize percolation dynamics in the unsaturated zone of karst systems. The Rüdersdorf limestone quarry in Germany was selected as study site because its dewatering tunnel, discharging approximately 12 million m³/a, allowed direct installations within the aquifer—an otherwise inaccessible setting where conventional boreholes provide only point-scale information. The Thomson–weir boxes were installed at the outlets of seven deep, horizontal boreholes forming a laterally distributed fan within undisturbed limestone.

High-resolution time series of water level, discharge, electrical conductivity, and temperature were collected continuously over a three-year period. A robust data-cleaning workflow was developed, including detection of measurement errors, data filtering, and event-based interpolation, resulting in consistent and reliable time series suitable for statistical analysis. Descriptive statistics combined with multi-panel visualizations revealed a pronounced hydrological variability of response on weather parameter and dynamics within the hard-rock aquifer. Weirs draining highly fractured zones exhibit high-magnitude, storm-responsive behavior, whereas weirs associated with weakly fractured zones show low, diffuse recharge signals and limited event responses. Baseflow separation further quantified this spatial heterogeneity. Parallel analysis of electrical conductivity, sulphate concentration, and temperature provided additional insights into conduit activation and temporal shifts or dampening in recharge signals. Overall, the integrated statistical–hydrological approach demonstrates how high-resolution monitoring combined with data-driven statistical analysis improves understanding of recharge variability, aquifer heterogeneity, and their response to precipitation patterns—particularly in the context of long-term drought assessment in complex karst environments. Finally, calculated recharge values were linked to precipitation using transfer functions, enabling a generalized estimation of recharge applicable for regions where data scarcity precludes the design of sophisticated models for thick unsaturated zones.

**Vulnerability of karst hydrosystems to climate change and anthropogenic stress:
a modeling approach applied to the asserdoune spring (Morocco)**

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The Mediterranean basin is particularly vulnerable to climate change. These changes, which lead to disruptions in the hydrological cycle, are potentially impacting groundwater resources and their aquifer recharge. In this context, reducing vulnerability to hydrological extremes (drought and flooding) on one hand and preserving both the quantity and quality of the resource on the other are two key priorities for public authorities. Due to their complex hydrodynamics, water resources in karst aquifers can be subject to severe water stress resulting from both overexploitation and climate change effects. Hydrological simulations are generally conducted based on different climate scenarios to provide information on how the resource may evolve in response to these various factors. Still, we do not yet have any tangible scenarios for the future water resources of karst aquifers.

The Asserdoune spring karst catchment is located in northern Morocco. It comprises Dogger limestones, which are karstified. The Asserdoune spring is used to supply drinking water to Beni Mellal (approximately 280,000 residents).

The two main objectives of this study are (i) to assess long-term trends in climatic (rainfall, temperature, potential evapotranspiration) and hydrological variables (spring and river discharges) and (ii) to develop hydrological projections based on hydrological modelling and CMIP6 climate projections under the SSP2-4.5 and SSP5-8.5.

The trend analysis results indicated a strong increase in temperature and evapotranspiration, but no significant trend in precipitation. The hydrological modelling gives insights about karst recharge and groundwater availability under different climatic scenarios, which might help to better understand the water resource evolution over different time horizons and support the decisions made by water resource managers.

Use of microbial biofilms to assess groundwater quality in karstic ecosystems

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About 25% of the world's drinking water resources come from karstic groundwater. In limestone formations, this karstic resource may be the unique source of drinking water. However, due to their heterogeneous structure and hydrodynamics properties, these aquatic systems are highly vulnerable to various contaminations, both through direct inputs and diffuse pollution. Consequently, groundwater is threatened by intensive agriculture, industrial activities and urbanisation. The assessment of the quantity and the quality of groundwater resources is currently based on chemical and hydrogeological parameters. Few specific bacterial indicators (abundances of *E. coli*, thermotolerant coliforms,...) are also used to detect fecal contaminations in groundwater. However, these biological indicators are restrained to a single type of contamination and cannot inform about the functioning of groundwater ecosystems facing multiple contaminations. Given the considerable hydrological variability observed in karstic systems, microbiological indicators capable of integrating the state of groundwater over time emerge as promising tools for bio-monitoring. In this context, the use of artificial substrates for microorganisms, initially developed for non-consolidated aquifers, proves relevant for monitoring the temporal dynamics of the microbial compartment.

Based on this approach, our study aimed to quantify the response of microbial communities to hydrological regimes and associated contaminations in a karstic system in the Alps (Bauges massif). It was expected to observe changes in the structure of communities within the karstic system based on seasonal variations associated with the hydrological cycle and human activities in the catchment (touristic activities in winter and agriculture activities in summer). Artificial substrates (clay beads) were deployed at three monitoring stations in the Bauges massif characterized by contrasting inputs of nutrients and organic matter from their respective catchments.

After successive incubation periods of two months, microbial biofilms developing on the clay beads were analyzed in terms of biomass, hydrolytic activity, dehydrogenase activity, and prokaryotic community composition. In parallel, concentrations of ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), and dissolved organic carbon (DOC) were measured in groundwater throughout the experimental period. Biofilm biomass and metabolic activities did not show positive correlations with nutrient and DOC concentrations, likely due to inhibition of microbial growth by antibiotics at the station exhibiting the highest levels of nutrients and organic matter. In contrast, prokaryotic diversity within biofilms increased with nutrient and DOC availability.

In these heterotrophic karst environments, resource inputs from surface catchments emerged as key drivers of both microbial diversity and biofilm community structure. Several microbial taxa were identified as potential indicators of groundwater quality. Future work will focus on testing the robustness and transferability of these indicators across other karstic ecosystems.

Investigating subsurface flow processes in a high-alpine karst system at Mt. Zugspitze by integrating superconducting gravimetry, hydrological and hydrochemical monitoring data

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Alpine karst aquifers are characterized by extreme heterogeneity in terms of hydraulic properties, rapid infiltration through epikarst, complex storage dynamics in the vadose and saturated zones and highly variable discharge behavior. Hydrological investigations often rely on lumped models constrained by spring discharge, which provide limited insights into internal aquifer properties and are prone to equifinality. This can be an even greater challenge in high alpine catchments where the groundwater recharge processes are influenced by snow cover and glaciers. Our recent comparison of inputs from snow models of different complexity (CemaNeige and Alpine3D) to the lumped runoff routing scheme of GR4H in the Partnach Spring Catchment (PSC, 15.4 km²) at the Zugspitze region in Germany, ranging from 1450 to almost 3000 m a.s.l., demonstrates this challenge. Despite achieving excellent discharge prediction (KGE: 0.91–0.92) and nearly identical annual water inputs, model setups differed by up to 78% in routing storage parameterization (1515 mm vs. 2701 mm) and have temporal, spatial and quantitative differences regarding snow. This demonstrates that the PSC discharge observations alone could not fully describe internal storage dynamics due to potential compensation of other model parameters, e.g., parameters representing snow melt.

To explore these limitations, we present a multi-method observational framework that provides independent constraints on subsurface storage dynamics, which is unique in terms of the excellent instrumentation with multiple traditional and experimental measurements within the PSC. This framework integrates: (1) temporal gravity variations from a continuously operating superconducting gravimeter at the summit of Mt. Zugspitze since 2019, which represent subsurface water mass changes with very high precision (1 nm/s²) and capture seasonal storage dynamics when decomposed into snow water equivalent, ice masses, and groundwater contributions; (2) continuously measured spring discharge, electrical conductivity (EC), and information from artificial tracer tests characterizing that the PSC acts like a lysimeter and for estimating effective porosity and mean groundwater residence times; and (3) stereo satellite-derived snow depth and snow covered area information from Sentinel-2 for capturing a realistic snowpack evolution. Based on these unique data sets, we aim to separate the flow dynamics in the vadose and phreatic zones.

Comparing the superconducting gravimetry observations with our modelling, subsurface storage dynamics fit with high fidelity ($r = 0.98$ and $RMSE = 40 \text{ nm/s}^2$). This confirms the method's sensitivity to water mass redistribution at magnitudes relevant for karst aquifer monitoring. In particular, the integration of the gravimetry data constrains our model regarding infiltration processes, e.g., from heavy rain or snowmelt, into the vadose zone and water movement through the karst system. This approach leverages the higher gravitational sensitivity close to the instrument in the vadose zone compared to the lower lying saturated phreatic zone. We will present first results on a more detailed characterization of subsurface flow processes in our case study using the proposed multi-method observational framework. This could potentially improve our understanding of how the internal compartments of karst aquifers respond to snow- and glacier-influenced recharge processes, enabling us to make more robust predictions for high alpine karst systems in the context of hydrological extreme events and climate-driven shifts.

Stochastic approach for karst network generation from heterogeneous porous media

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We study the speleogenesis through dissolution of heterogeneous porous media. In heterogeneous porous media, the spatial distribution of hydraulic conductivity induces a complex flow organization and the creation of preferential solute transport pathways. Infiltration of CO₂-rich water leads to the dissolution of the solid matrix along such pathways. We propose a coupled stochastic approach for karst network generation that is based on dissolution proportional to the particle visitation frequency, which naturally maps out the underlying network of transport pathways. The model accounts for the coupling of the alteration of the hydraulic medium properties, flow and transport. We consider multi-Gaussian and connected hydraulic conductivity fields. We solve the Darcy flow and perform particle tracking transport for the visitation maps corresponding to a continuous fluid injection. Following the paper by Jaquet et al. (reference), the increase of porosity and thus permeability is proportional to the number of passages of particles. Finally we analyze the network patterns and compare them to the categories defined by Palmer et al. (reference). We find that the degree of initial heterogeneity influences strongly the final patterns of the networks. We also find that the Damköhler number (Da) comparing the kinetic rate of reaction to the advective rate of the flow is a key parameter for the classification of the different types of networks created. These findings shed some new light on the link between geological heterogeneity and speleogenesis.

3D-BOS, a new borehole strainmeter for investigating hydromechanical processes

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In 2023, a newly developed 3-dimensional tensor optical borehole strainmeter (3D-BOS) (Foin et al. 2025) was installed on the Larzac Observation Station (Larzac karstic plateau in southern France, SNO H+-OZCAR), a site dedicated to critical zone monitoring and geophysical instrumentation development. This innovative instrument measures the complete 3-dimensional strain tensor with a resolution on the order of 10^{-9} over periods ranging from seconds to several weeks. Several heavy rainfall events were recorded together with their associated deformation signals.

After correction of instrumental drift and tidal signals, analysis of the measured strain tensor reveals a proportional relationship between vertical strain and cumulative rainfall. The measured vertical strain was compared with theoretical surface loading, and the inferred mechanical properties are consistent with those measured in a nearby drill core. By contrast, horizontal strain response reveals a positive correlation between its amplitude and karst saturation, that could be linked to the amount of water stored into the matrix or in the fractures surrounding the instrument.

Analysis of the principal horizontal strain directions shows a reproducible response for each rainfall event, characterized by dominant compression oriented N45° and extension oriented N135°. These results are consistent with previous tiltmeters studies (Deville et al. 2013; Jacob et al. 2010) conducted in the area and suggest that the observed tilt vector is related in both orientation and amplitude to hydraulic loading of fractures. Geological observations further indicate the presence of a fracture network on this part of the Larzac plateau oriented N130°–N140°. This direction appears consistent with observed both tilt and strain measurements. Moreover, a high similarity between water flow at the Larzac karstic outlet (at 5 km and 200 m below the plateau surface) and the amplitude of the tilt vector is observed studies (Deville et al. 2013; Jacob et al. 2010). Such a similarity points a potential direct relationship between water flow at the system scale and induced deformation as already observed within the Fontaine de Vaucluse karstic system (Lesparre et al. 2017). Moreover, a high similarity between water flow at the Larzac karstic outlet (at a distance of 5 km and 200 m below the plateau surface) and the amplitude of the tilt vector is observed. Such a similarity points a potential direct relationship between water flow at the system scale and induced deformation as already observed within the Fontaine de Vaucluse karstic system.

New 3D-BOS have recently been installed at the LSBB observatory, located within the Fontaine de Vaucluse karstic system. These instruments will enable direct comparison between full-tensor strain measurements and previous tiltmeters observations, thereby confirming the potential of borehole strainmeters for investigating hydromechanical processes in karst environments, particularly through the joint measurement of vertical and horizontal strain components. Strainmeters and tiltmeters through their singular accuracy of deformation measurement, seem the only geophysical tool directly sensitive to groundwater flow in karst hydro-systems.

The Barrois Limestone program: Integrated characterization and multi-scale modeling of a complex karst aquifer

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The Cigéo deep geological repository project currently pending authorisation (www.andra.fr), developed by Andra, the French national agency for radioactive waste management includes surface facilities such as shaft and ramp zones planned for construction within the Barrois Limestone formation. This formation contains a structurally complex, fissured and locally karstified aquifer characterised by the superposition of permeable and semi-permeable limestone units that overlie low-permeability Kimmeridgian marls. The organisation of groundwater flow is governed by stratigraphic architecture, fracturing and variable degrees of surface alteration and karstification. This leads to complex interactions between groundwater and surface water, high flow velocities within karst networks and strong spatial heterogeneity with scale-dependent hydrodynamic behaviour.

In this context, a detailed and robust understanding of the structure and functioning of the Barrois Limestone hydrosystem is required to provide the scientific basis for the Barrois Limestone Programme, which is dedicated to characterising and representing this system at multiple scales. The programme (2021–2028) has been established within a collaborative framework between Andra and the French Geological Survey (BRGM). Its development has been undertaken to improve the conceptual and numerical representation of this karst aquifer, with the objective of meeting engineering and environmental assessment requirements. The programme is predicated on an integrated methodological framework combining data acquisition, conceptual modelling and numerical simulation across multiple spatial and temporal scales. Data integration is inspired by the KARSYS (Karst System Characterisation) methodology (Malard et al., 2010; Jeannin et al., 2013), ensuring consistency between local and regional representations of the hydrosystem.

As illustrated in Figure 1, a series of hydrogeological tracing experiments have been conducted thus far, with further experiments planned to enhance comprehension of groundwater flow pathways and groundwater–surface water connections within the karst system. Concurrently, a network of 19 hydrological stations dedicated to the characterisation of river and spring discharges was established at the end of 2025. The establishment of discharge rating curves is currently underway for these stations, thereby providing quantitative constraints on surface water dynamics and their interactions with the karst aquifer. A significant component of the ongoing programme is a large-scale drilling campaign that commenced in January 2026 and is scheduled to extend over a period of approximately 18 months. The present campaign comprises 102 cored boreholes, which are distributed across 50 drilling platforms. The objective of the campaign is to investigate the different aquifer units of the Barrois Limestone formation. The borehole data that has been acquired will be utilised to facilitate the updating and refinement of the geological model, with a scale of approximately 1,000 km².

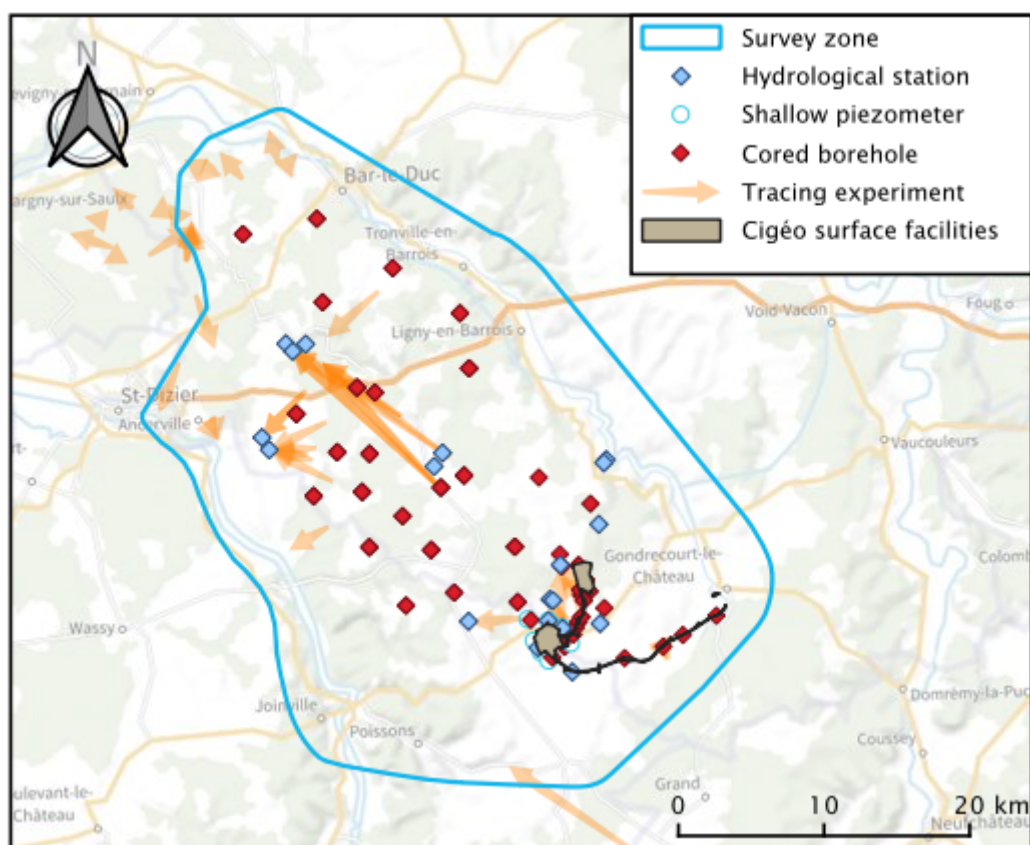


Figure 1. Characterisation work for the Barrois limestone recognition program

Boreholes will be utilised for a variety of measurements, including borehole logging, hydrogeological testing, and piezometric monitoring. A detailed geological analysis of the recovered cores will provide new insights into lithological variability and karstification processes within the limestone units.

The Barrois Limestone Program is an ambitious project that aims to significantly enhance our understanding and representation of the structure and functioning of a heterogeneous karst aquifer system through the integration of these new acquisitions with existing datasets.

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Groundwater flow dynamics and aquifer connectivity in the karst transition zone between the Murgia and Salento aquifers (Southern Italy)

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Apulia represents the main karst region of Southern Italy and is subdivided into three major physiographic and hydrogeological sectors: from north to south, the Gargano Promontory, the Murgia Plateau, and the Salento Peninsula. The Murgia and Salento aquifer systems are partially interconnected across the Messapian Threshold watershed, allowing limited groundwater recharge from the former toward the Salento aquifer.

The study area includes the elevated inland sector and the adjacent coastal plain located within the transition zone between the Murgia and Salento aquifers. The inland area is characterized by a wide range of karst landforms, including the Canale di Pirro polje, which extends for more than 12 km along a W–E direction. This polje hosts the deepest cave in Apulia, providing direct access to the groundwater table and enabling detailed in-situ hydrogeological investigations.

The inland sector is separated from the coastal plain by a major fault system responsible for a downthrow of approximately 150–200 m. From a geological perspective, the coastal plain is mainly composed of Pleistocene calcarenites, whereas the inland area is dominated by Cretaceous limestones. Along the coastline, several major groundwater discharges occur into coastal lakes that are hydraulically connected to the sea, highlighting the vulnerability of the aquifer to seawater intrusion and anthropogenic pressures.

The methodological approach is based on a series of artificial tracer tests using Tinopal CBS-X and sodium chloride to investigate groundwater circulation within the karst aquifers. Point-to-point tracer tests were conducted to constrain groundwater flow paths and assess the hydraulic connectivity of the elevated inland recharge sector, while single-point tracer tests were used to derive the main hydrodynamic characteristics of the aquifer system.

Two back-dune karst springs, Fiume Piccolo and Fiume Morello, were selected as monitoring sites for tracer arrivals through the installation of continuous fluorometric probes. Tracer monitoring at the coastal outlets provides key insights into aquifer functioning and groundwater discharge mechanisms, forming the basis for extending the investigation toward inland recharge areas.

By improving the understanding of regional groundwater flow dynamics, recharge–discharge relationships, and aquifer connectivity, this study provides essential knowledge to support sustainable groundwater management and optimized utilization of local karst water resources in a region characterized by very limited internal water availability and a strong dependence on groundwater supplies imported from outside its boundaries.

Preliminary results from the hydrogeological monitoring of the Mt. Cucco karst system and the Scirca spring (Central Italy)

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This work presents the first outcomes of the monitoring system designed and established in 2024, and implemented thereafter, at the Mt. Cucco cave–spring system (peak elevation 1562 m a.s.l.), in Central Italy.

The Mt. Cucco cave is the deepest and most extensive karst system in the Umbria–Marche Apennines, characterized by a complex geo-structural setting capable to conditioning the groundwater flow (Fronzi et al., 2025). With more than 30 km of surveyed passages, it offers a unique opportunity to observe groundwater flow from the infiltration zone down to the water table.

The cave is predominantly hydraulically connected to the Scirca spring (575 m a.s.l.), with an average annual discharge of about 210 L/s and supplying water to both the surrounding villages and Perugia, the largest city in Umbria Region (Dragoni et al., 2013).

Owing to the uniqueness and significance of this cave–spring system, a new monitoring scheme was designed and installed in August 2024. The system includes a multi-parametric probe capable of monitoring water level, electrical conductivity, and both water and air temperature at the cave's lowest point (i.e., terminal siphon of Franco Pit, 918 m below the surface).

This system integrates the pre-existing hydrogeological monitoring network of the area of Mt. Cucco, which consists of continuous monitoring of the Scirca karst spring discharge, two rain gauges and one snow-depth sensor.

An integrated analysis was carried out using both recharge input data (rainfall and snowfall) and data acquired from the multi-parametric probe. Hourly data collected by the probe were aggregated to the daily scale, calculating minimum, mean, and maximum values for each measured parameter. The resulting datasets were analysed to evaluate autocorrelation and cross-correlation functions with the mean daily discharge of the Scirca spring.

Our observations have documented phreatic-level fluctuations approaching approximately 100 m, controlled by both focused and diffuse autogenic recharge resulting from precipitation (snowfall and rainfall).

Despite the cave–spring system is located at mid-mountain elevations, the cross-correlation analyses indicate that the recharge of the aquifer feeding the spring is driven to a comparable extent by both rainfall and snowfall. However, snow-derived recharge exhibits longer time lags in its correlation with spring discharge compared to rainfall. As a result, snowmelt (mostly occurring between December and February) plays a key role in sustaining the spring baseflow until late spring–summer, whereas rainfall produces rapid, impulsive responses, leading to sharp rise in water levels within the karst conduits and a consequent rapid increase in spring discharge.

This methodological approach has provided key insights into the hydrogeological functioning of the spring by directly investigating the karst system within the cave, rather than relying solely on surface or outlet-based observations. By coupling in-cave monitoring with recharge and discharge data, it was possible to resolve the relative roles of rainfall and snowfall and their

distinct temporal signatures in controlling groundwater dynamics. Moreover, the resulting dataset and analytical framework represent a robust data-driven basis for the development of predictive models aimed at forecasting the spring behaviour under varying hydrological and climatic conditions.

Integration of artificial tracer tests at the cave bottom, complemented by hydrochemical and isotopic monitoring, will allow to improve the understanding of the hydrodynamic characteristics of the aquifer segment connecting the lowest point of the karst system (i.e., the terminal siphon) to the spring.

From a broader climatic perspective, these findings may be particularly relevant in the Mediterranean context, where a progressive decline in snow accumulation and persistence has been widely documented (Masloumidis et al., 2025). A reduction in snow-related recharge is expected to weaken the delayed contribution that currently sustains spring baseflow, potentially increasing the system's vulnerability to prolonged dry periods. In this framework, understanding the hydrodynamics of the investigated karst aquifer becomes essential for the sustainable management of the Scirca spring, in terms of seasonal water availability and regulation. These analyses allow to take proper actions for the protection of the aquifer against the changing climatic threats and potential contamination events.

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Characterising karst vadose-zone climate by observations and modelling

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Karst massifs are permeated by solutional structures of all sizes, shapes, and connectivities, which give rise to a characteristic yet difficult-to-characterise hydro(geo)logy. In the vadose zone, above the water table, water shares the available space with air. The vadose zone of karst massifs hosts a unique climate that to some extent reflects the external climate and also depends strongly on the properties of the karst structures themselves—namely the size, shape, and connectivity of solutional features.

Airflow through a karst massif is an important mechanism of heat transport in the vadose zone and is therefore worthy of study. It also affects gas composition, particularly the concentration of CO₂, which plays a pivotal role in karstification processes. Airflow through the vadose zone is driven by pressure differences that may arise from barometric disequilibrium between the interior and exterior, or from buoyancy forces resulting from density differences between air masses within the karst massif and between underground and external air.

Advective transport by water or air dramatically increases the characteristic lengths over which external influences can penetrate a massif, making karst massifs distinctive in both hydrological and thermal contexts.

Simple models that couple airflow and heat transport in air and the surrounding rock reveal the basic mechanisms of the chimney effect. Such models have been used to demonstrate how conduit geometries can lead to asymmetries between winter and summer ventilation regimes, temperature anomalies, and other non-obvious phenomena.

In addition to modelling efforts, observations of airflow, gas composition, and temperature in underground passages reveal a wealth of phenomena that are often difficult to interpret. Here we present several results and their interpretation.

The first two sites are prominent Dinaric caves, namely Postojnska Jama (Postojna Cave) and Škocjanske Jame (Škocjan Caves). In show caves, it is difficult to delineate the impact of tourists from natural processes; however, the visitor hiatus during the COVID period in Postojna Cave clearly demonstrated that the role of tourists is not limited to the visited parts of the cave, and that the post-COVID rebound to pre-COVID thermal conditions is still ongoing. In Postojna Cave, the direction of the airflow driven by the chimney effect in winter is frequently turned into a summer ventilation mode due to dynamic barometric effects caused by strong bora wind.

The climate of Škocjan Caves exhibits two contrasting regimes. The Silent Caves display a typical chimney-effect regime, which is enhanced by an artificial tunnel that is opened when tourist groups enter the cave. However, along the main canyon, strong intrusions of cold air in winter may cause freezing almost 2 km into the cave, when an exchange flow develops, with cold air descending along the riverbed and warm air returning through the upper sections of the cave.

Exchange flows typically prevail in caves with one dominant entrance and often result in cold or warm traps. Because the canyon in Škocjan Caves—up to 120 m high and several tens of metres wide—is difficult to study in detail, we investigated exchange flow in a much smaller system: Košelevka, a low-dipping cave slightly over 150 m long with a single known entrance. We observed intrusions of cold air along the lower section of the passage and returning air along the ceiling. An intricate system develops in which heat is transferred from the cave walls to the air and further exchanged between the counterflowing air layers. When the outside temperature rises above the cave temperature, airflow asymptotically drops to zero, and temperatures along

most of the cave asymptotically approach a uniform value. We also observe seasonal changes associated with the cooling of the floor sediment layer and the walls.

An even more intriguing site is the Petnjak collapse doline, where a large inclined chamber continues into a breakdown pile. Between the wall and loose “breakdown” material, cavers have progressed more than 100 m deeper. Strong winter exchange flow cools the breakdown in the entrance chamber, where temperatures before the first intrusions of cold external air barely rise above 5 °C (approximately 7 °C below the external average). An interesting feature of this cave is a constant upflow of warm air in the passage, dug along the breakdown.

U-shaped cave systems exhibit peculiar dynamics: even in idealised configurations with uniform passages and both entrances at the same elevation, airflow can be triggered by intrinsic instability, leading to a feedback mechanism. U-systems are typical cold traps and are prone to the formation of low-altitude ice caves.

CO₂ is an important gas, as its exchange with groundwater drives dissolution and precipitation processes that underlie many karst-specific features. Caves are often considered high-CO₂ environments, frequently erroneously: if the main source of underground CO₂ is the surface organic layer, then well-ventilated caves must be parts of the system with the lowest CO₂ content. In some poorly ventilated caves on the Kras/Carso Plateau, CO₂ concentrations reach between 2% and 3%. A notable example is the terminal chamber of a dead-end passage in Postojnska Jama, where we observe high CO₂ concentrations during the summer ventilation regime and low concentrations during the winter ventilation regime. During the former, air enters from the surface through a system of small conduits and fractures and is highly enriched in CO₂. The specific positions of inlets and outlets in the chamber result in pronounced CO₂ stratification. High CO₂ concentrations are also one of the factors contributing to the formation of dissolution features, such as cups and runnels, within the chamber.

Faced with a wealth of intricate data, modelling appears to be an effective approach for understanding these processes. All models, however, rely on simplifications: highly irregular geometries are replaced by regular ones; many aspects of airflow are neglected by (over-)simplifying the governing equations; thermal diffusivity of rock is often assumed to be uniform; also, heat advection coefficients can vary widely within a single cave.

Despite these limitations, models allow us to test hypotheses in well-constrained, well-observed systems to optimise parameters and assess sensitivity to uncertainties, and evaluate the plausibility of conceptual models.

Risk assessment of gypsum sinkholes with a fuzzy model: A case study of Jaber and Maroun plains

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The presence of gypsum layers leads to the formation of gypsum-bearing karst phenomena, and the thickness and purity of these layers play an important role in the creation of sinkholes. These phenomena, especially in areas with the Gachsaran Formation, can have destructive effects on roads, agricultural lands, and settlements. Despite its economic and environmental importance, limited and scattered studies have been conducted in this field. The aim of this study is to identify and assess the risk of gypsum-bearing sinkholes in two plains with different mechanisms and to prepare a mapping of karst evolution using a fuzzy model.

Study area

Jaber Plain is located northwest of Ilam city and in the Zagros anticline unit and geologically includes the Gachsaran, Armari, Bakhtiari, Pabdeh, and Gurpi formations and sediments of the present era. The approximate thickness of the Gachsaran layers is up to 1000 meters and consists of gypsum, anhydrite, and red marls. The Maroon Plain is located in the Zagros plain and in the provinces of Khuzestan, Kohgiluyeh, and Boyer-Ahmad, and the Gachsaran Formation is also dominant there. The topographic features of the plains are different; the Jaber Plain consists of relatively high mountains trending northwest to southeast, and the Maroon Plain consists of gentle slopes along the waterways. The climate of the Jaber Plain is arid to semi-arid with an average annual rainfall of 440 mm, and the Maroon Plain has similar conditions.

Methodology

In this study, a fuzzy model was used to assess the risk of sinkholes. This model is capable of processing uncertain and ambiguous variables and can perform scoring and combination of effective factors based on expert knowledge. Ten main factors were selected for modeling: slope, terrain relief, geology, distance from the channel, distance from waterways and flow concentration points on slopes, distance from the river, elevation classification, land use, climate, and NDVI index. The data included Landsat 8 satellite images, 10-meter DEM, topographic and geological maps, land use maps, and meteorological station data. Sinkhole locations were identified using field visits and Google Earth and used to score each layer. After fuzzing the layers, a final risk map was prepared using GIS software and the gamma operator ($\gamma = 0.8$) and high, medium, and low risk areas were identified.

Findings and results

In the Jaber Plain, 58 sinkholes were identified. The results of the fuzzy model showed that 36.9% of the plain area is at high risk, 49% is at medium risk, and 14.1% is at low risk. Field studies have shown that the most important factors controlling karst development in this plain are the slope and intersection of watercourses on slopes. Most sinkholes have formed near rivers and canal lines, and the low elevation and gentle slope have increased the risk. An example of a large sinkhole, such as the Zamzam Well with a diameter of 95 meters, indicates the influence of the groundwater level and the presence of gypsum layers on sinkhole formation.

In the Maroon Plain, 61 sinkholes were identified with an average diameter of 21 meters for small sinkholes and 25 meters for large sinkholes. Most sinkholes occurred along watercourses and gentle slopes, and the length-to-width ratio (1:3) indicates the influence of the thickness of the gypsum layers on the shape and development of sinkholes. The results of the fuzzy model showed that 11.2% of the area is at high risk, 18.5% at medium risk, and 15.1% at low risk, while 55.2% of the plain area is located outside the gypsum layers and has zero risk. The most important factors affecting this plain include slope and the location of watercourses in the path of gypsum layers.

Conclusion

The study shows that the mechanisms of sinkhole formation in the Jaber and Maroon plains are different; in the Jaber plain, sinkholes are mainly formed near rivers and canal lines and at low elevations and gentle slopes, while in the Maroon plain, the path of watercourses and gentle slopes are the main factors for sinkhole development. The results of the fuzzy model have good accuracy and can help in land management, urban planning, and prevention of damage caused by sinkholes. This study highlights the importance of investigating geology, topography, and water resources management to reduce natural hazards in areas with gypsum layers.

Modeling and prediction of nitrate contamination in four aquifers of Isfahan province using random forest (RF) and support vector machine (SVM) algorithms

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Introduction

Groundwater is one of the most important sources of drinking and agricultural water supply in the world, and its importance is very high, especially in arid and semi-arid regions, including Iran. Population growth, industrial and agricultural development, and land use changes have increased pressure on groundwater resources and concerns about their quality. Groundwater pollution can have serious environmental, social, and economic consequences and threaten human health and ecosystems. Nitrate (NO₃) is one of the most important chemical pollutants, and the use of chemical fertilizers and agricultural activities increases its concentration in groundwater, and the consumption of nitrate-contaminated water can cause serious health problems.

Objective of the study

The main objective of the present study was to assess the extent and spatial distribution of groundwater pollution by nitrate in the four main aquifers of the study area and to investigate the role of environmental, geomorphological, and hydrological factors in determining the level of pollution. In addition, the use of machine learning algorithms including Random Forest and Support Vector Machine (SVM) for accurate and reliable prediction of nitrate concentration was another goal of the research.

Methods

In the water year 2022–2023, 137 groundwater samples were collected from four aquifers. In this study, colorimetric (UV-Vis) or ion chromatography methods were used to measure nitrate concentration. Environmental data of this study included slope, slope direction, geomorphology, geology, land use, vegetation cover index (NDVI), soil properties, distance from fault, and light shade. The data were preprocessed and standardized, and the VIF test was performed to examine multicollinearity, which showed that the variables did not have a significant linear correlation with each other and were suitable for modeling. The data were entered into the models based on a ratio of 80% for training and 20% for testing. The random forest model was run with 100 decision trees and the SVM model was also used to predict nitrate pollution. The importance of features was analyzed for both models and the performance of the models was evaluated using the ROC curve and AUC value.

Findings

The random forest model was able to make 95% accurate predictions of nitrate concentration and The SVM model also produced relatively similar results (83%). The analysis of the importance of features showed that in the random forest model, geomorphology and slope direction had the greatest impact on the pollution level, and land use and soil had the least impact. In the SVM model, soil characteristics and slope direction were the most important, and distance from the fault and land use had the least impact.

Analysis of the relationship between nitrate and environmental characteristics showed that nitrate concentration was higher in areas with high geological fractures and fault erosion, especially in limestone formations with high aquifer capacity. With decreasing distance from the fault and increasing soil permeability, nitrate levels increased. Also, areas with low and flat slopes, where mostly runoff has more opportunity to penetrate the aquifer, have higher nitrate concentrations, while slopes show a decrease. Slope direction and light shade also showed that the northern and northeastern areas have the highest concentrations, and southern areas with direct sunlight due to faster evaporation of moisture have lower nitrate concentrations in the aquifer. Natural vegetation such as pasture and forest also reduces nitrate concentrations, and agricultural lands with human activity show the highest pollution.

Spatial prediction maps showed that the highest nitrate concentrations were recorded in the eastern and northeastern areas of the Chadegan and Domaldaran aquifers, and the lowest values were observed in the Buin aquifer. The Chehelkhaneh aquifer is at a moderate level of pollution. This heterogeneous spatial distribution indicates the role of environmental, hydrological, and geomorphological factors in controlling the distribution of nitrate.

The performance evaluation of the models with ROC curve and AUC calculation showed that both models have excellent performance and AUC value was equal to 1.000, which indicates their unique ability to distinguish contaminated and uncontaminated samples and high prediction accuracy.

Conclusion

The present study showed that advanced machine learning models such as random forest and SVM are capable of accurately simulating complex groundwater pollution processes. Analysis of the importance of the characteristics and spatial distribution of pollutants showed the key role of geomorphology, slope direction, soil and distance from the fault in determining the amount of nitrate. Chadegan and Domelandaran aquifers had the highest level of nitrate pollution and Bouin aquifer had the lowest level, and Chehelkhaneh aquifer was at an intermediate level. These results highlight the importance of using advanced machine learning algorithms in groundwater resource management, pollution status prediction and environmental decision-making, and provide valuable insights for water resources specialists and environmental planners.

Temporal fluctuations in spring discharge turbidity: insights from this fecal source indicator into contamination sources and transport pathways within a karst aquifer

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This research explored how temporal fluctuations in microbial contamination from diverse sources relate to different flow components within a karst aquifer feeding a perennial spring in western Ireland. The study site, situated in the west of Ireland, employed turbidity time series as a proxy indicator of microbial contamination. The investigation was structured around two core questions (i) How does the temporal variability of Turbidity correspond to these flow components? and (ii) Is the variability of turbidity controlled by internal aquifer dynamics, rainfall intensity, or a combination of both? To address these questions, several analytical methods were employed, including Auto correlation function (ACF), Cross correlation function (CCF), and Fast Fourier Transform (FFT) analyses. Results revealed that variations in turbidity were weakly associated with the slow or baseflow component but strongly linked to the intermediate and fast-flow responses of the spring. The observed turbidity dynamics were found to be primarily governed by the internal hydraulic structure and flow partitioning within the aquifer. In contrast, no discernible influence of rainfall intensity or recharge events was detected within the study’s temporal resolution. Overall, the findings indicate that fluctuations in turbidity and consequently, microbial contamination signals are mainly controlled by internal aquifer flow architecture rather than by external hydrological drivers.

**From the sewers to ecohydrology and back to wastewater effluent again –
adventures in the lowland karst of Ireland**

Laurence Gill

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This talk will document the research carried out over the past 25 years in the karst areas of Ireland. Originally working in the wastewater treatment industry in the UK, I moved to academia in Ireland and recognised the parallel between urban sewer networks and the conduit dominated lowland karst networks in the west of Ireland. I used my wastewater network pipe modelling skills to model a 500 km² allogenic karst network using urban drainage software modified for use in karst groundwater scenarios. The main focus was to simulate the groundwater-surface water interactions which generate a number of ephemeral wetland lakes across the region, known locally as *turloughs*. This lowland karst area yielded a lot of field investigations over the years to refine understanding about the underground network and improve the model, including tracer studies as well as the use of rare earth element signatures to partition flows between allogenic sources (from neighbouring Old Red Sandstone hills) and autogenic recharge on the lowland limestone plain. Several different analytical techniques were also used on the time series data of recharge and turlough water levels (auto and cross correlation, Fourier analysis, discrete and continuous wavelets), again to improve knowledge about the hydraulic connections in the underlying karst network.

This work then led to research targeted on the ecohydrology of Groundwater Dependent Terrestrial Ecosystems supported by karst aquifers. The combination of hydrological field data and the use of semi-distributed pipe network modelling of the karst networks to simulate the groundwater-surface water interactions of the turloughs has enabled water level / duration metrics to be defined for the different unique vegetation habitats that exist within these wetland environments. These findings have also been combined with novel remote sensing-based algorithms to enable widespread classification of the habitats across these wetlands and to monitor their changes over time. This work is currently being extended to calcareous fen wetlands across Ireland.

The semi-distributed pipe network modelling has been extended to help with the design of a major flood alleviation scheme in the lowland karst area of south Galway. The model is used to define overflow levels for the network of turloughs such that flood water will be decanted from one to the other via overflow channels more quickly down to the sea following extreme rainfall events, thereby preventing damaging groundwater flooding in the area. This has required a careful balance between the prevention of extreme flood water levels whilst also maintaining the ecohydrological regimes needed for the unique turlough vegetation habitats. The model has also been used to quantify the freshwater discharge into the sea at Kinvara bay via submarine/intertidal groundwater discharge and used to assess any local impacts to the mariculture industry there.

More generically, research has also been carried out across several other karst catchments in Ireland to develop an analytical approach using rainfall and spring discharge time series data to quantify and numerically represent recharge and flow components in karstified aquifers, as a starting point for the development of semi-distributed models. Other modelling approaches have also been developed for comparison with the semi-distributed approach including a distributed Modflow unstructured grid (USG) with CLN model and more recently the increasing the use of machine learning based techniques. Nonlinear time series and machine learning algorithms have been developed for forecasting groundwater-surface water interactions (i.e. flooding) from the lowland karst catchments. A nonlinear autoregressive model with exogenous variables (NARX) model was demonstrated to be a viable alternative to the other semi-distributed groundwater models that had been developed and makes the relationships between key input variables easier to characterize. The research then moved on to

develop a different approach for the same catchment using a neural network model which incorporated Bayesian regularization and Scaled Conjugate Gradient training algorithms for model training and optimization which has demonstrated high predictive accuracy for short- and medium-term forecasts up to 45 days in advance. This model has then been used for climate change predictions which has shown that high-emission pathways will substantially amplify groundwater flood magnitudes and frequencies in this region.

Finally, the talk will present field and modelling investigations on the impact of human wastewater effluent in karst groundwater. Research has focussed on the suitability of the use of human specific tracers in a karst environment such as fluorescent whitening compounds (FWCs), faecal sterols, microplastics and pepper motile virus, as well as continuous monitoring proxies such as turbidity, flow cytometry and tryptophan like fluorescence. Ongoing research is attempting to develop a semi-distributed modelling approach for karst catchments that incorporates a water quality component to simulate the impact of septic tank pollution on the springs, distinguishing it from agricultural sources of pollution in the typical predominantly rural catchment areas of Ireland.

Geo-hydrological features contributed to the choice and configuration of the ancient Roman Augustan and Sannitico Aqueducts from Serino springs

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Since ancient times, access to huge and good-quality water resources has been important for populations. Among the other ancient populations, Romans, first, turned the aqueduct from an early invention into a large masonry work serving cities. They valued the use of good-quality springs for citizens, unlike water from wells, reservoirs or polluted rivers like the Tiber River in Rome. This supported the economic and demographic growth of cities and empire. Roman engineers designed aqueducts to bring spring water from distant reliefs, adapting to all terrains. As a result, these hydraulic achievements became common across the empire.

In Campania Region, the Romans built two important aqueducts: Augustan and Sannitico aqueducts, both fed by the Serino karst springs (Acquaro-Pelosi and Urciuoli; Figure 1a) located along the Sabato river, near Avellino and connected with the wide aquifer of the Terminio-Tuoro karst massif.



Figure 1. (a) Layout of Augustan and Sannitico Aqueducts; (b) Layout of Bolla Aqueduct inside Naples city; (c) Map of Roman thermal facilities across Benevento city.

The Augustan aqueduct (Esposito et al., 2025), built between 33 and 12 BD, provided drinking water up the Puteoli area and the imperial fleet stationed at Capo Miseno. Designed by Marco Vipsanio Agrippa, this aqueduct started from Acquaro-Pelosi springs (377-380 m a.s.l.) crossed the Forino and Sarno plains, flanking Sarno springs, reaching then Campanian Plain. After, it reached Naples city in Ponti Rossi locality (Figure 2a), joining with Bolla aqueduct (Figure 1b), and, crossing Phlegrean Fields area, finally conveying to Piscina Mirabilis reservoir, located in Bacoli, near the Roman military harbor of Misenum. Several branches started from the main

layout feeding Nola, Pompei, Oplontis, Herculaneum, Acerrae, Atella, Naples, and Cumae cities and Nisida and Posillipo localities. The total length of the aqueduct, branches included, is equal to about 140 km.

The Sannitico aqueduct (Esposito et al., 2024) fed Benevento, presumably built during the 1st Century AD, long about 33 km, was fed by Urciuoli spring (330 m a.s.l.; Fig. 2b). Passing across Cesinali, Atripalda, and Prata Principato Ultra (where some remains are still visible) municipalities, the aqueduct tapped Fonte dei Formosi spring located in Altavilla Irpina. After, crossing Barba canyon and flanking Sabato River, the aqueduct reached the reservoir currently located under Rocca dei Rettori building. From this reservoir, it branched off an underground urban aqueduct network that supplied several parts of ancient Benevento town, including thermal facilities (Figure 1c).



Figure 2. (a) Ruins of Ponti Rossi in Naples urban area and (b) Sannitico aqueduct near Serino springs.

Literature mainly focuses on archeological, architectural and engineering aspects of these aqueducts; however, hydrogeological and hydrological characteristics have been analyzed to reconstruct the rationale behind the selection of the aqueduct's water sources: flow rate, ground level, and quality of the karst waters. Some historical considerations and specific geo-hydrological features have highlighted how the Aqua Augusta and Sannitico aqueducts should have many links. Both could be part of a unique and great hydraulic system, built in the 1st century BC to supply residential areas of great importance (cities and patrician villas) or military areas (Miseno Harbor and Benevento). In the stretch where the two aqueducts run parallel to each other (in the Sabato River Valley), it is difficult not to hypothesize their connection, as well as because the Urciuoli Spring has a higher and more stable flow than Acquaro and Pelosi springs and the water demand throughout the coastal area (from Pompeii to Misenum) was greater. Furthermore, Benevento itself appears to have been an important Roman city since the 1st century BC, and therefore the construction of the two aqueducts was likely actually the project of a single, grandiose hydraulic water supply system. Chronologically, this wide hydraulic system appears second only to those already supplying Rome since the 3rd century BC, with the Aqua Marcia Aqueduct, which first tapped a karst spring in 144 BC. From this perspective, the Aqua Augusta and Sannitico aqueduct emerge not only as a complex water infrastructure, born from careful hydrogeological and engineering considerations, but also as a vital tool for territorial planning and political-military control, aligning with the strategies of Emperor Augustus.

Both aqueducts were destroyed after the Roman fall, due to the barbarian invasions and the consequent lack of maintenance after floodings of Sabato River, landslides and seismic events.

In current era, to supply the area of Naples, Urciuoli (1885-1888) and Acquaro-Pelosi springs (1934) were re-tapped by the “Serino Aqueduct” through a gravity channel, followed by a system of pressure conduits.

Keywords: ancient aqueducts, Romans, Serino springs, Augustan aqueduct, Sannitico aqueduct

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**Flow cytometry for groundwater quality studies at alpine karst springs:
applicability and challenges**

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A flow cytometric approach to investigate microbiological indicators is emerging and promising, as this technique allows fast and on-site analyses of the total and intact cell count, depending on the applied staining protocol. The staining with SYBR Green allows to detect viable and dead cells which yield the total cell count. If this staining protocol is combined with the use of propidium iodide, it is possible to further distinguish between viable and dead cells. Furthermore, it is possible to distinguish between microorganisms with a low (predominant in groundwater) and a high nucleic acid content (predominant in surface water). Recent studies show that this technique is suited for groundwater systems which suffer from highly variable bacteria concentrations during contamination events associated with rainfall events which require flexible sampling strategies.

The main goal of our study at an alpine karst spring was to achieve a better understanding of the transport processes governing the temporal dynamics of fecal bacteria after hydrological events, as a basis for a better management and protection of these valuable but vulnerable freshwater resources. Results from the comprehensive year-round monitoring demonstrate two major scenarios for groundwater quality deterioration (i) hydrological events, such as heavy rainfall, in summer and (ii) agricultural practices, such as manure spreading at the end of winter.

Carbonate rocks and karst water resources in the European Alps

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Carbonate rock massifs and karst landscapes characterize large parts of the European Alps. Groundwater resources from these karst systems are used by many cities and municipalities in the Alpine region for drinking water supply and feed a multitude of karst groundwater-dependent ecosystems (KGDE). The study presented here [1] quantifies for the first time the distribution of carbonate rocks and karst water resources in the Alpine region, based on the data from the Mediterranean Karst Aquifer Map (MEDKAM) [2] in combination with other datasets.

According to this study, approximately 76,200 km² (40%) of the Alps consist of exposed carbonate rocks. The Austrian Alps contain the largest absolute area of carbonate rocks (21,200 km²), while the French Alps have the highest percentage (51%). Since the highest mountain ranges mostly consist of crystalline rocks, only a relatively small proportion of Alpine glaciers are located in karst areas. These mostly small glaciers are rapidly retreating, which has a significant impact on the water storage in the catchment areas and the discharge dynamics of the associated karst springs.

The Alps contain some of the deepest and longest caves, as well as one of the world's largest karst water supply systems, the Vienna Mountain Spring Water Pipeline. By combining climate data and karst maps, groundwater recharge and sustainably available groundwater resources could be estimated: The long-term (1991-2020) mean annual recharge in Alpine karst regions is approximately 823 mm. This corresponds to renewable Alpine karst water resources of about 57,500 million cubic meters (MCM) per year – more than the volume of Lake Constance. These data form the basis for improved management of Alpine karst water resources and projections of karst water availability under climate change.

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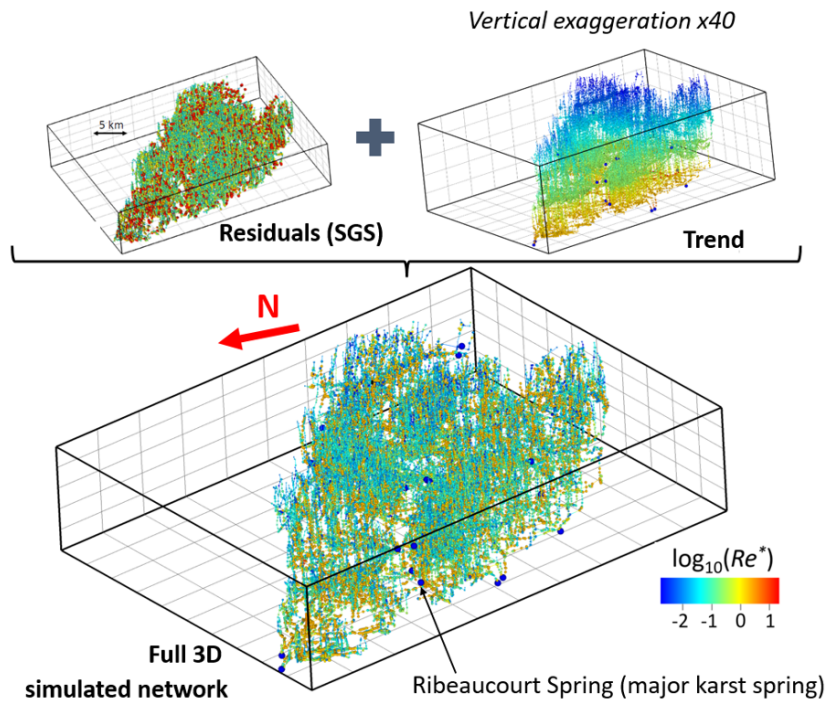
Modeling the Barrois karst in 3D: From skeleton simulation to conduit sizing

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The Barrois region is a karstified Limestone Plateau situated in the east of the Paris Basin. The regional karst appears underground in the form of a dense network of conduits of variable size (centimetric to pluri-metric scale), and at the surface in the form of sinking streams, dolines, springs, and various cave entrances. The karst network itself is polyphased, and was created over a complex history of karstification that involves and intertwines ghost-rock karstification, crypto-alteration, and epigenic alteration under cover. Most conduits there being inaccessible and difficult to detect, the only way to factor them explicitly in a broader flow and transport model would be to simulate them. Several attempts were made in that direction (Jaquet, 2004 ; Gouy et al., 2024). The latest one (Gouy, 2025) uses KarstNSim, an open-access code that stochastically simulates 3D karst networks constrained by geological and karstological knowledge and data. It captures most of the processes involved in shaping the Barrois karst network, but its handling of the simulation of conduit sizes lacks realism.

In this work, we thus propose an enhanced conduit-sizing methodology that builds on a karst network skeleton. Conduit dimensions (e.g., equivalent radius and aspect ratio) are simulated at the skeleton's discrete nodes using a 1D-curvilinear, branchwise Sequential Gaussian Simulation (SGS) scheme adapted from Frantz et al. (2021). Branches are part of the network between two junction nodes. Spatial correlation is represented through a multiscale variographic structure (intra-branch, inter-branch, and global variograms), allowing the model to reproduce variability within branches, between branches, and at junctions. The method explicitly honors measured or interpreted values at selected nodes (springs, inlets, explored caves), including constraints related to conduit enlargement when traversing ghost-rock volumes. To relax the stationarity limitation of simple kriging with fixed neighborhoods and to better reproduce large-scale organization, we introduce an external drift so that the simulated radius is expressed as the sum of a deterministic trend and a zero-mean stationary residual field. The drift is formulated as a regression on normalized explanatory variables that reflect (i) the node vertical distance to the water table, and (ii) the upstream integrated curvilinear length, thereby capturing contrasts between vadose and phreatic settings and the general downstream increase in conduit size respectively. Regression parameters are calibrated using a weighted least-squares strategy on all available observations except ghost-rock-driven voids that would otherwise bias the drift. This workflow produces observation-consistent 3D conduit networks that display both a local spatial correlation from the variogram models and a long-range trend that is directly inferred from available observations. This approach allows the construction of a 3D network that can be exported directly in a suitable flow model such as MODFLOW-CFP.



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Managing caves and karst landscapes in a changing climate: A climate change action plan for the Southeastern Cave Conservancy, Inc.

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This document is a Climate Change Action Plan (CCAP) prepared by the Southeastern Cave Conservancy, Inc. (SCCI). SCCI is the largest land conservancy solely focused on cave and karst conservation. SCCI manages thirty-eight preserves and cooperatively managed caves, protecting over 200 caves and over 3,000 acres of karst in seven southern states. As an on-the-ground conservation trust seeking to manage caves and karst to minimize the impacts of climate change, SCCI recognized the urgent need to develop a climate change action plan. Accordingly, we conducted a literature review and identified the most important and locally addressable climate change concerns including changes in hydrology, temperature, and microclimate. We also examined the relationship between climate change and speleothems, biodiversity, refugia, and karstification.

Informed by our literature review, we developed actions to guide the management of the caves and karst SCCI conserves to improve climate resiliency. Examples of our recommended management actions include promoting soil conservation practices, conducting hydrogeological monitoring, advocating for appropriate water use, and protecting and restoring primary forests and native vegetation. The development of this CCAP was limited due to the lack of published guidance and research regarding on-the-ground climate-based management of caves and karst. Accordingly, a section of the CCAP identifies areas for future research that might benefit cave and karst managers such as: anthropogenic displacement modeling, micro refugia mapping, and an enhanced understanding of invasive species ecology in order to implement biosecurity measures. In sum, this CCAP is an effort to begin filling the gap in management guidance and to identify areas of future research.

**Note: Artificial Intelligence (A.I.) was not used in the creation of this document. The authors made this decision primarily based on the negative climate impacts associated with A.I. use.*

Dispersion on laminar and turbulent network flow

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Karst aquifers are highly dynamic and heterogeneous systems, where solutes can be transported rapidly through conduit networks while parts of the contaminant mass temporarily reside in immobile zones, resulting in complex transport behavior and prolonged tailing in breakthrough curves. Accurately predicting solute dispersion in these systems remains challenging due to their multiscale structure and highly variable flow dynamics. To investigate these processes, flow in synthetic karst networks and in the real conduit system of the Seefeldhöhle (Switzerland) is simulated using a graph-based Laplacian solver capable of capturing both laminar and turbulent conditions. Solute transport is modeled using a Time-Domain Random Walk (TDRW) particle tracking approach. Particular attention is given to the role of mixing at conduit intersections, where both complete-mixing and streamline-routing rules are implemented to assess their influence on longitudinal and transverse dispersion. Transport behavior is characterized through first passage time distributions, particle visitation maps, and spatial moments. To further analyze the structure of particle velocities along trajectories, Lagrangian speed series are derived and their dependence structure is quantified using speed copulas. This analysis reveals distinct forms of correlation and intermittency that govern spreading, breakthrough tailing, and the sensitivity to network heterogeneity. While specific mixing processes at intersections affect local dispersion patterns, bulk metrics such as breakthrough curves and spatial moments remain comparatively insensitive. Building on these findings, the framework will be extended toward a multiscale upscaling approach based on a Continuous-Time Random Walk (CTRW), aiming to link conduit-scale velocity statistics with emergent network-scale transport dynamics.

**Towards a semi-distributed modeling approach to assess karst water resources:
First comparative application of ISPEEKH and KARSTMOD models on the
Ouyse system (France)**

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Karst aquifers represent a strategic water resource, providing freshwater to a significant part of the global population. However, these systems are characterized by strong spatial heterogeneity and increased vulnerability to global changes, including climate change and land use changes. The complexity of their structure, organized around a triple-porosity medium (matrix, fractures, conduits), renders their modeling particularly challenging (Hartmann et al. 2021).

In South-West France, the sustainable management of these resources requires predictive tools capable not only of simulating discharge at the outlet but also of faithfully representing internal storage and transfer processes. This study proposes a methodological comparison between two modeling approaches applied to a major regional system in order to identify the most robust modeling strategy to assess the impact of future changes on the karst water resource.

The study focuses on the Ouyse basin (Lot, France), a large-scale karst system covering a catchment area of approximately 650 km² (Viennet et al. 2023). This system presents a complex functioning characterized by three main outlets (Cabouy, Saint-Sauveur, and Fontbelle springs) and highly variable discharge rates, ranging from 0.5 m³/s during severe low flow to 150 m³/s during floods. Unlike simpler systems, the Ouyse is a binary system: it is fed by both diffuse infiltration on limestone plateaus (autogenic recharge) and localized river losses (allogenic recharge).

We implemented and compared two distinct hydrological models. First, the conceptual approach using KARSTMOD (Mazzilli et al. 2019; Sivellev et al. 2025). This widely proven model conceptualizes the system as a set of global reservoirs (Epikarst, Matrix, Conduit) connected by mathematical transfer laws. It treats the basin as a homogeneous entity, averaging precipitation and evapotranspiration at the catchment scale. Second, the semi-distributed approach using ISPEEKH. Recently developed based on the SWAT+ code (Soil and Water Assessment Tool), the ISPEEKH model (Integration of Surface ProcEssEs in Karst Hydrology) explicitly integrates spatial heterogeneity (Al Khoury et al. 2023). It divides the basin into Hydrological Response Units (HRUs) based on the superposition of land use, soil properties, and topography. This approach allows for the spatialization of recharge and models the physical interactions between the unsaturated zone, the matrix, and conduits.

The implementation and calibration of these two models on recent discharge time series of the Ouyse allowed for the evaluation of their performance. Results obtained with KARSTMOD confirm its robustness for reproducing flood hydrographs and simulating overall flow volumes. Its modular structure allows for rapid implementation and good performance in reproducing the output signal.

However, the application of the ISPEEKH model has highlighted the importance of spatialization in understanding internal processes. By integrating spatialized precipitation and evapotranspiration data, ISPEEKH allows a better constraint of the water balance, particularly during summer recession periods where actual evapotranspiration plays a critical role. Preliminary results show that distinguishing between diffuse recharge zones and localized losses improves the simulation of groundwater storage dynamics, a key variable for resource

management during low-flow periods. Sensitivity analysis methods based on wavelets are currently being deployed to optimize the parameters of this semi-distributed model.

This modeling work on the Ouyse pilot basin constitutes the initial step of a broader approach. Once validated locally, the methodology will be extended to a set of representative basins to propose a truly regionalized approach. Future work will integrate climate scenarios (DRIAS portal) and land-use evolution to project the state of the resource at the regional scale. The final objective is to provide water managers with robust quantitative tools to assess the resilience of karst systems in the face of combined pressures from climate and anthropogenic activities, beyond the specific case of the Ouyse.

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Connectivity and dynamics of karst aquifers in a semi-arid environment: an integrated study of the Hammamet plain, north-east of Algeria

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This study presents a multidisciplinary investigation of groundwater resources in the Hammamet Plain (semi-arid high plains of eastern Algeria), with a particular focus on the role and connectivity of karstified carbonate aquifers within a complex multi-layer system. The system comprises principal carbonate units (Maestrichtian and Eocene limestones) in hydraulic interaction with an overlying Quaternary alluvial aquifer.

The research employs an integrated methodology to delineate karst aquifer functions, combining: i) hydrogeological modeling (Visual MODFLOW) to simulate flow dynamics; ii) detailed hydrochemical (major ions, Piper diagrams) and stable isotopic ($\delta^2\text{H}$, $\delta^{18}\text{O}$) analyses to trace water origins and rock-water interaction; and iii) remote sensing for structural lineament mapping to identify preferential flow paths associated with karst development.

Results elucidate a conceptual model where the deep carbonate aquifers, influenced by NE-SW and E-W fracture networks, act as significant recharge sources and conduits for the alluvial aquifer. Hydrochemical data confirm the dominant Ca-HCO_3 signature, characteristic of carbonate dissolution, while stable isotopes validate modern meteoric recharge. A notable piezometric decline (5-7 m over 2010-2022) highlights the vulnerability of the system to combined climatic stress and overexploitation.

This work underscores the critical influence of karst hydrodynamics on regional groundwater resources in semi-arid environments. The findings directly support recommendations for sustainable management, including the targeted protection of karst recharge zones, the potential for managed aquifer recharge leveraging karstic conduits, and the necessity of integrated monitoring. The study provides a transferable framework for assessing karst-alluvial aquifer interactions in water-stressed regions.

Characterizing CO₂ degassing during dry-wet Alternations in a subtropics intermittent karst river

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Alternating dry-wet conditions are the defining hydrological feature of karst streams, yet the mechanisms through which they regulate biogeochemical processes and carbon cycling remain poorly understood. The CO₂ pulses caused by alternating wet and dry conditions increase the uncertainty in CO₂ degassing estimates. This study performed year-long, monthly monitoring of hydrochemical and hydrodynamic parameters in karst streams of southern China to examine CO₂ degassing, biogeochemical characteristics, and their key controlling factors under alternating dry-wet conditions. The results showed that groundwater exerts dual control on intermittent karst rivers by regulating dry-wet dynamics and governing biogeochemical processes, with direct consequences for riverine carbon cycling. FCO_2 ranged from -29.20 to 2507.64 (mmol·m⁻²·d⁻¹). Frequent Groundwater-surface water (GW-SW) interactions intensify water-rock reactions and modify hydrodynamic conditions, promoting DIC enrichment and calcite supersaturation in the water column, thereby facilitating the formation of localized carbon sinks. The highest mean FCO_2 (1326.85 ± 888.64 mmol·m⁻²·d⁻¹) occurred in June, whereas the lowest mean value (147.96 ± 157.20 mmol·m⁻²·d⁻¹) was observed in July. The rainy season contributed 38.98% of the total annual CO₂ degassing. Moreover, short-term dry-wet alternation triggered distinct degassing pulses, which accounted for 17.37% of the total CO₂ degassing. This pattern primarily arises from the rapid degassing of DIC and Ca²⁺ rich groundwater during dry-wet alternations, facilitated by slope enhanced hydrodynamic conditions. Concurrent carbonate dissolution further amplifies this response, leading to pronounced CO₂ degassing pulses. Therefore, enhanced high-frequency monitoring of dry-wet alternation processes in intermittent karst rivers is essential for resolving transient CO₂ degassing pulses and constraining uncertainties in regional and global river carbon budgets.

Thermal drifts, ruptures, and instabilities in karst caves under climate change.

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The impact of climate change on cave microclimates is characterised by a loss of stationarity in temperature and atmospheric composition (CO_2 , O_2 , ^{222}Rn) time series. The most striking manifestation is a gradual increase of subterranean temperatures, primarily attributed to thermal conduction through rock formations. However, comprehensive analysis of multidecadal records show that the thermal evolution of karst caves is far more complex, exhibiting ruptures, instabilities and unexpected shifts. These changes are now affecting cave walls interfaces with the atmosphere, raising serious concerns for heritage conservation.

Eight caves of across southern France have been under continuous environmental monitoring for nearly 30 years to support conservation of their natural (speleothem caves) and cultural (prehistoric decorated caves) heritage. These sites span a wide diversity of configurations including variations in chambers size and depth, network organization, entrance's location and number, levels of fluid exchange with external environment, and management approaches ranging from full protection to controlled scientific access to public show caves. This suite of caves experiences the same regional surface climate forcing, making them ideal for distinguishing fundamental karst processes from site-specific anomalies.

The monitoring program employs consistent measurement protocols established at inception, with 15-minute data acquisition and emphasis on accuracy and continuity. Only two measurement systems have been used: i) data logger units (SA32 and Campbell CR3000) with regularly calibrated Pt100 Class A wired sensors, achieving ± 0.01 °C accuracy; and ii) Seabird SB56 autonomous thermistor sensors, which have a stability exceeding 0.002 °C/year. Parallel deployment enables ongoing verification of instrumental stability.

Temperature drift values in many sites are especially high : 1.04 °C/decade in the Red Paintings Room and 0.81 °C/decade in Breuil Gallery at Mas d'Azil cave, as well as 0.66 °C/decade in the Lower Gallery at Gargas. These values substantially exceed the average warming rates for metropolitan France (0.3–0.4 °C/decade), raising the question of whether warming is being amplified in the underground environment. Comparison with nearby meteorological stations indicates that underground drifts values approaches local external drift of 1.2 to 1.4 °C over the past decade also pointing to intensified regional warming in recent years.

Drift values obviously depend on the depth of the caves: for example, it is 0.71 °C/decade at the deepest air monitoring point (18.4 m depth) in Marsoulas and 0.079 °C/decade in the remote Aragonite Gallery in Esparros cave (96.5 m depth). Within individual site, the drift value decreases with depth: in Gargas with 0.47 °C/decade at 30 m depth and 0.35 °C/decade at 39 m depth; in Bruniquel with 0.31 °C, 0.26 °C and 0.18 °C at 32 m, 38 m and 55 m depth, respectively.

Interestingly, drifts reach greater depths than expected: 0.093 °C/decade at 80 m in Gouffre d'Esparros and 0.15 °C/decade at 125 m in Aven d'Orgnac. Therefore, conduction through the encasing rock volume cannot be the only driver of heat transport. Similar drift values (0.15 °C/decade) are found at 33 m depth in Pech Merle cave and at 125 m depth in Aven d'Orgnac. These apparent discrepancies can be explained by contrasting direct air exchange rates with external and internal aerological processes, as described in previous detailed papers. Furthermore, drift acceleration was recorded in Gargas cave in 2016 at the deepest station (42.5 m depth), illustrating the complexity of the propagation of warming towards deep areas.

As the shallower parts of caves experience faster warming than the deeper parts, the location of warm and cold zones within most sites is shifting, resulting in modifications to the thermal gradients. These changes have tangible consequences: in the prehistoric Gargas cave, periodic changes in wall conditions were observed for the first time and were attributed to aerological disturbances that alter the conditions and locations of drying and condensation.

Notably, thermal drift occurred simultaneously in all sites monitored for over 20 years in 2012, despite their unique characteristics (Gargas, Pech Merle, Marsoulas, Chauvet and Aven d'Orgnac), with the exception of the deepest, thermally stable Niaux cave (< 200 m depth). A similar turning point in 2012 is evident in local external temperature time series and corresponds to the end of the “global warming hiatus” between 1998 and 2012 (IPCC, 2013).

Alongside gradual changes, sudden thermal shifts have been documented following intense climatic events. For example, 100 mm of rainfall at Gargas cave on 17 October 2024 resulted in the infiltration of warmer water, causing a permanent temperature shift of between 0.02 and 0.03 °C throughout the entire cave (including shallow and deep stations, soil vaults and walls). This later integrated the long-term drift effect.

The profound and ongoing disruptions described in previously stable underground environments represent an emerging threat for its fragile heritage. Monitoring is a prerequisite to anticipate and mitigate the most damaging effects.

**Land cover influences on Asian summer monsoon $\delta^{18}\text{O}$ signals in groundwater:
Implications for paleoclimate interpretation**

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The stable oxygen isotope in speleothems in the monsoon region of China provides a widely used record for inferring the history of the Asian summer monsoon (ASM). However, the influence of non-climatic factors, such as land cover, on ASM $\delta^{18}\text{O}$ signals in stalagmite-feeding groundwater at sub-annual and annual scales during precipitation infiltration processes remains unclear. Herein, we studied five simulated watersheds, differing solely in land covers, and two local caves in Southwest China, to investigate the influences of land cover on the hydrological strength and ASM $\delta^{18}\text{O}$ signals in groundwater. Based on 3 years of hydrometeorological and isotopic data, we found that groundwater $\delta^{18}\text{O}$ in simulated watersheds can effectively represent the $\delta^{18}\text{O}$ of natural drip water. It also reliably captures both seasonal and interannual changes in precipitation $\delta^{18}\text{O}$. However, the annual mean groundwater $\delta^{18}\text{O}$ of soil-covered lands failed to reflect interannual variations of precipitation $\delta^{18}\text{O}$ during ASM period, due to the interference of $\delta^{18}\text{O}$ from non-summer monsoon precipitation. On the contrary, ASM groundwater $\delta^{18}\text{O}$ strictly followed the variations of ASM precipitation $\delta^{18}\text{O}$. Moreover, we discovered that land cover regulates hydrological strength and subsequently influences groundwater $\delta^{18}\text{O}$ seasonality and ASM $\delta^{18}\text{O}$ enrichment (Fig. 1). Our results highlight the need to eliminate non-summer monsoon precipitation $\delta^{18}\text{O}$ interference on groundwater or drip water $\delta^{18}\text{O}$. This is crucial even in regions of Southwest China, where non-summer monsoon precipitation accounts for less than 30% of the annual precipitation. The key step for this elimination is identifying well-preserved $\delta^{18}\text{O}$ seasonality in groundwater. We propose that bare karst with minimal soil is indicative of conditions favorable for groundwater infiltration and the conservation of precipitation $\delta^{18}\text{O}$ seasonality and ASM $\delta^{18}\text{O}$ in groundwater.

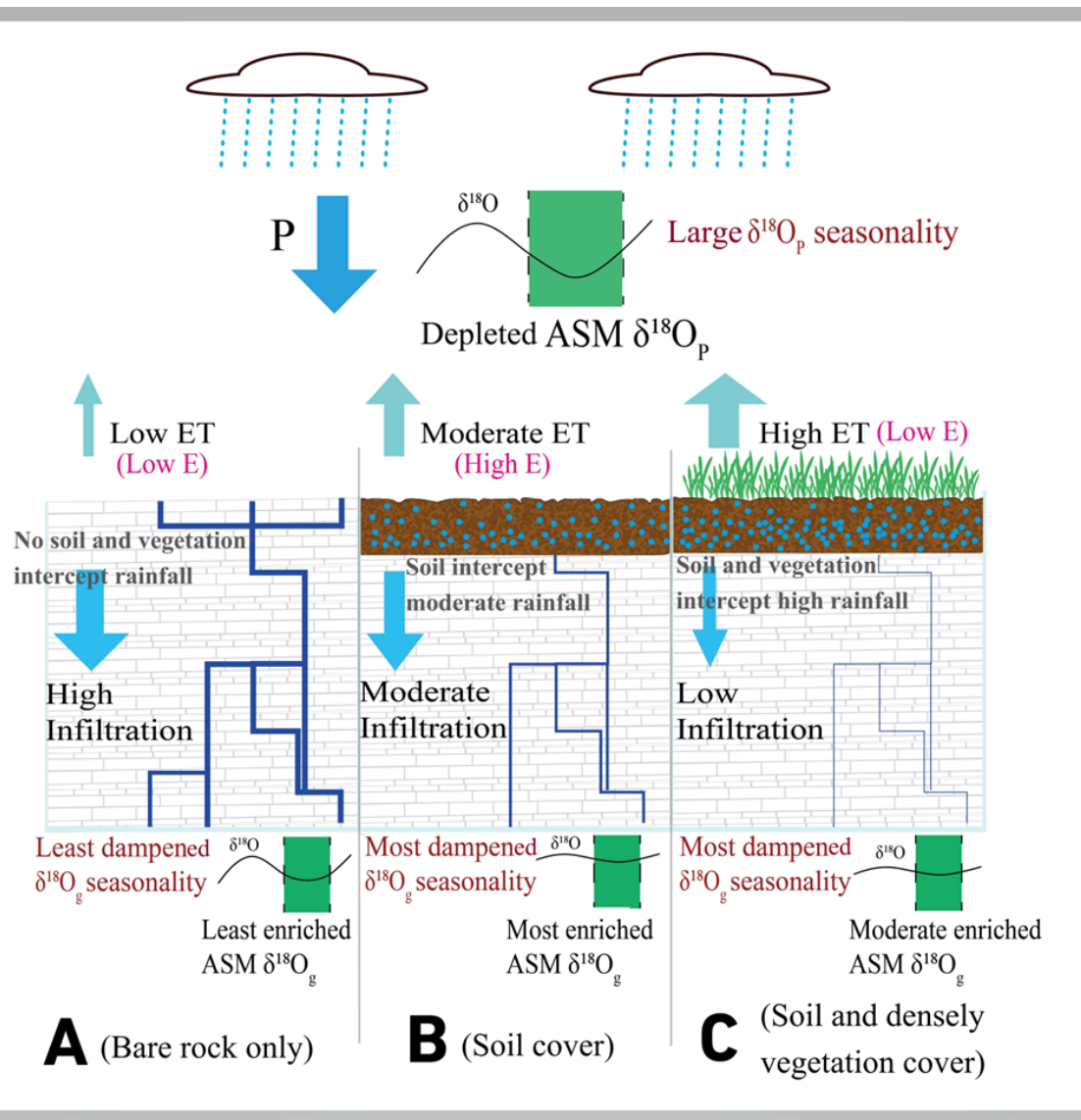


Figure 1. Simplified conceptual model showing the influence of soil and vegetation cover on hydrological strength and $\delta^{18}\text{O}$ signal conservation in a karst environment. The model includes three scenarios (A, B, and C), where only land cover changes, and aquifer heterogeneity is not considered. Rainfall interception of by soil and vegetation reduces groundwater infiltration from A to C, while evapotranspiration (ET) exhibits the opposite trend. Due to soil's role in moderating precipitation $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_p$) seasonality, groundwater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_g$) seasonality is the least dampened in scenario A. Higher evaporation (E) results in greater enrichment of ASM $\delta^{18}\text{O}_g$, with scenario B exhibiting the most enriched ASM $\delta^{18}\text{O}_g$.

Regressive erosion and morphogenesis of underground knickpoints. The Rupt-du-Puits waterfalls (Paris Basin, France).

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As river systems become incised, the base level falls and karst systems reorganize themselves in line with this new altitudinal control. Underground, new drains connect to the new outlet while conduits connected to the paleo-outlet are abandoned. This drainage reorganization is not synchronous. It progresses upstream, by regressive erosion. Its upper limit is an underground knickpoint. In detail, this takes the form of one or more cascades, separating an upstream zone, perched and under the altitudinal control of the old base level, and the downstream zone, already controlled by the new base level. To study these underground knickpoints is to understand the temporality of karst readjustment, to accept that a karst is both under the control of current parameters, but also marked by past heritages.

A 3D analysis of the Rupt-du-Puits waterfalls (Paris Basin, Champagne / Lorraine, France) is proposed here to study the variability of erosion between upstream and downstream. In the field, this zone of regressive erosion is less than 50 m long, making up for a 5 m difference in level - not insignificant for low-plateau karsts whose total difference in level is around 50 m. Four waterfalls of 1.2 m, 0.8 m, 0.3 m and 0.8 m constitute clear topographic breaks in the bedrock's longitudinal profile. The variability of water heights at each waterfall was studied using a device of table soccer balls arranged along a metal ruler (Jaillet et al. 2017). This device made it possible to finely characterize maximum flood heights with an altitudinal resolution of 10 cm.

An analysis of the evolution of the wetted perimeter and wetted surface was carried out using a 3D survey (Faro Focus 3D scanner, Racine et al., 2024). The results are presented in a longitudinal profile. 53 sections are extracted, and the four waterfalls are each framed by sections. With each waterfall passage, the wetted area and perimeter increase. Upstream, the increase stops immediately once the gradient is crossed. On the other hand, towards the downstream end, the increase continues several meters downstream of the obstacle. This would indicate greater maturity for the forms furthest downstream, and confirm the more juvenile upstream forms. The rate of increase in surface area is calculated in relation to the average of the four preceding sections. This shows a maximum increase in the upstream waterfall, where the wetted area rises rapidly from 2 m² to 3.4 m². We know that the maximum flood recorded on the Rupt-du-Puits is 7 m³/s downstream of the collector (Jaillet, 2005). If we take a range of 5 to 10 m³/s as the maximum flow, this would give velocities of 3 to 6 m/s in the upstream part of the cascades and 1 to 2 m/s in the downstream part, with greater water heights. This suggests maximum erosion at the knick-point weir in the upstream waterfall.

This organization of forms, known externally (Whipple et al., 2000; Richardson et al., 2005; Crosby et al., 2007), enables us to propose a conceptual diagram of the evolution of an underground regressive erosion zone (fig. 2). The aim is to identify the spatial organization of forms, integrate the role of water level variations (high and low water) and locate any sedimentary deposits. Four zones are organized from upstream to downstream: (1) the upstream river, whose bedrock is not yet affected by incision, (2) the emerging and coalescing potholes, (3) the waterfalls and their knickpoint and (4) the mature canyon zone, where the river profile is relatively flat. Active morphogenesis takes place between the low-water and high-water marks. Upstream, loading is limited, as the channel has retained its considerable width.

Key points in time, marked by 6 synchronous surfaces, have been identified: (1) surface abandonment of the drowned phase, (2) top of the alluvial terrace, (3) deposition of draining clays and first incisions, (4) mature pothole downstream and flood clays further upstream, (5) and (6) continuation of regressive erosion. On a chronological timeline, synchronous and diachronous objects can be identified. There is a temporal decorrelation between the upstream

and downstream parts of the system, and it is this decorrelation that constitutes the particularity of regressive erosion zones. Upstream always seems to be under the yoke of the past, while downstream is in tune with the present. This local dilatation of time within a defined space creates a zone of tension, implying intense morphogenesis at the knickpoint.

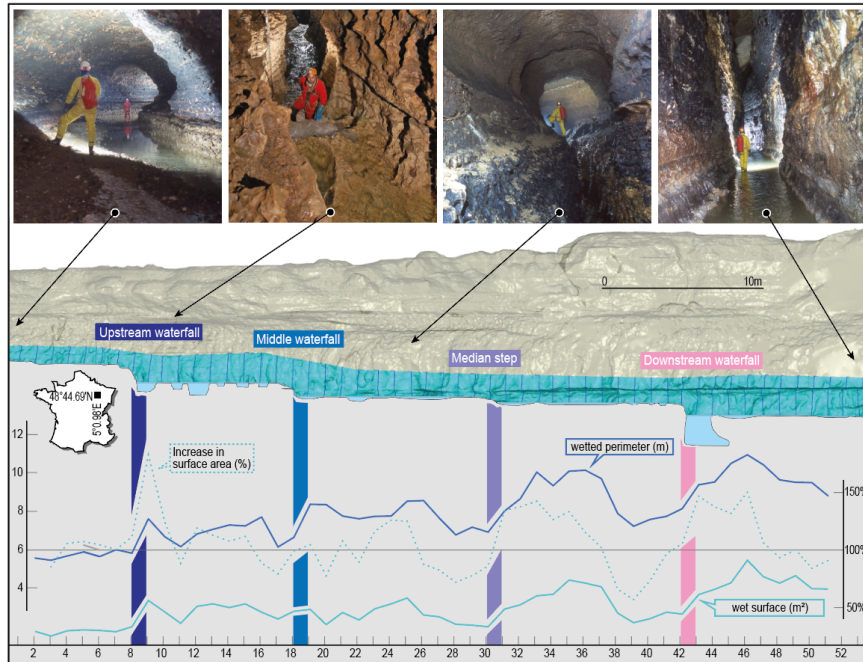


Figure 1. Longitudinal cross-section of the Rupt-du-Puits waterfalls, based on a 3D lasergrammetric model. More than 50 cross-sections (metric spacing) are extracted, enabling us to measure changes in wetted surface and wetted perimeter. The rate of increase in wetted surface at each cascade shows that velocity is highest upstream. These are the points of greatest morphogenesis.

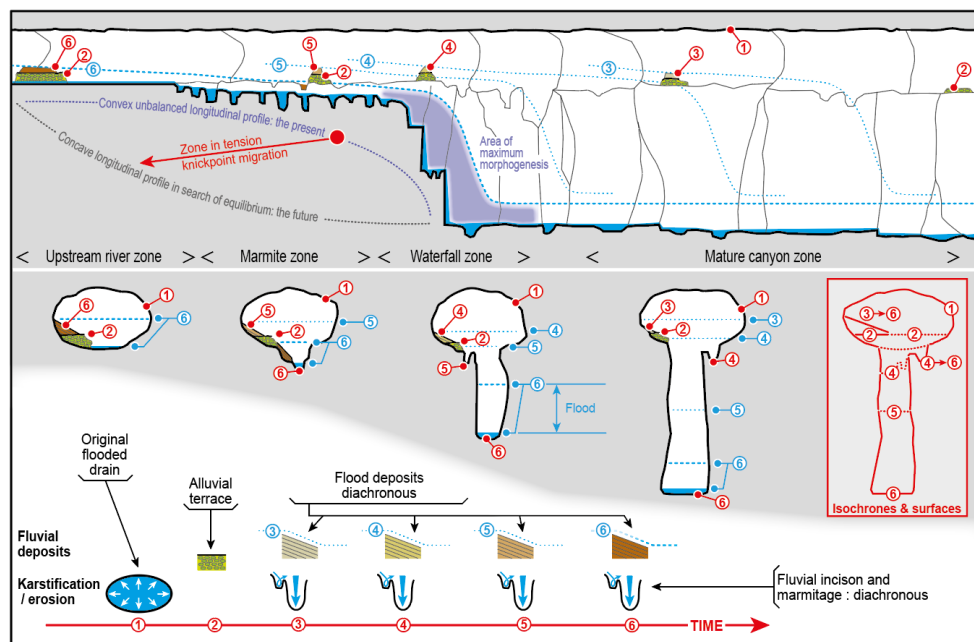


Figure 2. Theoretical conceptual model of the organisation of forms and deposits in a zone of regressive erosion in an underground river undergoing incision. From upstream to downstream, four zones are identified. Low-water and high-water water lines (blue) structure the dynamics of erosion and deposition. Six isochrones are identified (red). These show the synchronous objects and diachronous surfaces of this evolving system.

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A way to characterize recession and drought in karst aquifer systems

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Quantifying groundwater storage in karst aquifers remains challenging due to their heterogeneous structure and the scarcity of direct observations. This study proposes a pragmatic approach to characterize storage and water availability in karst systems at the regional scale, using long-term hydrographs from 16 Swiss karst springs and rivers. We distinguish between seasonal storage, related to recharge events, and low-water storage, which sustains discharge during periods without groundwater recharge. Seasonal storage was estimated at 30–70 mm, with maximum short-term storage up to ~140 mm, based on recharge–discharge modelling. Low-water storage was consistently ~200 mm across most systems, despite variability in hydrogeological settings. Recession curves analysis revealed that nearly all analyzed natural springs follow a similar “master recession curve”, starting at a specific discharge of $11.25 \text{ L s}^{-1} \text{ km}^{-2}$. This uniformity enables the definition of a regional drought index that quantifies the expected remaining groundwater storage and predicts discharge several weeks in advance. Comparison with non-karstic catchments shows that karst hydrogeological systems dampen peak flows but sustain baseflow through distinct storage reservoirs. The proposed approach provides explicit indicators that can be applied across karst regions to assess drought severity, guide groundwater management, and anticipate water shortages. Despite uncertainties in discharge measurements and catchment delineation, results demonstrate that simple hydrograph-based analyses can yield robust, transferable insights into karst groundwater storage at regional scales.

Instabilities and hydrogeology: a case-study in the region south of Basel

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Southeast of Basel, the Rhine flows through the first sedimentary layers overlying the crystalline basement visible a little further north in the Black Forest. Karst collapses are regularly observed there, as well as active subsidence (several mm/year) in an area approximately 1 km in diameter.

The middle and upper Triassic consists of an evaporitic series with deep layers of salt, then anhydrite, interbedded with clay formations. On top of it are limestone beds from the Upper Muschelkalk, topped by clay-gypsum formations from the Keuper.

The limestones are highly karstified and very permeable. They are therefore widely used as an aquifer, both for an artificial groundwater recharge station using water from the Rhine, as well as for the extraction of industrial water for neighboring businesses.

3D models of the underground were constructed and calibrated using a multitude of boreholes and piezometric data to assess water circulation in this area. The models indicated a probable hydraulic link, along faults, between the main aquifer of the Upper Muschelkalk and the roof of the salt formations located 50 to 100 m below. Two boreholes confirmed the existence of such a hydraulic connection. A flow of a few L/s appears to be flowing at the top of the salt, causing dissolution and the ground to subside. In this highly urbanized area, underground flows are almost exclusively controlled by human activities (dam on the Rhine, industrial water pumping, water injection for drinking water, clear water infiltration, etc.).

Along the next phase of the study we will assess the effect of these various activities on the rate of subsidence.

The real-time monitoring technology of karst groundwater-air pressure and its application in the prevention of induced karst collapse

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Monitoring and prediction for karst collapse is considered a worldwide problem. The main reason is that the monitoring technique for the dynamic condition of karst collapse is still used the traditional method of groundwater level monitoring, which is a long period and groundwater table connected with atmospheric pressure. The author's research team has developed karst groundwater-air pressure monitoring technology to reflect the change conditions of groundwater-air pressure within karst fracture and conduit system. This technique has special requirements for drilling, sealing on the top of borehole, and monitoring frequency.

In 2023, there has been a karst collapse incident in Longgang District, Shenzhen, China. The incident caused subsidence and cracking of residential buildings, endangering residents and infrastructure. The affected covered karst area features 5-20m Quaternary silty clay overlying Lower Carboniferous Shitdengzi Formation limestone with developed karst cavities, and the depth of karst groundwater is about 3-5 meters. There are 3 construction sites within a radius of 1 kilometer from the collapse, including a shield tunnels construction for subway and two excavations of deep foundation pits for skyscrapers. Six monitoring boreholes equipped with piezometers and dataloggers recorded groundwater-air pressure changes 12 times/hour were installed to confirm the triggering factors of collapse. The monitoring results indicate a close relationship between changes in karst groundwater-air pressure and engineering construction. The karst groundwater-air pressure monitoring project has continued for 2 years. It dynamically guides the construction of the shield tunnels and foundation pits, preventing occurrence of new collapses.

A large-sample dataset of karst spring hydrographs and catchment attributes in the alpine region

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Karst springs play a crucial role in the Alpine water cycle and are important sources of regional drinking water supply. At the same time, spring discharge dynamics are sensitive to changing climatic conditions, potentially leading to seasonal flow redistribution. To enable robust predictions of Alpine karst spring discharge and to improve the understanding of the dominant hydrogeological processes, a comprehensive and consistent data basis is required. Within the DFG- and FWF-funded project AlKa-DL (Prediction of Alpine karst spring discharges in view of climate change using recent advances in Deep Learning), a harmonised dataset of karst spring discharge time series, meteorological forcings, and static catchment attributes was compiled for the wider Alpine region (EUSALP). The dataset is inspired by the CAMELS datasets widely used in catchment hydrology and is intended to support a broad range of applications in Alpine karst hydrogeology.

The dataset contains more than 240 daily and over 180 hourly karst spring discharge time series covering all seven countries of the EUSALP region. These data were obtained from public authorities, scientific monitoring networks and individual researchers and subjected to a uniform data preprocessing workflow. The time series were cleaned of outliers and artefacts using a combination of manual inspection and automated methods and were annotated with various quality flags. Depending on the original temporal resolution, the data were aggregated to hourly and daily time steps. To support flexible and efficient data selection, additional flags were introduced indicating the temporal resolution and quality of individual time series segments, as well as questionable breakpoints within the time series.

In addition, a comprehensive set of catchment-scale variables was derived by spatial aggregation over two alternative catchment representations provided with the dataset: (i) catchment boundaries obtained from public authorities and the literature, where available, and (ii) buffer-based catchment approximations derived for all karst springs based on a simple local water balance approach to estimate catchment size and on available tracer information to approximate catchment orientation. For each catchment representation, precipitation and temperature time series were aggregated from domain-wide and national gridded meteorological data products. Static attributes related to topography, positioning, meteorology, land cover, soil and hydrogeology were derived by aggregating multiple, predominantly pan-European data products over the respective catchment representations. Moreover, statistical descriptors and karst-specific indicators describing storage properties and flow behaviour were derived from the hydrographs.

The dataset enables (i) comparative analyses and classification of Alpine karst systems, (ii) training and benchmarking of both traditional and data-driven models, and (iii) prediction of karst spring discharge and climate change scenario analyses across the Alpine region. The consistently processed and comprehensive set of variables is particularly well suited for machine-learning-based applications.

Understanding karst processes through converging karst diagnostic and statistical approaches

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Karst aquifers are complex, heterogeneous, and anisotropic hydrosystems. These characteristics result in non-linear hydrodynamic behaviors that are strongly dependent on hydrometeorological conditions, exploitation, geological structures of several steps of karstic evolution. Understanding their piezometric response is therefore a major challenge for sustainable water resources management, particularly in Mediterranean regions. Piezometric analysis is generally conducted on the basis of simplified conceptual models (dual-porosity or Drainage Accessory System); however, recent concepts associated with ghost-rock karstification and high variability of the base level since the messinien event offer new perspectives, particularly regarding the use of complementary approaches.

This study focuses on a karst aquifer located near Nîmes (southern France), within a Mediterranean context. This complex outcropping karst hydrosystem, referred to as the “Garrigue limestone aquifer”, is used for both drinking water supply and production of bottled natural mineral water.

In order to better characterize the hydrodynamic behavior of this complex karst aquifer, this study combines two complementary and interdependent approaches: *i.* statistical analysis of piezometric and hydrometeorological time series; *ii.* karstological and geological analysis integrating data and field observations focusing on the identification of hydrodynamic blocks inducing different piezometric conditions characterizing the karstic reservoir.

The statistical methodology is based on the analysis of piezometric time series from several piezometers distributed across the study area, together with rainfall data. Several statistical analyses were implemented, including cross-correlation analysis between rainfall and piezometric levels (Mangin, 1984), inter-piezometer correlations, clustering methods based on cumulative frequency curve of groundwater levels (Erguy et al., 2023), and K-means approaches. These analyses allow the evaluation of system response times, the degree of connectivity between observation points, the identification of homogeneous behavior groups, and the similarity or, conversely, the singularity of certain piezometric responses. The analyses were conducted over five periods (a three-year period, a dry hydrological year, and three major rainfall events) using data from 4 to 18 Cretaceous piezometers, depending on the period.

In parallel, a karstological diagnosis developed since several years by CENOTE and applied in academic domain (Jouves, 2015 ; Baral, 2024) was carried out. This analysis was based on geological maps, cross-sections, borehole logs and targeted field observations, with a focus on identifying karst features and geological structures likely to control groundwater flow. Particular attention was given to the geometry of the Hauterivian carbonate reservoir and to the identification of hydraulic barriers and structural discontinuities that may induce compartmentalization of the reservoir and paleo karstic alteration controlling the stretching of the water catchment during the geodynamic evolution and the water input of hydrosystem.

The statistical approach makes it possible to distinguish several groups of piezometric behaviors within the Cretaceous aquifer. These contrasting responses suggest the existence of hydraulic compartments and preferential flow paths. The analyses also highlight atypical behaviors that cannot be fully explained by statistical analysis alone but are consistent with hypotheses derived from the geological approach. In particular, the karstological study identified preferential drainage axes controlled by the presence of hydraulic barriers and by the geometry of the Hauterivian carbonate reservoir. These structures, corresponding to different step of karstic

history of the Hauterivian reservoir, appear to play a major role in flow orientation and system compartmentalization, thereby explaining the observed contrasts in piezometric responses.

In conclusion, this study highlights the strong complementarity between statistical and karstological approaches for understanding the functioning of complex karst aquifers. By jointly constraining hydrodynamic behaviors and structural properties, the proposed integrated approach provides a robust basis for improving sustainable water resource management in heavily exploited karst contexts and can be transferred to other complex hydrosystems facing similar challenges. Moreover, it constitutes a key preliminary step for subsequent modeling efforts, particularly regarding recharge and exchanges between aquifers.

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Role of rapid and slow groundwater flows in the transport of S-Metolachlor and its metabolites in a multi-layer karst aquifer

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The Moulineaux spring is a major drinking water resource for the city of Périgueux (Dordogne, France), with a mean flow of approximately 1100 L·s⁻¹. The spring drains a multilayer karst aquifer system in which groundwater is mainly present within Upper Cretaceous limestones. The saturated zone exists in bioclastic and sandy limestones of the Coniacian and Santonian formations, whereas the unsaturated zone is within chalky and marly limestones of the Campanian.

Previous investigations have shown that, the system has a strong global inertia that provides an effective natural attenuation capacity. However artificial tracer tests revealed locally very rapid groundwater flow velocities, reaching up to 65 m·h⁻¹. This apparent contradiction between global inertia and episodic fast flow raises critical questions regarding the actual vulnerability of the spring to diffuse pollution. Particularly pesticides applied within the catchment area, where more than 50% of the recharge area is occupied by agricultural land (cereal crops and cow farming). Current knowledge remains limited concerning the partitioning of anthropogenic substances between slow and fast flow components and the efficiency of long residence times in mitigating contamination peaks.

The objective of this study is to better characterize the vulnerability and resilience of this karst system to anthropogenic pressures. To address the issue a large approach is adopted, combining conceptual modelling of pollutant transport, statistical analyses, and long-term monitoring of contaminants. Particular attention is given to the analysis of S-metolachlor (SMET) with its metabolite, metolachlor oxanilic acid (MOXA) and metolachlor ethanesulfonic acid (MESA), which are used as indicators of degradation processes and groundwater transport pathways.

At the karst spring outlet only chlorothalonil R471811, a metabolite of chlorothalonil (prohibited in 2020) and S-metolachlor with its metabolites MESA and MOXA remain detectable. Chlorothalonil R471811 and metolachlor ESA are the most frequently detected compounds, respectively occurring at low concentrations ranging from 0.05 to 0.2 µg·L⁻¹ and from 0.05 to 0.3 µg·L⁻¹. In contrast, metolachlor OXA and parent S-metolachlor are less prevalent and are often below the analytical detection limit, with occasional concentration peaks respectively reaching up to 0.08 and 0.14 µg·L⁻¹. These compounds were therefore monitored every two weeks from October 2023 to December 2025, along with the main anions and cations and physicochemical parameters. The results show a strong correlation (≈70%) between MESA, nitrates, and sulphates, indicating common transport pathways related to agricultural inputs. Seasonal peaks in MESA concentration above 0.25 µg·L⁻¹ occur at the beginning of the hydrological cycle, reflecting both the historical use of S-metolachlor and the high persistence of its metabolites in soils, despite the ban on the original compound in France in 2024.

Hysteresis analyses between magnesium and MESA concentrations reveal distinct hydrological regimes and contrasting contaminant behaviors under variable flow conditions. Mass balance calculations indicate that at least approximately 1% of the S-metolachlor applied in the watershed is recovered at the source outlet, mainly in its degraded form (MESA). The contrasting physicochemical properties of S-metolachlor and its metabolites (persistence, solubility, and adsorption) provide additional insight into degradation and transport processes at the spring outlet. These processes are studied using graphical analysis, plotting the ratio of ESA metolachlor concentration to the total concentrations of S-metolachlor related compounds

($\frac{ESA}{SMET+ESA+MOXA}$) against the ESA/MOXA ratio. This approach also makes it possible to

distinguish between contamination associated with long residence times and contamination caused by rapid groundwater flow.

Overall, this study demonstrates that, although rapid flow pathways contribute significantly to the transfer of contaminants in a karst system traditionally considered to be very inert, long-term vulnerability is mainly due to inertial transport processes capable of maintaining pesticide contamination over long periods of time. These results highlight the relevance of using S-metolachlor and its metabolites as natural groundwater tracers, enabling the quantification of the respective contributions of fast and slow flow components. This approach can be integrated into a methodological framework for assessing the vulnerability of karst sources to pesticides, with direct implications for drinking water management in agricultural karst regions.

Spatial mapping of P_{CO_2} – $\delta^{13}C$ relationships across karst springs to investigate CO_2 evolution and karst system functioning.

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Dissolved carbon dioxide (CO_2) plays a fundamental role in the development of karst aquifers by controlling carbonate dissolution processes and influencing groundwater chemistry. When water circulates through the carbonate aquifer, CO_2 concentrations and the isotopic composition of dissolved inorganic carbon (DIC) change as a result of various geochemical processes including the dissolution and precipitation of carbonates, CO_2 degassing... (Peyraube et al., 2012; Pu et al., 2014; Binet et al., 2020). Identifying and understanding the interaction of these processes within complex karst systems remains a major challenge for karst hydrogeology.

The partial pressure of CO_2 (P_{CO_2}) and the carbon isotopic composition of DIC ($\delta^{13}C$ -DIC) are recognized as valuable tracers of carbon sources and geochemical evolution in karst waters (Azzaz et al., 2008; Milanolo, 2016). P_{CO_2} is used to assess the openness of the system to gas exchange and the intensity of soil-derived CO_2 inputs, while $\delta^{13}C$ -DIC provides insights into the relative contribution of biogenic CO_2 , carbonate dissolution, and isotopic fractionation associated with degassing and precipitation (Cao et al., 2019; Lyu et al., 2024).

This study examines the spatial variability of P_{CO_2} and $\delta^{13}C$ -DIC signatures within a well-characterized karst aquifer, with the aim of assessing how combined carbon tracers can provide information on CO_2 evolution in different geological compartments. The approach is applied to the Moulineaux spring system (Dordogne, southwestern France), a multi-layer karst system. Groundwater flow mainly occurs within the Upper Cretaceous limestones, where the Coniacian and Santonian formations constitute the principal aquifer. Above these units, the Campanian formation composed of heterogeneous chalky and marly limestones acts as a semi-permeable layer.

Water sampling was conducted at 8 permanent outlets and one temporary stream (Cerf) between January 2024 and June 2025. Among the permanent springs, five are mainly fed by the unsaturated zone: Mournat (Alterite); Chabanne (Middle Campanian); Rosier (Upper Campanian); Bassonie (Lower Campanien) and Voulon (Lower Campanien). While the other three drain the deeper saturated zone: Moulineaux (Santonian); Saint-Laurent (Santonian); Cité (Coniacian). In addition, occasional measurements were conducted at 27 non-permanent springs to further refine the spatial characterization of P_{CO_2} and $\delta^{13}C$ -DIC. Parameters relating to calcium-carbon dioxide equilibrium (P_{CO_2} and calcite saturation index) were calculated from in situ measurements (temperature, pH, electrical conductivity, dissolved oxygen) and laboratory analyses of major ions. $\delta^{13}C$ -DIC was also analysed directly in the laboratory.

The combined interpretation of $-\log(P_{CO_2})$ versus $\delta^{13}C$ -DIC reveals a structured vertical pattern across the spring outlets. Waters draining shallow compartments influenced by soil and epikarst processes are characterized by elevated P_{CO_2} (ranging from 2.5% to 3.1%) values and strongly depleted $\delta^{13}C$ -DIC signatures. Isotopic $\delta^{13}C$ -DIC values range between -16‰ and -18‰ for soil waters and between -16‰ and -14‰ for epikarstic springs. These characteristics indicate a dominant contribution of biogenic CO_2 and limited water-rock interaction. In contrast, outlets associated with the saturated zone display lower P_{CO_2} values (between 1% and 2.5%) and relatively enriched $\delta^{13}C$ -DIC signatures (ranging from -14‰ to -11‰). This trend reflects progressive CO_2 consumption, partial degassing, and increased interaction with the carbonate rock. Temporal variability linked to hydrological conditions modulates these signatures, particularly during high-flow periods when rapid circulation and mixing can temporarily shift P_{CO_2} and $\delta^{13}C$ -DIC values toward more soil-influenced compositions. Spatial mapping of P_{CO_2} and $\delta^{13}C$ -DIC across the 36 sampled points reveals slight spatial variability in carbon geochemistry at the scale of the karst system. The results indicate a shared common

geochemical functioning of the system, despite locally contrasting conditions. Spatial variability is mainly expressed by differences in P_{CO_2} linked to the variable influence of biogenic CO_2 from the soil, as well as by differences in residence times and circulation depths.

The results highlight the contrast between relatively capacitive compartments, where water behaves close to a closed system, and more transmissive compartments characterized by rapid circulation and a high degree of openness to CO_2 degassing. These results show that, despite the hydrogeological semi-permeability of the Campanian unit, CO_2 exchange processes between air and water are very intense, contrary to what one might think at first glance. In other words, hydrogeological semi-permeability does not imply hydrochemical semi-confinement.

Considering the spatial and vertical variability between several outlets, this study reinforces the value of integrating carbon geochemistry into the geological and hydrogeological context to improve conceptual models of complex karst systems.

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Tracer recovery over extended time periods

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Little Valley is in northern Bath County, Virginia, USA and the 7.8 km² watershed is tributary to Bolar Run and the Jackson River. Little Valley Run flows north on Ordovician carbonates exposed on the valley floor by an anticline with the valley confined by younger clastic rocks on both sides. Numerous dolines on carbonate rocks attest to karst development, but no caves or distinct ponors have been found. Bolar Warm Spring (38.21651°N, 79.67372°W) is at the mouth of the valley near the confluence with Bolar Run and is the only large spring in the area. Water temperature at low flow (6000 L/minute) is about 23°C and the water is a mixture of deeply circulating thermal water and recent meteoric water from storms. Travel velocities in karst aquifers are typically in the range of hundreds to several thousand meters/day and monitoring for the tracer at the resurgences is usually terminated shortly after dye recovery is confirmed and/or the breakthrough curve is established. The persistence of the tracers in the system is usually assumed to be relatively short, especially following one or two storm events to “flush” any storage within the karst channels. Seven tracer tests were conducted from small surface streams sinking through cobbles during low-flow conditions. When storm events occurred within about 40 days of dye injection, surface flow resumed in the stream channel drowning out the sink area but releasing low concentrations of the tracer back into the stream at or below the dye injection point. When storms did not appear within 40 days of dye injection the tracers were not recovered at all. For the recovered tracers, very low concentrations of dye persisted at or immediately downstream from the sink areas for over a year following the introduction of the tracers (Figure 1). The dye concentrations were below the detection limit (< 0.005 µg/l) in water samples and all of the recovery was from carbon packets changed at two-week intervals. All of the dye recovery was from the surface water sampling sites downstream from the sink points and no dye was found at Bolar Warm Spring. The tracers were apparently stored in a shallow reservoir (hyporheic or epikarst zones) beneath the surface channel with water and tracers leaking downward into and through this reservoir under low flow conditions and then returning to the surface stream channel with changes in the hydraulic head in the reservoir (Figure 2). Loss to deeper circulation, possibly related to recharge to Bolar Warm Spring, is likely. Some subsurface down channel migration of the tracers is probable, but the tests to date cannot confirm this because of the resurgence of the tracers at the sink points. This appears to be a heterogeneous hydrologic system comprised of karst and nonkarst components, with storage, transmission, and flow direction dependent on groundwater levels and precipitation patterns.

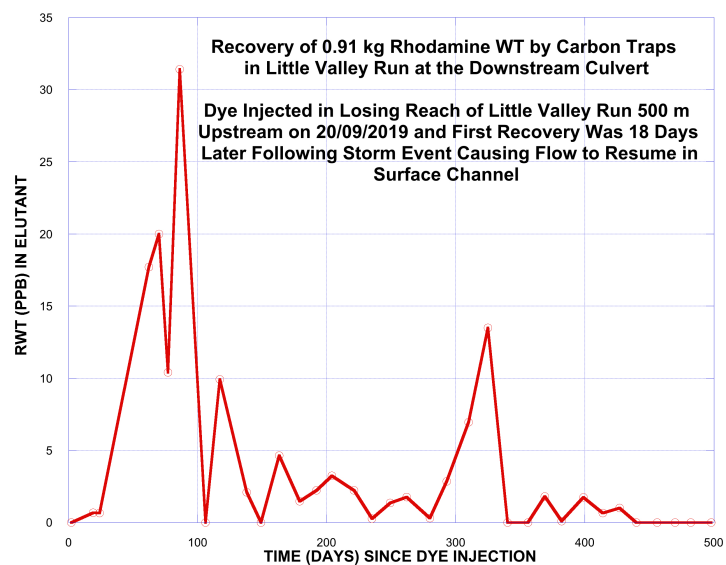


Figure 1. Time-series plot of dye recovery from carbon detectors changed at two-week intervals.

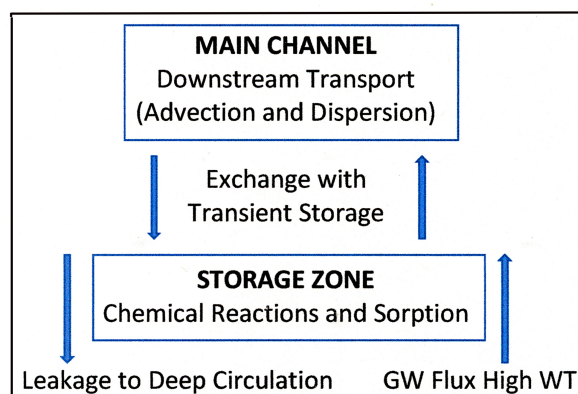


Figure 2. Diagram of possible flux of water at the sink point in response to changes in ground-water levels.

Characterising the Barrois karstic aquifer in northeastern France using a fully coupled 3-D overland and groundwater flows model

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Within the framework of the ANDRA (French National Agency for Nuclear Waste Management) Cigéo project for a deep geological disposal of radioactive waste in Bure site (France), the Barrois karstic aquifer has been intensively investigated over the last decades because it is intended to contain the surface access infrastructures of the future repository. This type of aquifer is characterised by strong spatial heterogeneity due to the presence of highly permeable conduit networks that are embedded in low-permeable carbonate rocks. This, in conjunction with perpetual exchange and interaction with surface flow, governs their hydrodynamical functioning.

The main objectives of this study are to : *i*) integrate the ensemble of existing and recent geological, hydrogeological and hydrological data into an updated flow model; *ii*) understand the local transient surface and subsurface flows behaviours in the karstic aquifer, before, during and after the installation of the surface engineered infrastructures; and, *iii*) to predict the short and midterm hydraulic impacts of multiple scenarios on the local groundwater resources. To achieve those objectives, a three-dimensional high resolution numerical model of fully coupled overland and groundwater flows was developed.

The hydrogeological conceptual model covers the sub-watersheds of the Orge and Ormançon rivers. It integrates 15 layers above the Kimmeridgian formation including three karstic aquifers: the Sublithographic limestones (with N1 to N5d markers), the Dommartin limestones and the *Calcaires Cariés et Tachetés*; and two aquitard marl formations: *Oolithe de Bure* and *Pierre Châline*. In addition, it considers discrete geological features like regional faults (ex.: Poisson, Brouthières), local fractures, and three levels of karstic networks. Of course, those discontinuities represent preferential paths that condition groundwater flow and mass transfer in the multilayered system.

The construction of a 3-D geological model was based on outcrops maps, seismic data, lidar survey data, tens of deep boreholes data, and hundreds of lithostratigraphic data points from archaeological survey boreholes carried out in the study area (Kerrou, 2024). The geological interfaces were then used as base to construct a fully unstructured finite element FE mesh in 3-D that reproduces the main geological complexities. The mesh integrates different types of elements particularly 2-D elements representing local faults and fractures, and 1-D elements representing three levels of karstic networks connected to the surface by vertical shafts (Jaquet et al., 2004). The FE mesh was horizontally refined around the lineaments of rivers and faults, and also around the surface engineered infrastructures. Vertically, the mesh was refined in low-permeable units to correctly reproduce vertical hydraulic gradients. On the mesh surface topography, a 2-D slice is dedicated to overland flow integration. The final nested mesh consists of more than 2.6 Mio elements with 1.1 Mio nodes (Figure 1a-c).

Regarding flow boundary conditions, time dependent hydraulic heads (Dirichlet type condition), extracted from the regional reference flow model (Kerrou, 2024) were attributed to model lateral limits. On model surface, hourly precipitation and evapotranspiration data over a complete hydrological year were imposed as overland flow sources.

Given the nonlinearity of the physically-based modelled processes (i.e.: diffusive wave equation coupled to the Richard's equation), as well as the very high number of involved parameters (i.e.: hydraulic conductivities for subsurface flow, and coupling coefficients for

surface flow), calibrating the coupled overland and groundwater flows in transient regime was carried out iteratively in several stages using multiple models at various spatial and temporal scales. First a steady state flow model was calibrated (mainly hydraulic conductivities) in order to ensure reliable initial condition for the flow. Then, unsaturated parameters and storage coefficients were calibrated in transient regime. And finally, Strickler coefficients, coupling coefficients, and rill-storage coefficients were adjusted based on geological, soil and land cover maps.

Model calibration was carried out using inverse modelling with the PEST algorithm (Doherty, 2004) and a test-and-error approach through successive parametric adjustments. The calibration aimed to strengthen the reproduction of relevant time series of state variables mainly hundreds of punctual hydraulic head data, 32 hydraulic head hourly chronics and observed hydrogram in EST3012 gauging station. This is with respect to the hydrogeological conceptual model characteristics, the measured values of parameters, and the hydrological water balance. The CS2par finite element code (see Kerrou et al. presentation) was used for the numerical simulation of fully coupled 3-D overland and variably saturated subsurface flows in the Barrois karstic aquifer.

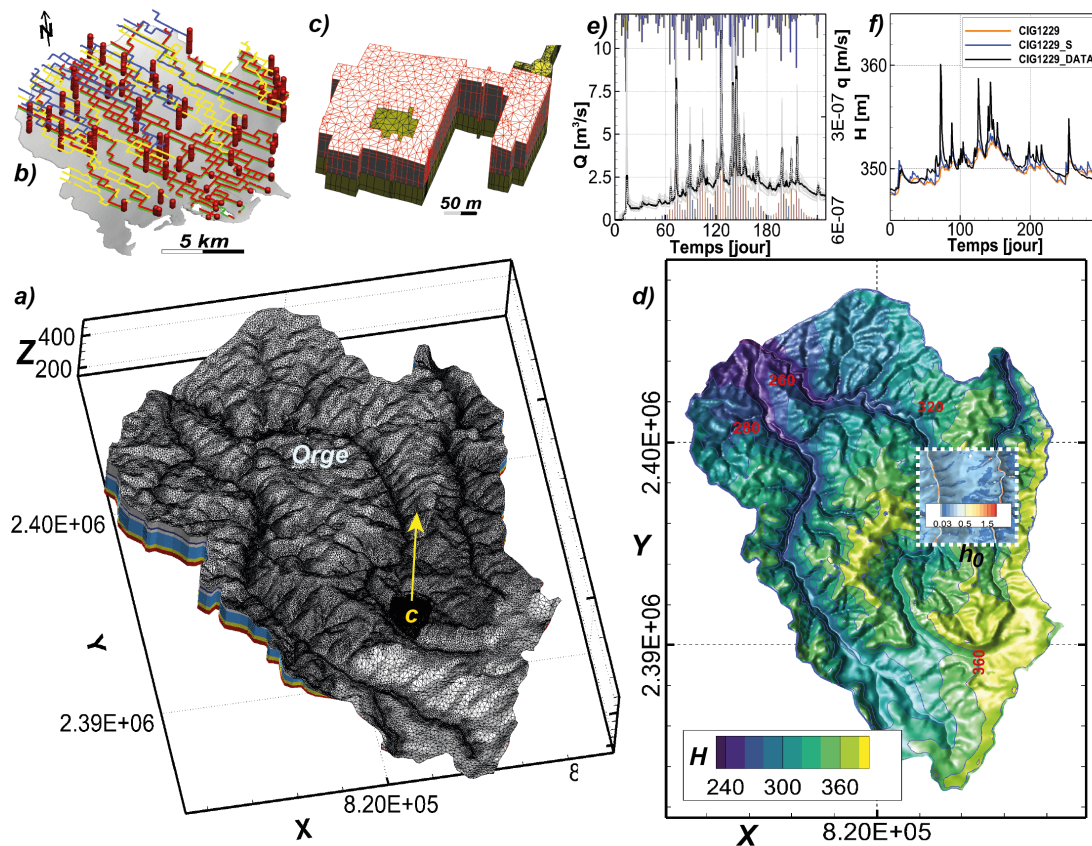


Figure 1. a) 3-D view of the finite element mesh, with b) and c) the karstic networks and the surface infrastructure; d) Hydraulic head H [m] and surface water depth h_0 [m] solutions; e) and f) comparison between measured and simulated EST3012 hydrogram [m³/s] and CIG1229 hydraulic heads H [m].

At the end of the calibration process a clear improvement of the characterization of the hydraulic properties of the multilayered aquifer system was reflected by multiple calibration criteria (ex.: AAE, RMSE, etc.). Furthermore, the model showed the key role played by faults and karstic networks in connecting surface to subsurface flow and being subject to faster groundwater circulations between recharge and discharge points (i.e.: doline, karstic spring). Figure 1d-f

show good matching between observed and simulated hydraulic heads and simulated Orge river discharge rates meaning that the model allowed to reproduce the local transient flow dynamics. At a final stage, the calibrated model was used to predict the short and midterm hydraulic impacts of multiple conceptual scenarios on the local groundwater resources (see Robineau et al. Poster).

Finally, further investigations of the Barrois aquifer will be made in order to construct more accurate and updated karstic networks conditional to speleogenetic concepts as well as field measurements and observations (see Gouy et al. presentation).

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Surface water and groundwater coupling: development and validation of the code CS2par

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The development of karstic aquifers is naturally influenced by lithology, tectonic structures, as well as geomorphology and surface hydrology. This type of aquifer is characterised by strong spatial heterogeneity, which is linked to the presence of highly permeable conduit networks contained within low-permeability rock matrix. This, in conjunction with perpetual interaction with surface flow, governs their hydrodynamic functioning. However, hydrogeological modelling tools usually consider the surface and subsurface systems separately.

The CS2par Fortran code was developed for the numerical simulation of fully coupled 3-D overland and variably saturated subsurface flows (Besson, 2021).

CS2par enables the modelling of surface flow by solving the diffusive wave equation (a simplified form of the Saint-Venant equation), while groundwater flow is Darcean with variable saturation. The coupling between these two systems ensures the continuity of both pressure and flux and has been implemented using two approaches: (i) The explicit method involves the use of exchange terms at the surface/subsurface interface. These are evaluated and prescribed at the beginning of each time step for both media; (ii) The implicit method is where the surface and subsurface equations are formulated and solved simultaneously for each time step.

More precisely, for a domain $\Omega \subset \mathbb{R}^3$, with Γ_s its top surface, we note $h(x) = \eta(x) + x_3$ the water surface elevation [L] which equals to the sum of the depth of flow $\eta(x)$ and the land surface elevation x_3 , with $x = (x_1, x_2, x_3)$, and $H(x) = \psi(x) + x_3$ the hydraulic head [L] which equals to the sum of the pressure head $\psi(x)$ and the elevation x_3 . Subsurface flow in Ω is governed by the Richard's equation which describes the three-dimensional transient groundwater flow in the variably saturated porous matrix, associated with the Van Genuchten constitutive model:

$$\partial\theta(\psi)/\partial t - \nabla \cdot k_r(\psi) \nabla H = 0 \quad (1)$$

where θ [-] is the mobile water content, k_r [-] the relative permeability of the medium as fonction of water saturation, and K the saturated tensor of hydraulic conductivity [LT⁻¹]. Dirichlet or Neumann boundary conditions can be applied to the vertical faces and the model bottom.

$k_r(\psi) \nabla H \cdot n + \lambda(H - h) = 0$ in the form of a Robin boundary condition is imposed on the top surface Γ_s to take into account the coupling between surface and subsurface domains. For the two-dimensional overland flow acting on Γ_s , a diffusive wave model is used:

$$\partial h/\partial t - \nabla \cdot k(h) \nabla h + \lambda(h - H) = f \quad (2)$$

where $k(h) = C_s \eta^{5/3} / II \nabla h II^{1/2}$ is a highly nonlinear diffusion coefficient, with C_s [L^{1/3}T⁻¹] the roughness Strickler coefficient. The function f [LT⁻¹] represents the sources (precipitation - evapotranspiration). The coefficient λ [T⁻¹], which physically corresponds to a first-order kinetic transfer coefficient, is the coupling coefficient between surface and groundwater flows. Different types of boundary conditions for surface flow, such as critical depth, can be considered.

For the discretisation of equations (1) and (2), the Finite Element Method (FEM) with the Galerkin scheme is used in space and a finite difference method is used for time with second-order accuracy and adaptive-time stepping (BDF2, Gear scheme). The software considers fully unstructured meshes, with 1-D and 2-D elements that can be inserted into the 3-D matrix. Those elements can be used to integrate faults, drains or karstic conduits in the subsurface domain using the common node technique.

Picard's fixed-point method, with Anderson acceleration, is used for solving the non-linear parts of these problems. For each iteration of the fixed-point method, it is necessary to reconstruct the matrices associated with the equations and then solve the associated linear systems using iterative methods. A GMRES-type solver, enhanced by several stabilisation techniques, was chosen for its robustness. It is important to note that explicit coupling is advantageous because of the differences in the time scales of the two types of flow.

The implementation of the diffusive wave equation in CS2par code has been verified against several analytical solutions and the very well-known rainfall-runoff simulation of diGiammarco et al. (1996). The problem corresponds to a V-shaped catchment with different surface slopes submitted to a rainfall event. The comparison between several solutions using different grids showed a general good agreement with CS2par results. CS2par has been also verified by solving coupled overland and 3-D variably saturated subsurface flow in the Borden site (Ontario, Canada) benchmark as presented by Therrien et al. (2010). Figure 1 shows the model geometry (finite element mesh) and compares the subsurface and overland solutions as function of time obtained with CS2par and the HGS (Therrien et al., 2010) codes.

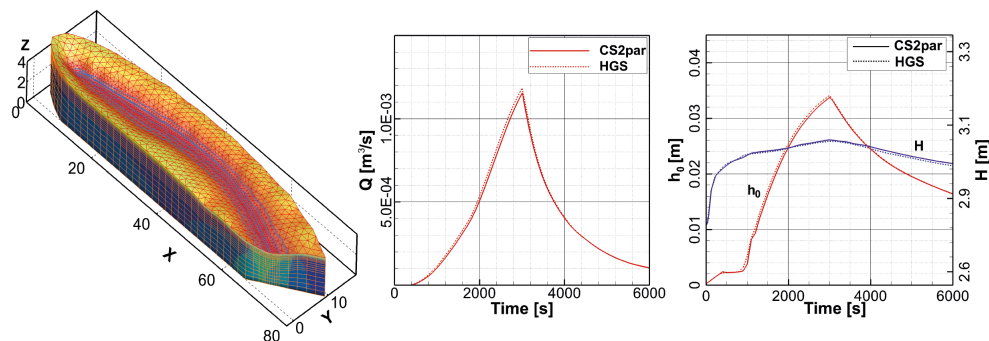


Figure 1. L-R: Borden site model; comparison between CS2par and HGS solutions for discharge rate [m^3/s], hydraulic head H [m] and surface water depth h_0 [m].

The results during the code validation phase were very encouraging and showed that CS2par is capable of correctly simulating the interactions between groundwater, surface and river water. To address the issue of high computational costs, particularly for large-scale spatio-temporal problems, the code was parallelised (Besson, 2021). This was achieved using the MPI environment (Message Passing Interface, Snir et al., 1998). In CS2par, not only the resolution of linear systems is parallelised, but the matrices assembly and filling as well.

Finally, CS2par code was used in the framework of ANDRA projects to characterise the Barrois karstic aquifer in East of France (see Kerrou et al. presentation).

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openKARST: Bridging network-resolved simulations and simplified hydraulic descriptions of karst flow and transport

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We present openKARST, an open-source flow and transport simulator for karst systems that resolves free-surface and pressurized dynamics in large conduit networks. The solver is based on the one-dimensional Saint-Venant equations and is designed to capture transient flood waves as well as steady flow states under mixed flow conditions. Turbulence is represented through Darcy–Weisbach friction, with support for classical correlations such as Churchill and Colebrook–White. A particle-tracking module enables conservative tracer transport and travel-time analyses. Verification and validation against analytical benchmarks and applications to large cave networks, including the Ox Bel Ha system, demonstrate numerical robustness across a wide range of regimes. In this work we introduce a steady-state analysis workflow that condenses distributed network solutions into interpretable hydraulic metrics. Using conduit-resolved Reynolds numbers and friction factors based on high fidelity simulations, we quantify how effective resistance evolves with discharge, viscosity, diameter, and partial filling along karst conduits. To explain and reproduce these trends without running full simulations, we propose a simple steady-state approximation in which the longitudinal water-surface is represented by a generalized hydraulic profile, while cross-sectional hydraulics follow circular partial-filling geometry. This reduced model predicts conduit-averaged Reynolds numbers and friction factors and provides conduit profiles that can be compared directly to simulated distributions, including regimes influenced by pressurization (e.g., via Preissmann-slot treatment). The framework offers a practical bridge between high-fidelity network hydraulics and compact predictive relationships to enable systematic exploration of parameter space and upscaling.

Stochastic generation of karst conduit networks conditioned by geology, geomorphology, and hydrodynamic behaviour

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Recent advances in karst conduit network generation produce ensembles of plausible subsurface geometries constrained by geological structure, hydrological observations, and karst morphological features such as springs, sinkholes, and known cave segments. These stochastic methods allow uncertainty in conduit location and connectivity to be quantified and propagated into flow and transport models. Approaches include fast-marching and rule-based growth algorithms, probability-map ensembles derived from soft data, modular simulators, skeleton-pattern generators, and deep generative graph models. Most rely on observed fracture networks or explored conduit segments for conditioning, yet simulations show these represent only a minor fraction of hydraulically active conduits. Hydrogeological evidence suggests that most conductive features follow conjugate fracture patterns, while bifurcating branches reflect only the most widely enlarged sections. Unconfined aquifer zones require spatially consistent conduit networks to achieve effective drainage, implying that structural density—not just enlargement—is hydrodynamically critical.

The method proposed here builds on these principles but introduces two key innovations: (1) it adopts a network maze conceptual model rather than a hierarchical branching structure, and (2) it conditions conduit spacing using hydrodynamic behaviour derived from hydrograph analysis. This geometric conditioning is essential to reproduce transient hydraulic responses observed in real systems. The workflow includes spatial identification of conductive features (e.g., caves, sinkholes, springs), directional analysis of conduit families using von Mises distributions, and hydrograph-based estimation of characteristic conduit spacing. Monte Carlo sampling and least-squares optimization are used to fit conduits to observed features along dominant directions, followed by stochastic generation of cross-conduits using spacing and orientation distributions.

This structural-statistical approach integrates geological realism with hydrodynamic plausibility. It operates in three phases: (1) extraction of structural patterns from karst features, (2) statistical characterization of directional and spacing distributions, and (3) stochastic conduit generation conditioned by both structural and hydraulic constraints. Implementation via Python and GIS libraries enables spatial conditioning and ensemble generation. Validation against the Bükk karst system in Hungary shows that the generated networks reproduce observed conduit orientations, spacing, and connectivity, while also satisfying transient hydraulic behaviour. The method offers a robust framework for simulating realistic conduit architectures in structurally complex karst aquifers.

Key controls on precipitation-driven groundwater recharge occurrences in southeastern Australia's karst sites

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Identifying the dominant controls on groundwater recharge occurrences remains a fundamental challenge in hydrology, particularly in water-limited regions. Although precipitation is commonly assumed to be the primary driver of groundwater recharge, rainfall alone often fails to explain when recharge actually occurs, suggesting that other variables maybe exerting stronger controls. While there is broad consensus on key variables that may play important roles in determining groundwater recharge occurrences, there is limited agreement on the extent of their influence and even less clarity on whether these variables share cause-and-effect relationships with occurrences of groundwater recharge. Studies that examine variable importance for groundwater recharge occurrences often rely on single measures of association which, although intuitive, fail to capture the multiple dimensions of these relationships. In particular, these studies tend to depend on a specific model or linear correlation metrics that neither explicitly address non-linear interactions nor capture inherent causality (Kumar et al., 2025).

In this study, we addressed this gap by examining the relationships between precipitation, soil moisture, evapotranspiration (ET), vegetation dynamics (8-day NDVI), and groundwater recharge occurrences across six karst sites within the Australian National Groundwater Recharge Observing System (NGROS) (*Figure 1, Table 1*). Daily recharge occurrences were derived from monitoring data collected by Stalagmate© loggers installed in caves, mines, and tunnels across Australia, which provide direct, event-scale indicators of recharge (Baker et al., 2024). The variable importance was assessed using a multi-perspective analytical framework that integrated (a) correlation analysis, (b) mutual information to capture non-linear and complex dependencies, and (c) causality analysis. Notably, this study is the first application of Convergent Cross Mapping (CCM) to identify causal relationships for groundwater recharge occurrences.

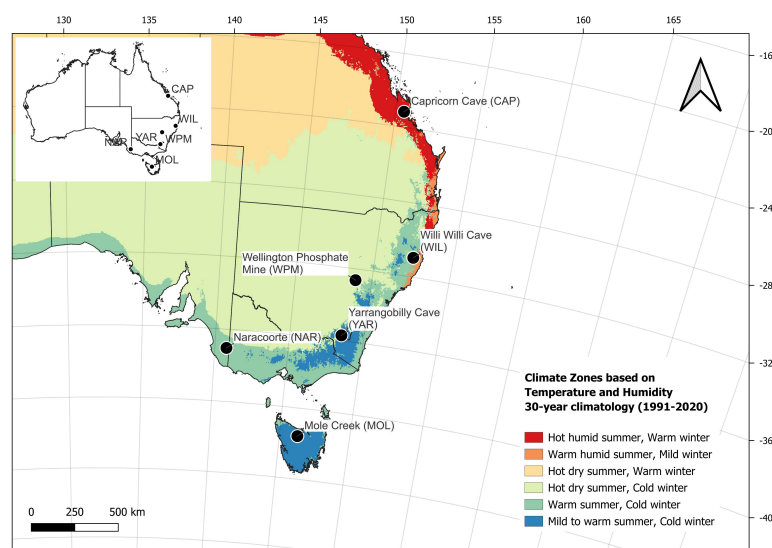


Figure 1. National Groundwater Recharge Observing System (NGROS) sites analysed in the study. The basemap is the climate zone map based on 30-year (1991-2020) temperature and humidity data from Bureau of Meteorology (BOM, 2025).

Table 1. Seasonal summary of precipitation, ET, temperature, and soil moisture at the sites during the study period. The data is from sources mentioned in Kumar et al. (2025).

site	Data availability (months)	Season	Mean seasonal rainfall (mm)	Mean seasonal ET (mm)	Mean seasonal temperature (°C)	Soil moisture (%)
Capricorn (CAP)	17	DJF	297.57	910.77	28.14	42%
		MAM	102.05	453.43	24.17	43%
		JJA	157.88	527.85	19.16	42%
		SON	128.79	1462.94	24.12	29%
Willi Willi (WIL)	37	DJF	1639.11	1885.24	21.53	58%
		MAM	938.92	1101.46	16.90	66%
		JJA	321.38	851.11	11.84	59%
		SON	792.35	1548.85	17.62	51%
Wellington Phosphate Mine (WPM)	36	DJF	459.86	2069.56	24.35	39%
		MAM	480.38	1313.41	17.22	43%
		JJA	257.36	676.54	9.51	50%
		SON	477.45	1448.66	16.51	46%
Yarrangobilly (YAR)	35	DJF	551.42	1520.83	17.13	51%
		MAM	485.96	1029.87	11.41	50%
		JJA	190.84	388.14	4.82	53%
		SON	547.80	989.36	10.88	53%
Naracoorte (NAR)	8	DJF	65.58	738.74	20.29	39%
		MAM	56.17	222.47	16.69	41%
		SON	200.69	335.35	14.37	58%
Mole Creek (MOL)	12	DJF	179.55	578.35	14.35	58%
		MAM	128.84	299.37	10.41	55%
		JJA	53.37	50.33	9.26	75%
		SON	133.43	392.09	9.94	69%
DJF - December, January, February; MAM - March, April, May; JJA - June, July, August; SON - September, October, November						

Our results showed that soil moisture and vegetation are consistently the strongest predictors of recharge occurrences across sites, with higher correlation, higher mutual information, and stronger causal influence (*Figure 2*). The findings indicate that recharge is primarily controlled by antecedent and concurrent land-surface conditions that regulate infiltration and percolation, rather than by daily rainfall alone which exhibited relatively weak association with recharge occurrences across all metrics. However, when aggregated over longer periods, its predictive strength increases substantially. In particular, cumulative rainfall over 6-7 days emerged as a much stronger predictor than single-day rainfall, highlighting the importance of sustained wetting required to overcome soil moisture deficits and ET losses.

ET, however, showed moderate predictive importance, mainly during the austral autumn (March-April-May) but remained secondary overall compared to soil moisture, vegetation or cumulative rainfall. It is likely that short-term recharge dynamics are more directly captured by variables such as vegetation and cumulative rainfall rather than by ET itself which is relatively continuous and largely driven by meteorological conditions with strong seasonal cycles (Fan et al., 2014; Neukum et al., 2023). The results also showed temporal lags between variables and recharge occurrences indicating presence of subsurface storage and flow paths with variable transit times. While rainfall and ET generally had shorter lags or memories (< 2 weeks), soil moisture and vegetation showed wider variability with many sites exhibiting lags longer than 2 weeks.

Spatially, three distinct recharge behaviour patterns were identified. Sites such as YAR and NAR displayed clear recharge and non-recharge periods, primarily constrained by soil moisture and ET dynamics. MOL exhibited limited recharge, largely attributable to rainfall events that failed to create favourable soil moisture and ET conditions. In contrast, WIL (2023-2024) and WPM show a marked decline in recharge occurrences. At WIL and WPM, this decline is linked to site-specific disturbances (a fire event in early 2023 and a mine collapse following extreme rainfall in late 2022, respectively).

Overall, this study provides new quantitative evidence that groundwater recharge occurrences are not primarily governed by short-term or single-day rainfall events, but rather by cumulative precipitation acting in conjunction with favourable soil moisture, vegetation, and ET conditions. By integrating correlation, mutual information, and causal analyses, the results present a robust multifaceted framework for assessing variable importance in recharge occurrences in underground spaces. The study also demonstrated the applicability of CCM for uncovering causal linkages in groundwater recharge occurrences.

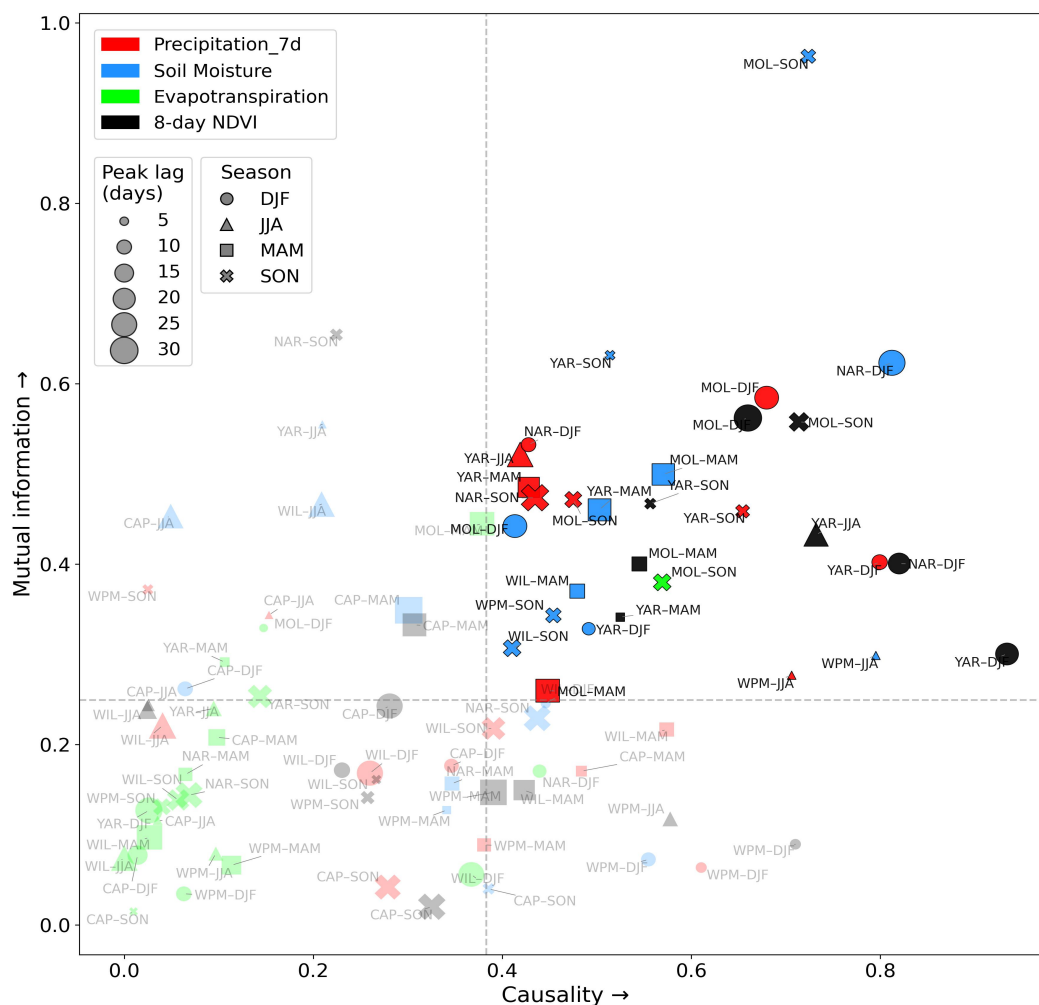


Figure 2. Scatterplot showing mutual information and causal strength for variables at different sites. CCM-derived causality relies on both library sizes (historical values) and correlation to determine strength of causality, however, for simplicity, causality has been shown as a normalized score of the product of library size and correlation on the horizontal axis. Maximum MI values were obtained at the ‘Peak lag’ and indicates the ‘memory’ of the variables at those sites. Horizontal and vertical dashed lines are the median causality and MI values, respectively.

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Understanding recharge dynamics using drip responses in underground spaces

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Groundwater recharge occurs when water moves downward through soil to replenish the aquifers. While climate, particularly rainfall, determines how much water is available to reach the aquifer, how quickly it gets there is controlled by the structure of the vadose zone - the unsaturated layer of rock and soil between the land surface and the water table. The vadose zone can slow down, store, or rapidly transmit water depending on its physical properties. Because these processes are difficult to observe and model, recharge modelling and management decisions often neglect vadose zone influences on recharge. This simplification can be problematic, particularly in arid and semi-arid regions, as the vadose zone can delay recharge by days to months and strongly influence when groundwater signals emerge. Studies at Australia's National Groundwater Recharge Observing System (NGROS) sites (Baker et al., 2024) have identified significant temporal lags between key recharge drivers and groundwater recharge occurrences (Kumar et al., 2025) as well as the presence of distinct recharge mechanisms (Sun et al., 2025) indicating the importance of vadose zone in controlling occurrences of groundwater recharge.

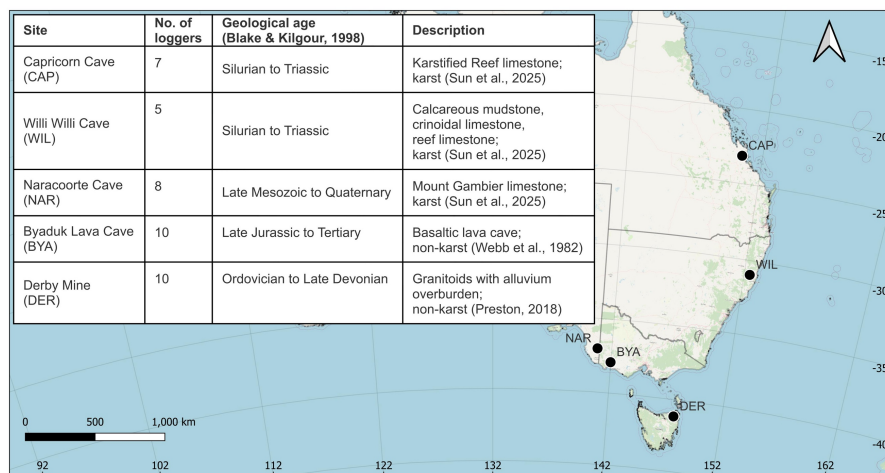


Figure 1. Map showing the location of NGROS sites used in the study. The inset table shows the geological age and a short site description. CAP and WIL are in Australia's New South Wales, NAR is in South Australia, BYA is in Victoria and DER is in Tasmania.

In this study, we explored the underlying recharge dynamics recorded by drip loggers at select NGROS sites (*Figure 1*) to uncover dominant modes of recharge. NGROS is a network of Stalagmate© loggers installed inside caves, mines and tunnels across Australia and provide direct, high-resolution, event-based indicators of recharge occurrences in the form of drip responses (Baker et al., 2024). The study used a combination of spectral analysis, transfer function and energy-weighted moment formulation to partition recharge regimes at 3 karst and 2 non-karst sites in Australia and estimate their travel times. The study identified three dominant modes of recharge dynamics or regimes – fast flow, slow flow and an intermediate mixed flow regime.

The results showed that although each logger had contributions from multiple recharge regimes, in mature karst systems like CAP and WIL, fast flow was the dominant mode with 4 out of 7 loggers at CAP and 3 out of 5 loggers at WIL exhibiting this behaviour. The mean travel times at these loggers ranged between 2-4 days. Mixed flow dominance was observed in 3 loggers at CAP and only one at WIL with mean travel times between 4-8 days. However, in young karst system like NAR, there was an even split with 4 loggers exhibiting mixed dominant flow and 4 out of 8 loggers exhibiting slow flow dominance. The mean travel times at NAR ranged from 5-9 days at the mixed flow dominant loggers to 54-134 days at the slow flow dominant loggers.

At BYA, a non-karst basaltic lava cave, the dominant mode of recharge appeared to be through the fractures in the rock with minimal mixed or slow flow dominance. 8 out of 10 loggers exhibited fast flow behaviour, with travel times of 3-4 days, while only one logger showed mixed or slow dominant flow. In contrast, loggers at DER, a historic mining tunnel in granite bedrock with alluvial overburden, exhibited delayed recharge responses with 4 loggers exhibiting mixed dominance and 5 out of 10 loggers exhibiting slow flow as the dominant mode. The travel times ranged from 12-28 days for mixed flow loggers and 35-70 days for slow flow loggers. Since flow through the granite layer occurs primarily through fractures, the dominance of slower recharge regimes is likely attributable to the thicker soil overburden, which may slow the movement of water to the fractured granite layer below.

The results demonstrate that recharge dynamics recorded by drip loggers are strongly controlled by vadose zone structure, with distinct recharge regimes producing delays ranging from days to months across different geological settings. Notably, regardless of whether a site is karst or non-karst, the mean travel times associated with a given recharge regime are broadly similar across sites. These range between 2-5 days for fast flow dominant loggers, weeks to a month for mixed flow loggers, and over a season for slow flow dominant loggers. This similarity suggests that travel times are governed less by whether a system is karstic or non-karstic and more by the presence and effectiveness of preferential flow pathways versus slower, more diffuse flow pathways. Where well-connected fractures or conduits exist, regardless of lithology, rapid recharge can occur, whereas slower flow through thicker soil layers or primary pores in rock leads to longer delays. The coexistence of multiple recharge regimes demonstrates that simplified, instantaneous recharge assumptions can misrepresent when recharge actually occurs. Incorporating vadose zone processes into recharge models is therefore critical for accurately linking climate drivers to groundwater responses and improving groundwater management decisions.

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Balancing water recharge and demand in a self-supplied island karst aquifer under climate and seasonal stress: Vis Island (Croatia)

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Small Mediterranean karst islands that rely on their own groundwater resources operate close to hydrological and hydrogeological limits: recharge is strongly seasonal, storage is inherently restricted, and coastal boundary conditions render the seawater–freshwater interface highly sensitive during prolonged dry periods—typically coinciding with peak tourism and the highest water demand. This study presents the island of Vis (Croatia) as a representative self-supplied karst system. Vis has no permanent surface streams and depends almost exclusively on groundwater stored in a karst aquifer that is recharged mainly during the autumn–winter season. In contrast, water demand peaks during the driest summer months, largely driven by tourism, creating a significant seasonal mismatch between recharge and consumption. With a resident population of about 3,300 (2021 census), Vis nevertheless hosts over 30,000 tourists each year. The island covers 89.72 km², has an 84.9 km coastline, and reaches a maximum elevation of 587 m a.s.l. and it represents a reference case within the Dinaric karst. Most of the island is underlain by highly karstified Cretaceous carbonates (limestones and dolomites), with extensive faulting that promotes rapid infiltration and predominantly subterranean drainage. As a consequence, permanent surface streams are absent and a large fraction of recharge is routed through the karst network toward coastal discharge zones and offshore losses.

A key hydrogeological peculiarity of Vis is the western sector, where the dominant carbonate platform is juxtaposed against the Triassic diapir complex (evaporitic, volcanic, and associated sedimentary rocks) along tectonic contacts. This non-carbonate unit with different permeability and storage behaviour than the surrounding karstified limestones acts as a structural–lithological boundary that constrains groundwater flow paths and locally modifies the position and dynamics of the freshwater–seawater interface. Such geological configuration favours focused coastal groundwater discharge and helps explain the occurrence of permanent coastal springs on the west side of Vis, despite the island-wide tendency toward diffuse subsurface outflow.

The Korita pumping site comprises six wells, five of which are currently operational; its designed abstraction capacity of 27 L/s was subsequently increased to 40 L/s through targeted research and optimization. The Ghyben–Herzberg principle, which relates freshwater head to the depth of the freshwater–seawater interface in coastal aquifers, implies that substantial freshwater storage may extend below present sea level. On Vis, this expectation is consistent with the island’s geological history: karstification likely progressed to much greater depths during major low-stand periods, including the Last Glacial Maximum and the Messinian Salinity Crisis. With the base level positioned far below today’s sea level, dissolution and conduit development could extend deep beneath the island, producing a highly heterogeneous karst network capable of hosting freshwater in deeper zones and influencing present-day freshwater–seawater equilibrium.

Climatically, Vis and the surrounding archipelago fall within the Köppen–Geiger Csa class (hot-summer Mediterranean), characterized by mild, wet winters and dry, warm to hot summers. Its offshore position also exposes the island to frequent strong winds, which can enhance evapotranspiration and exacerbate summer water stress. Mean annual precipitation over 1956–2022 is 773 mm, with a pronounced seasonal signal: the highest monthly totals occur in winter (~89 mm) and autumn (~75 mm), followed by spring (~58 mm), while summer is the driest season (~36 mm). Groundwater levels typically reach annual minima in August–September and maxima in January–February, reflecting the strong seasonality of recharge and storage.

Within this specific climatological, hydrological and hydrogeological settings, this work presents the development of a monitoring system intended to complement and safeguard groundwater abstraction. The concept builds on historical hydroclimatic and operational records to capture baseline conditions, seasonal variability, and lessons from past drought episodes, while integrating near-real-time observations to track current recharge, storage, and salinity stress. By translating these indicators into actionable thresholds and alerts, the system will support day-to-day decision making for adaptive water management—helping operators optimize pumping, anticipate drought impacts, and reduce the risk of overextraction and seawater intrusion.

Trends in karst groundwater resources using standardized time series

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Karst aquifers host significant groundwater volumes and represent a primary source of potable water in Europe and the Mediterranean region. These systems are particularly sensitive to changes in environmental conditions driven by natural factors and by anthropogenic pressures. Monitoring hydraulic head and spring discharge is essential to assess the impacts of these forcings on groundwater resources. Statistical analysis of monitoring time series is widely used for this purpose, but it requires long historical datasets which are rare in karst areas. Consequently, the impacts of historical climate change on karst aquifers remain still poorly understood. Using hydraulic head and spring discharge data from a typical Mediterranean karst system (Terminio–Tuoro massif, southern Italy), we investigated long- and short-term trends in groundwater resources and their relationships with climate drivers using statistical methods.

Ten observation piezometers located in the Serino discharge area at different depths have provided hydraulic head data since 1963. The study emphasizes several practical and formal aspects of statistical analysis of real hydrological time series. To facilitate comparison among different datasets, values were standardized using the z-score transformation (Figure 1):

$$Z_i = (x_i - \mu) / \sigma$$

where Z_i is the standardized value of the observation x_i , and μ and σ are the mean and standard deviation of the series, respectively. The standardized value represents the instantaneous deviation of a variable from its reference state (the mean), expressed in units of standard deviation, with positive values indicating observations above the mean and negative values and observations below the mean. Standardization adjusts the location and scale of datasets, yielding dimensionless time series with zero mean and unit variance, while preserving other statistical properties such as autocorrelation and probability distribution. Its main advantage lies in enabling direct comparison among time series regardless of measurement location (e.g., hydraulic head records from different piezometers) or physical units (e.g., precipitation versus spring discharge).

Standardization is recommended for these analyses, where the relative amplitude of trends and cycles is more relevant than absolute physical values. This approach also allowed us to obtain a single hydrological signal from the ten hydraulic head time series by stacking them (Figure 1). This combined signal reflects the same hydrological phenomenon across all monitoring locations, namely ascending groundwater flow affecting the Sabato Plain where springs are located (Fiorillo et al., 2018).

Results show that the karst groundwater resource has undergone long-term depletion, inducing a persistent negative trend in both hydraulic head and spring discharge since the early 1960s. Rainfall explains most of the annual variability and cyclical behavior of hydrological variables; however, it exhibits no long-term trend, indicating that precipitation alone cannot account for the observed groundwater decline. The year 1986 represents a changepoint. Figure 2 shows the year-by-year difference, ΔZ , between standardized annual spring discharge, Z_Q , and standardized annual precipitation, Z_P . z-values were calculated using metrics from 1963–1986. Due to the strong correlation between precipitation and discharge, wet years (above-average precipitation) correspond to high-flow periods, and dry years correspond to low-flow periods. Prior to 1987, the difference between standardized variables oscillated around zero. Since 1987, however, this difference has remained consistently below zero, indicating a weakened response of the karst system to precipitation (Leone et al., 2026).

To investigate the causes of this weak response, a multivariate linear model was applied, considering that precipitation is only one component of the spring discharge time series. Statistical analysis indicated that precipitation, primarily, and aquifer memory, secondarily, are the main causes of groundwater variability and control annual fluctuations and trend cycles. Owing to aquifer memory, groundwater drought (or surplus) in one year has negative (or positive) effects on the discharge in the following year, thereby modulating the aquifer response to precipitation. Multivariate analysis confirmed a residual trend in the spring discharge time series, explained by long-term reduction of the effective recharge caused by the persistent atmospheric warming.

This analysis provides an overview of the impacts of historical climate change on groundwater resources in a relatively undisturbed karst catchment. The results are consistent with findings from other areas of the Mediterranean basin. In the studied region, rainfall shows no long-term trend, but the late 1980s mark a clear changepoint. Since then, groundwater resources have experienced significant depletion that cannot be explained solely by rainfall cycles and aquifer inertia. Atmospheric warming appears a contributing factor.

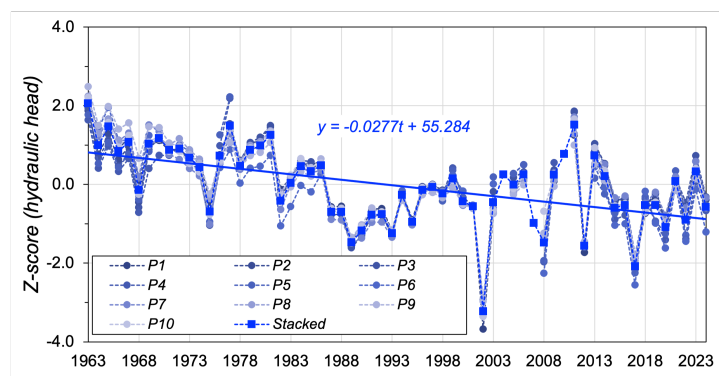


Figure 1. Standardized annual time series of the hydraulic head of piezometers (P1-P10); trend line of the stacked signals is shown (continuous blue line).

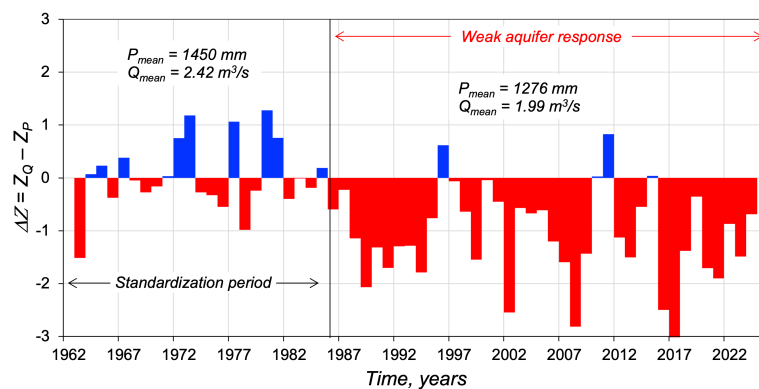


Figure 2. Year-by-year difference, ΔZ , between standardized annual spring discharge, Z_Q , and standardized annual precipitation, Z_P .

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Groundwater quality dynamics in a coastal karst aquifer under urban pressure: evidence from a basin-to-reef monitoring network in the Mexican Caribbean

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Coastal karst aquifers represent some of the most hydrogeologically complex and vulnerable groundwater systems worldwide. Their intrinsic characteristics—high secondary porosity, well-developed conduit networks, rapid groundwater flow velocities, and limited natural attenuation capacity—result in a strong hydraulic and geochemical connectivity between inland recharge areas, coastal discharge zones, and adjacent marine ecosystems. In tropical coastal settings, these characteristics are further exacerbated by intense land-use change, population growth, tourism-driven urbanization, and inadequate wastewater management. Under these conditions, groundwater quality degradation poses significant risks not only to drinking water supplies but also to sensitive coastal ecosystems such as coral reefs, seagrass meadows, and mangrove systems.

The northeastern Yucatán Peninsula, Mexico, is underlain by a highly permeable eogenetic karst platform that hosts the sole source of freshwater for human consumption and ecosystem support. Within this region, the Tulum Basin constitutes a priority coastal watershed where groundwater flows from inland recharge zones toward the Caribbean Sea through an interconnected network of fractures, dissolution conduits, cenotes, and coastal springs. The basin is characterized by rapid urban expansion, high tourism pressure, and the widespread use of on-site sanitation systems, which together create conditions conducive to nutrient enrichment and microbiological contamination of groundwater.

This study presents the results of an integrated groundwater quality assessment based on a basin-to-reef monitoring framework implemented in the Tulum Basin. A comprehensive monitoring network comprising 35 sites was designed to capture the spatial and temporal variability of water quality along the inland–coastal gradient. The network included urban and peri-urban observation wells, inland cenotes, coastal cenotes, lagoons, and marine sites located up to 60 km inland and 3 km offshore. Sampling was conducted during three contrasting hydrological seasons—rainy, cold fronts (nortes), and dry—between October 2022, April 2023 and 2026, allowing for the evaluation of seasonal influences on groundwater quality.

A total of nineteen parameters were analyzed, encompassing physicochemical, biological, and bacteriological indicators. These included temperature, pH, electrical conductivity, dissolved oxygen, ammoniacal nitrogen, nitrites, nitrates, phosphates, total phosphorus, biochemical oxygen demand, chemical oxygen demand, suspended solids, surfactants, chlorophyll-a, fecal coliforms, *Escherichia coli*, enterococci, and trace metals. Analytical procedures followed Mexican and international standard methods, and results were evaluated against national drinking water standards and ecological quality criteria for freshwater, coastal, and marine environments.

The results reveal marked spatial heterogeneity in groundwater quality across the basin. Urban and peri-urban recharge areas exhibited the most pronounced signs of anthropogenic impact, with elevated concentrations of nitrates, ammoniacal nitrogen, phosphates, biochemical oxygen demand, and fecal indicator bacteria in several observation wells and nearby cenotes. Nitrate concentrations reached values as high as 59.9 mg/L in shallow groundwater wells, exceeding drinking water standards and indicating significant inputs from wastewater and urban sources. Microbiological contamination, including high levels of fecal coliforms and *E. coli*, was frequently detected in urban cenotes and wells, underscoring the limited attenuation capacity of the karst system.

Seasonal variability was evident for several parameters, with higher nutrient and bacterial concentrations generally observed during the rainy and cold-front seasons, reflecting enhanced

recharge, surface runoff, and rapid transport through the karst conduit network. In contrast, some parameters, such as electrical conductivity and nutrient concentrations in coastal cenotes, showed indications of saline mixing and marine influence, particularly during the dry season.

Coastal cenotes and marine sites revealed clear evidence of land–sea connectivity and nutrient transfer from groundwater to coastal waters. Phosphate and nitrate concentrations in coastal and marine environments frequently exceeded ecological thresholds for the protection of marine life, suggesting that groundwater-derived nutrient fluxes may contribute to coastal eutrophication processes. Elevated chlorophyll-a concentrations in lagoons and nearshore sites further support the link between nutrient enrichment and primary productivity responses in coastal ecosystems.

The findings demonstrate that groundwater contamination in the Tulum Basin is not confined to localized urban areas but propagates rapidly through the karst aquifer toward coastal and marine systems. This connectivity highlights the inadequacy of conventional groundwater management approaches that focus solely on drinking water protection without considering downstream ecological impacts. Instead, the results emphasize the need for integrated basin-to-reef management strategies that explicitly account for groundwater pathways and karst system vulnerability.

This study provides one of the most comprehensive basin-scale groundwater quality assessments conducted in a tropical coastal karst setting in the Mexican Caribbean. By combining multi-site, multi-season monitoring with a basin-to-reef perspective, it offers robust scientific evidence to inform land-use planning, wastewater management, groundwater protection policies, and reef conservation strategies. The approach and findings presented here are directly transferable to other coastal karst regions facing similar pressures worldwide and underscore the critical role of groundwater in sustaining both human and marine ecosystems.

Traffic-light classification of water quality in urban cenotes of a coastal karst aquifer: an integrated monitoring and communication framework from groundwater to reef in the Mexican Caribbean

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Coastal karst aquifers represent some of the most vulnerable groundwater systems globally due to their high secondary porosity, rapid infiltration, limited natural attenuation capacity, and strong hydraulic connectivity between land, groundwater, and marine environments. In the Mexican Caribbean, this vulnerability is exacerbated by accelerated urbanization, tourism-driven development, inadequate wastewater management, and diffuse pollution sources. The absence of surface rivers in the Yucatán Peninsula results in groundwater being the primary freshwater resource, while also acting as the main transport pathway for contaminants toward coastal ecosystems, including coral reefs.

Cenotes; natural sinkholes that provide direct access to the groundwater table, are a defining feature of tropical karst landscapes in the region. Beyond their cultural, ecological, and economic importance, cenotes function as highly sensitive indicators of aquifer health. Their open connection to the subsurface karst network makes them particularly susceptible to contamination by nutrients, organic matter, heavy metals, and fecal microorganisms derived from urban, agricultural, and tourism-related activities. Despite growing monitoring efforts, the interpretation and communication of complex water quality data remain a challenge, often limiting their usefulness for decision-making, risk management, and public engagement.

This study presents the development and application of a traffic-light (semaphorization) water quality framework for urban cenotes located within a coastal karst aquifer of the Mexican Caribbean, using data generated through the Operación Rescate Cenote monitoring program. The proposed framework integrates physicochemical, nutrient, microbiological, and contaminant indicators with established trophic and regulatory assessment tools, translating scientific data into an accessible and decision-oriented classification system. The approach is explicitly framed within a basin-to-reef (ridge-to-reef) perspective, recognizing the direct influence of inland groundwater quality on coastal and reef ecosystems.

The monitoring network included four representative urban and peri-urban cenotes located in the municipalities of Puerto Morelos, Solidaridad, Tulum, and Benito Juárez. Seasonal sampling campaigns were conducted between March and April 2025, covering bacteriological, physicochemical, nutrient, and contaminant analyses. In situ measurements included temperature, electrical conductivity, salinity, dissolved oxygen, pH, and chlorophyll-a, while laboratory analyses quantified nutrients (nitrites, phosphates, total nitrogen), organic matter (chemical oxygen demand), major ions, and trace contaminants. Microbiological quality was assessed using total coliforms and *Escherichia coli* as indicators of fecal contamination.

Water quality evaluation combined two complementary assessment tools. First, the TRIX trophic index, originally developed for coastal waters, was adapted to cenote environments to characterize trophic status based on chlorophyll-a, dissolved oxygen saturation, inorganic nitrogen, and phosphorus. Second, the CONAGUA water quality indicators and semaphorization criteria for groundwater were applied to classify compliance with Mexican regulatory thresholds. These tools were integrated into a unified traffic-light system with three categories: green (good quality / low risk), yellow (intermediate quality / alert), and red (poor quality / high risk).

Results reveal a consistent pattern of severe microbiological contamination across all monitored cenotes, with *Escherichia Coli* and *Total Coliform* concentrations exceeding national limits for groundwater use. Nutrient enrichment and organic matter loads varied spatially, reflecting differences in surrounding land use, urban density, and potential wastewater inputs. TRIX

values indicate predominantly eutrophic to hypereutrophic conditions, confirming excessive nutrient loading and ecological imbalance in most sites. According to CONAGUA criteria, the majority of cenotes were classified under red semaphorization, indicating poor water quality.

Beyond its diagnostic capacity, the traffic-light semaphorization framework proves to be a powerful science–policy and science–society interface tool. By converting complex hydrogeochemical and microbiological datasets into a clear visual language, the framework facilitates communication with non-technical stakeholders, supports prioritization of management actions, and strengthens public awareness of groundwater vulnerability in karst environments. This approach offers a transferable and scalable model for groundwater management in coastal karst regions worldwide.

Experimental framework for quantifying coarse sediment transport in a confined karst system

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Quantifying coarse sediment transport in karst systems is fundamental for reconstructing paleo-hydrological regimes and understanding landscape evolution. While the hydraulics of fine-grained particle transport are well-documented (e.g. Vuilleumier, 2018), the thresholds for coarse bedload entrainment remain poorly constrained. This knowledge gap is primarily due to the episodic nature of high-magnitude floods and the technical challenges of in-situ observation in active conduits (Herman et al., 2012). Although coarse sediment deposits in caves are often interpreted as relic features associated with extreme hydrodynamic conditions (White and White, 1968), recent research suggests that entrainment-thresholds for pebbles may be exceeded by relatively frequent, storm-induced discharges (Dogwiler and Wicks, 2004; Woodside et al., 2015).

This case study presents a multi-instrumental methodology implemented within Milandre Cave (Switzerland), an active system featuring an underground river approximately 4 km in length. This experience focuses on a 600m-long cave section to determine the hydraulic conditions required for clast mobilization. To characterize the conduit's complex boundary conditions, a high-resolution LiDAR scan was integrated with traditional topographic surveys. This provides the precise geometry required to calculate the hydraulic radius and shear stress all along the conduit. Hydrological monitoring is supported by a rating curve established through dilution gauging using salt and fluoresceine.

The experimental tracking of bedload mobility utilizes autochthonous limestone clasts (3–15 cm) equipped with Passive Integrated Transponder (PIT) tags. After each flood event, a handheld RFID antenna is used to locate the displaced traced pebbles. By recording these new positions and overlaying them onto the cave map, we can precisely measure the travel distance of each clast relative to the hydraulic forces recorded. The objective of this framework is to establish a standardized protocol for monitoring bedload transport in karst environments, ultimately providing a robust tool for interpreting subterranean sedimentary records and their relationship to modern and paleohydrological drivers.

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High-flow water gauging in deep karst systems

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Water discharge determines the hydraulic response of a karst conduit network and is key for modelling sediment transport and assess its geomorphic impact. Whilst site-specific flowrates can be quantified by bucket gauging or salt dilution techniques, measuring the discharge during floods becomes tremendously challenging in deep-cave settings where accessibility is hindered by high water levels. Here, we test an instrumental design in the middle of Milandre cave which injects a given amount of fluorescent tracer (uranine) depending on the water level measured with a pressure probe. The tracer breakthrough is monitored c. 200 m downstream using an automated field fluorometer. Results are compared with independent gauging from the two principal tributaries feeding the cave stream. Measurement uncertainties associated with the tracer pumping system and the effect of turbidity on fluorescence intensities are being discussed as well as their consequences on shear stress calculation and clast remobilization.

Underwater dynamics and exploration of Almonda Spring Cave (Portugal)

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The Almonda Spring Cave, located on the southeastern margin of the Serra de Aire anticline in central Portugal, represents the main resurgence of the largest karst system currently known in the country. The cave developed at the geological contact between the Estremenho Limestone Massif and less permeable Meso-Cenozoic formations of the Lower Tejo Basin, a structural and lithological boundary that exerts a strong control on groundwater circulation and spring emergence. With a currently surveyed development of 17 213 m and a vertical extent of 285 m, including a 197.5 m deep underwater siphon (on its northern extreme), Almonda Cave is both the longest and the deepest cave in Portugal and constitutes a reference site for karst and underwater speleological research.

Geological and hydrogeological framework

The Estremenho Limestone Massif hosts a highly compartmentalized karst aquifer system characterized by conduit-dominated flow, rapid hydraulic responses to recharge events, and marked seasonal variability in discharge. Almonda Spring is one of the main perennial outlets of this aquifer, with estimated annual discharges ranging between 80 and 100 hm³. Dye-tracing experiments conducted between 1986 and 1991 demonstrated clear hydraulic connections between sinkholes (Algar do Zé Lenha) located in the southeastern sector of the Polje de Minde and Almonda Spring, while excluding connections with sinkholes located in other sectors of the polje. Measured groundwater flow speeds exceeded 200 m/h during high-flow conditions, confirming the presence of large, well-organized conduits and explaining the rapid transmission of flood pulses to the spring. Two possible areas of origin to Almonda's spring water are Serra d'Aire anticline (northern sector), and Polje de Minde (western sector).

Scientific archaeological relevance

Beyond its hydrogeological importance, Almonda Cave is one of the most significant archaeological sites in Portugal. Archaeological deposits span from Lower Palaeolithic Neanderthal occupations (approximately 400,000 years BP) through to the Roman period. According to archaeologists, the stratigraphic continuity and preservation of deposits have few parallels worldwide. This dual scientific relevance—hydrogeological and archaeological promote an Underwater exploration with a strong emphasis on minimal impact, precise navigation, and accurate data collection.

Early underwater exploration

Underwater exploration of Almonda Cave began in the second half of the twentieth century and was initially marked by severe logistical difficulties. Early dives required carrying heavy equipment through long and narrow dry passages to reach flooded zones, often under conditions of limited visibility and strong currents. The unblocking of the submerged spring entrance in 1991 enabled direct underwater access, but recurrent collapses and intense seasonal flow continued to restrict exploration windows. Despite these limitations, pioneering cave-diving expeditions during the 1980s and 1990s produced the first underwater profiles and maps of the system, laying the groundwork for later systematic work.

The almonda project and systematic exploration (2007-2025)

A new phase of exploration started in 2007 and was formally structured in 2011 under the Almonda Project, a collaborative initiative involving XploraSub, AESDA, and later GEM. The project sought to move beyond exploratory dives toward a comprehensive and methodologically consistent investigation of the submerged system. Standardized rigging protocols were introduced, durable navigation markers were installed, and high-precision underwater surveying techniques were applied. Emphasis was placed on integrating dry and submerged topographies, allowing the building of a coherent three-dimensional representation of the cave and the correction of earlier mapping inaccuracies.

Between 2013 and 2016, more than 110 exploration dives were carried out in the entrance sector, submerged labyrinth, and northern and western galleries. These dives, with average durations exceeding two hours and maximum depths reaching 77 m, resulted in significant improvements to existing surveys and the identification of previously unregistered secondary passages. The refinement of underwater topography also facilitated the direct comparison with earlier maps, revealing scale and compass direction errors in previous representations of the submerged network.

Recent breakthroughs on edge sectors

From 2022 onwards, exploration efforts focused on the most remote and faraway sectors of the cave, particularly the northern Almonda Novo galleries and deep western passages near the spring. These campaigns required advanced technical diving methods, including the use of dual rebreathers, underwater scooters, thermal protection systems, and complex gas management strategies. Access to the northern sector involved long underground approaches, combining extensive dry passages with multiple submerged siphons, and demanded substantial logistical support from large teams of cavers.



Figure 1. Survey map of the cave

Recent exploration campaigns (2024) resulted in major breakthroughs. In the northern sector, where the main guideline was extended by approximately 400 m, reaching a maximum depth of 197.5 m (in 1997 was 75 m) and establishing a new national depth record for caves in Portugal. In (2025) the western sector, submerged passages were extended 200 m beyond previous limits, reaching depths of 115 m (in 1997 was 43 m) and confirming the presence of deep, multi-level conduit systems near the spring outlet. The integration of these new data significantly enhanced understanding of conduit geometry, depth distribution, and hydrodynamic behaviour within the aquifer. The diving team for the most recent explorations consisted of Armando Ribeiro (push diver), Tiago Grosso, Hugo Ballester, Nuno Sousa, Rui Luís, Luís Gonçalves, and Rui Ferreira.

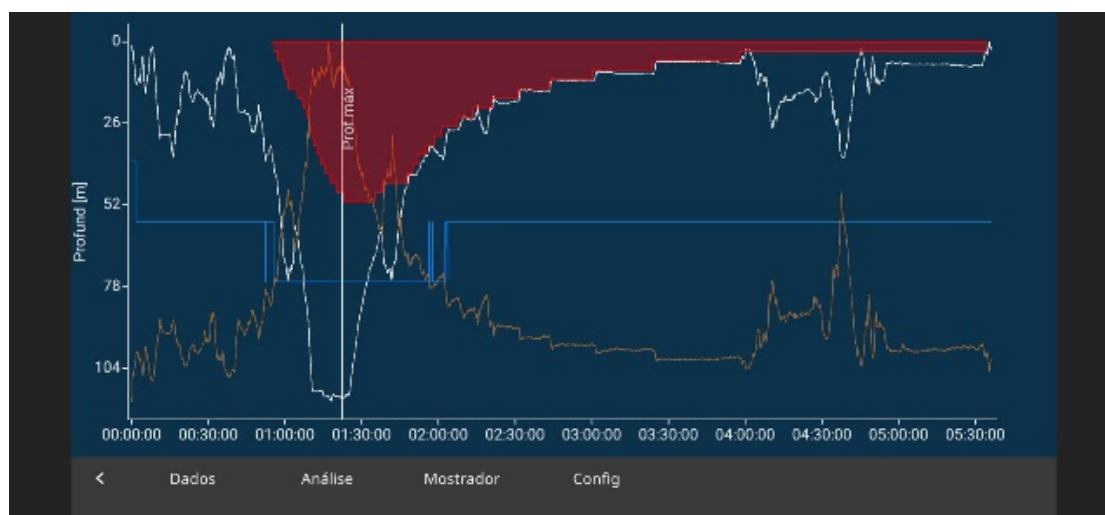


Figure 2. Profile from the last dive on the west gallery – Almonda Entrance.

Conclusion

The results obtained show that Almonda Spring Cave functions as a major structural and hydraulic axis of the Estremenho karst system, reflecting long-term speleogenetic evolution controlled by lithology, tectonics, and fluctuating base levels. Despite nearly a century of exploration, substantial portions of the system remain unexplored, particularly in deep and distant submerged areas. This work highlights the provisional nature of knowledge in large karst systems and underscores the importance of sustained, interdisciplinary, and collaborative approaches to underwater speleological research.

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The Alviela Deep Karst Spring and the hydrogeological role of the Monsanto Syncline (Portugal)

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Introduction

The Alviela spring (Olhos de Água do Alviela) is a permanent karst resurgence located on the southern margin of the Estremenho Limestone Massif, in central Portugal. Emerging at approximately 77 m above sea level, this spring represents the deepest known karst upwelling in Portugal and one of the deepest underwater cave systems explored worldwide. Due to its geological setting, hydrological relevance, and extreme depth, the Alviela spring constitutes a key site for understanding deep phreatic karst development and groundwater circulation within large carbonate aquifers. The submerged cave system presents exceptional opportunities for investigation, requiring long-term multidisciplinary cooperation and advanced underwater data collection. This contribution synthesizes the geological, geomorphological, and hydrogeological framework of the Alviela spring and summarizes the main results of underwater explorations carried out over several decades, with emphasis on the systematic work conducted by the AESDA/XploraSub project since 2016.

Geological and geomorphological setting

The Estremenho Limestone Massif is a large Jurassic carbonate block covering approximately 800 km², extending between Rio Maior, Tomar, and Leiria. The Alviela spring is located at the contact between this massif and the Lower Tagus Tertiary Basin, within a small limestone block preserved inside the Monsanto syncline. A marked geological discontinuity exists between the Jurassic limestones of the massif, approximately 160 million years old, and the Miocene formations of the Tertiary Basin, dated at around 20 million years. Structural controls play a decisive role in groundwater circulation, particularly by the faults parallel to the Costa de Minde fault system. Several of these faults are locally intruded by basic rock dykes, which act as partial or total hydraulic barriers, diverting groundwater flow toward the Alviela spring. The spring lies at the southwestern vertex of the Alviela–Almonda–Polje de Minde triangle, a geomorphological configuration that strongly influences regional karst drainage patterns.

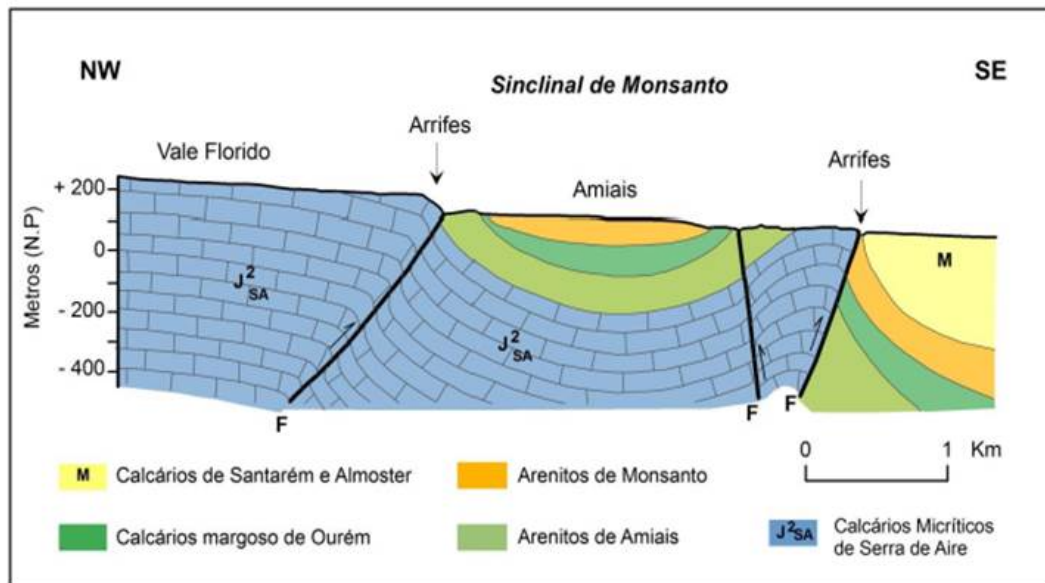


Figure 1. NW-SE geological profile passing through the region of the Olhos de Água do Alviela Spring (Leal, C., 2014).

Hydrogeological characterization

The Alviela spring drains a complex karst aquifer developed within the southern sector of the Estremenho Limestone Massif. Its recharge area is mainly associated with the Santo António Plateau, covering approximately 180 km² and characterized by a general southward slope coincident with limestone bedding. Groundwater circulation is strongly controlled by structural features, including faults and lithological contacts, which concentrate flow toward the spring. Dye tracing experiments conducted in the Polje de Minde since the 1980s demonstrated rapid underground connections between sinkholes and the Alviela spring, confirming a well-organized conduit flow system. Multi-tracer tests revealed hydraulic partitioning within the polje, with some sectors draining preferentially toward Alviela and others toward neighboring springs such as Almonda, depending on hydraulic head conditions. During periods when secondary outlets remain inactive, groundwater flow is largely captured by the Alviela spring. The high discharge variability, combined with the great depth of the submerged system, indicates a predominantly phreatic circulation regime, reflecting the spring's role as a major outlet of the regional karst aquifer.

History of underwater exploration

Underwater exploration of the Alviela spring began in 1961, when initial dives reached 35 m depth and approximately 150 m of development. Over subsequent decades, progress was achieved by Portuguese and international teams, gradually extending known passages to depths of 50 m in the 1980s and beyond 120 m in the early 2000s. By 2010, underwater development exceeded 1500 m and depths of 134 m were reached. Despite these advances, exploration remained incomplete due to technical limitations, strong seasonal discharge, and the extreme depth profile of the cave. The spring can only be accessed during dry periods, as winter flow may reach average values of 17 m³/s, preventing safe underwater operations.

Recent exploration and methodology

A new phase of systematic exploration began in 2016 through a partnership between AESDA and XploraSub. Initial efforts focused on compiling historical data, improving logistics, and re-

equipping the cave with more durable navigation lines. From 2016 onward, exploration progressively advanced into deeper areas using closed-circuit rebreathers, redundant configurations, diver propulsion vehicles, and underwater decompression habitats. Between 2017 and 2019, several passages were connected and new ones discovered, revealing a more complex internal geometry than previously recognized. Automated survey systems coupled to propulsion vehicles allowed efficient mapping at great depths. In 2019, exploration exceeded 190 m depth, and in 2020 a maximum depth of 215 m was reached (by Armando Ribeiro), establishing a national record and placing Alviela among the deepest explored underwater caves worldwide.

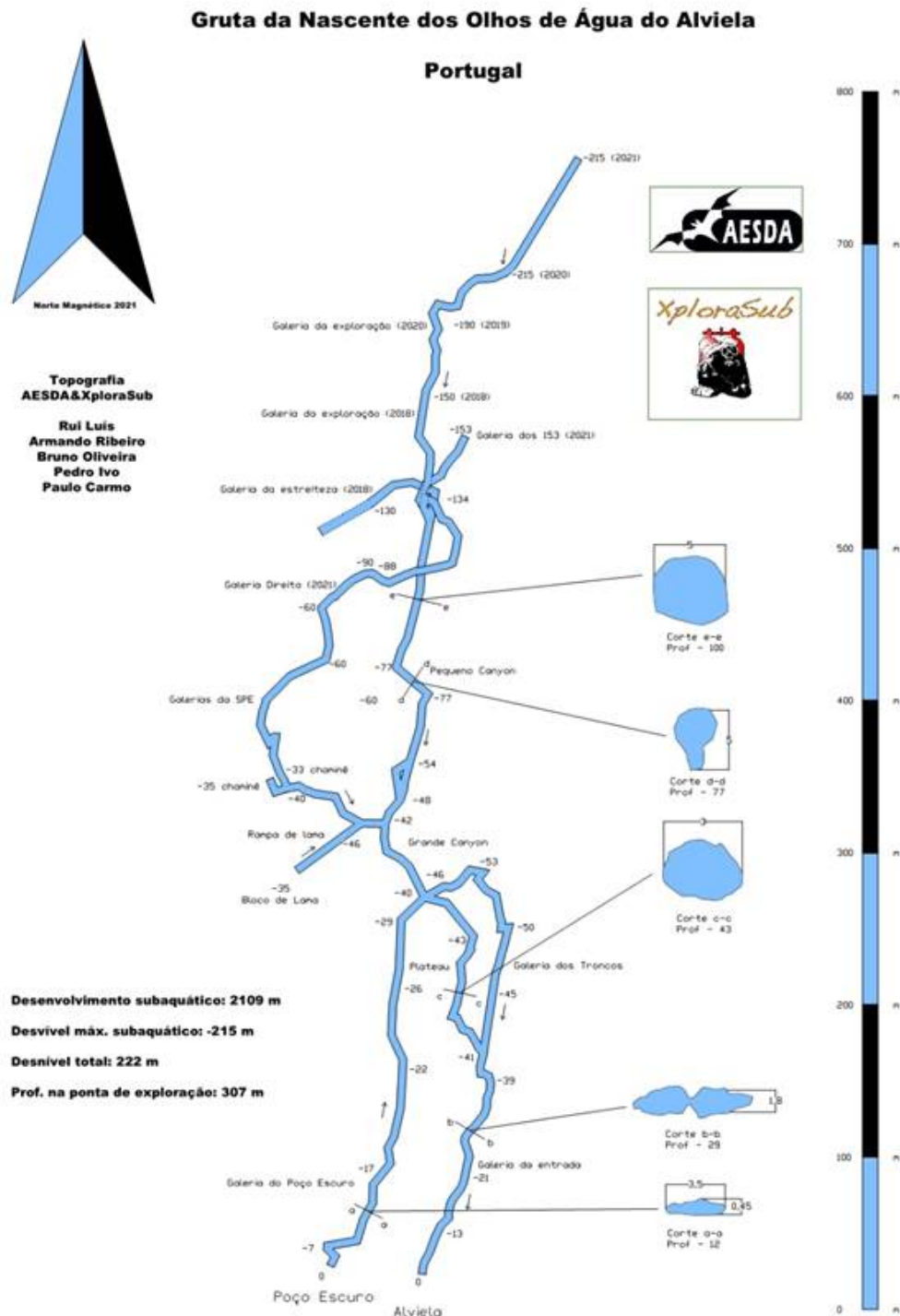


Figure 2. Survey 2022

Cave morphology and survey results

The submerged cave system of Alviela currently comprises more than 2100 m of known underwater passages, with an absolute vertical range of 222 m. Large phreatic conduits dominate the deeper sections, without fine sediment accumulations. These deposits suggest that all of the deepest (below 130 m) explored passages may correspond to the main active flow routes feeding the spring. More than 1200 m of passages have been surveyed by the AESDA/XploraSub team, including approximately 200 m of virgin tunnels between depths of 130 m and 215 m. Several exploration fronts remain open at different depths, indicating significant potential for further discoveries and a complex hydraulic organization.

Conclusions and perspectives

The Alviela spring represents an exceptional example of deep phreatic karst development and a key site for understanding groundwater circulation in the Estremenho Limestone Massif. Decades of underwater exploration, culminating in recent systematic advances, have substantially expanded knowledge of its geometry, depth, and internal organization. Beyond exploration achievements, the results provide valuable insights into structural controls, recharge mechanisms, and conduit-dominated flow in large carbonate aquifers. Continued exploration, combined with hydrogeological monitoring and interdisciplinary research, is essential to fully characterize this complex system and to assess its broader implications for karst science, groundwater management, and the protection of strategic water resources.

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Deep karst drainage at Olho de Mira Spring: New knowledge on the Mindinho–Mira System (Portugal)

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Introduction

The Estremenho Limestone Massif (Maciço Calcário Estremenho, MCE) hosts one of the most complex and extensively studied karst systems in Portugal. Within this massif, the Polje de Minde represents a key hydrological unit, characterized by seasonal flooding and large water table oscillations. The Olho de Mira spring, a temporary karst resurgence located at the northern margin of the polje, has long been recognized as hydraulically connected to the Mindinho depression and its associated sinkholes.

Previous dye tracing experiments confirmed this connection, but the internal geometry, depth, and hydraulic role of the Olho de Mira conduit system remained poorly known. Recent cave-diving explorations have significantly extended the known depth and length of the spring, providing new data that allow a reassessment of its hydrogeological function within the Mindinho–Mira system.

Geological and geomorphological setting

The MCE is a Jurassic limestone plateau covering approximately 800 km², with elevations generally exceeding 200 m. It forms the core of the Serras d'Aire e Candeeiros Natural Park. The Polje de Minde is a closed karst depression approximately 4 km long and 1.5 km wide, with a floor elevation near 200 m. To the north lies the Mindinho depression, whose base is elevated to around 275 m.

The geological framework is dominated by Middle and Lower Jurassic limestones, strongly affected by faulting, particularly the Costa de Minde–Costa de Mira fault system and associated structures. These tectonic features exert a primary control on underground drainage organization, conduit orientation, and hydraulic connectivity between depressions and springs.

Hydrogeological context

The Polje de Minde experiences periodic winter flooding due to the limited capacity of its sinkholes and the rapid response of temporary springs, including Olho de Mira (215 m) and Pena/Poio (210 m). Seasonal water table fluctuations can reach approximately 80 m.

Groundwater from the polje ultimately drains southward toward the major perennial springs of Alviela, Almonda, and Olho de Maria Paula (intermittent), located between 80 and 105 m elevation. Dye tracing campaigns conducted between 1986 and 2007 demonstrated that waters infiltrating in the Mindinho depression feed the Olho de Mira spring during high-water conditions, confirming a functional hydrogeological connection across structural boundaries.

The infiltration area of Olho de Mira is part of the broader Alviela aquifer system, although it represents a distinct northern sector with independent overflow behavior during recharge peaks.

Speleological background

Exploration of the Olho de Mira spring dates back to 1758, when approximately 350 m of passages were documented up to a terminal siphon. Systematic speleological surveys during the 20th century increased the known development to about 500 m and a depth of 80 m.

The Mindinho cave, located roughly 2 km northwest of Olho de Mira, underwent significant exploration from the 1970s onward. Repeated pumping operations allowed the extension of its mapped development to nearly 1 km, with depths approaching 100 m. Despite extensive efforts, a physical connection between both systems has never been directly accessed.

Underwater exploration and methods

Between 2020 and 2021, a joint venture by AESDA and XploraSub carried out deep cave-diving operations at Olho de Mira. These dives were conducted during the rainy season, under high-flow conditions, using advanced cave-diving techniques and closed-circuit rebreathers adapted for deep and prolonged penetration.

Progressive exploration focused on extending the terminal siphon beyond previously reported limits, documenting conduit morphology, depth profiles, and general flow orientation.



Figure 1. Plan of Mindinho Cave in red (Robalo, M. 2021) and plan of Olho de Mira Spring in white (Ribeiro, A., 2021) – AESDA/XploraSub 2022.

Results

The 2021 exploration campaign, lead by Armando Ribeiro as push diver, extended the Olho de Mira spring to a maximum submerged depth of 139.3 m below the water surface at the time of the dives. Accounting for seasonal water level differences, this corresponds to an absolute depth of approximately 149.5 m from the entrance, increasing the known depth by nearly 70 m. An additional 250 m of submerged conduits were mapped, bringing the total known development to approximately 750 m.

The new depth data indicate that Olho de Mira functions as a deep subsidiary collector within the Mindinho depression drainage system. The conduit geometry and depth suggest that the main groundwater flow occurs well below the floor of the Polje de Minde, following a general northwest–southeast direction before being redirected southward toward the major springs of the MCE.

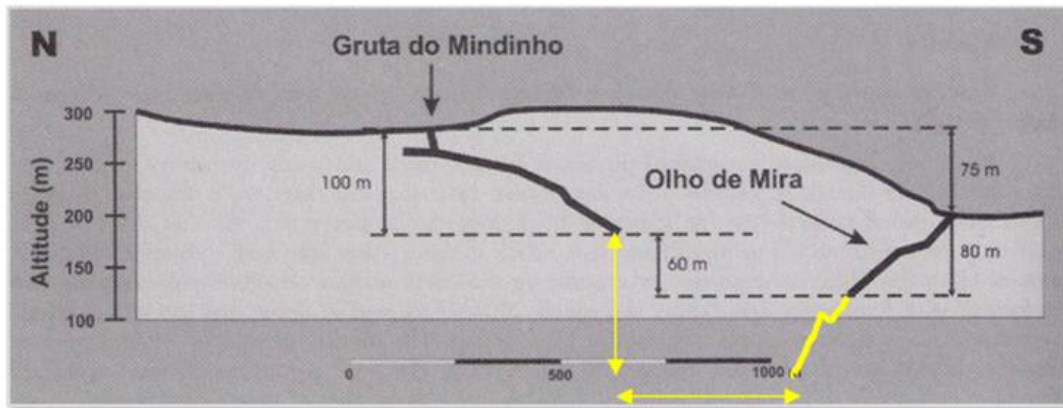


Figure 2. Schematic section between the Mindinho depression and Polje de Minde with the representation of the Mindinho Cave and Olho de Mira Spring – AESDA/XploraSub Adaptation 2026 (Lopes *et al.*, 2007).

Discussion

The absence of a direct upward gradient toward the Mindinho cave, combined with the significant depth reached at Olho de Mira, supports a model in which both systems are connected through deep phreatic conduits rather than shallow vadose passages. Olho de Mira appears to act as an overflow outlet triggered during periods of high recharge, while the bulk of groundwater follows southward at depth.

These findings refine previous conceptual models of groundwater circulation in the northern MCE and highlight the importance of deep conduit systems in controlling polje flooding dynamics and spring activation thresholds.

Conclusions

Recent cave-diving explorations at Olho de Mira substantially improve the understanding of the Mindinho–Mira karst system. The newly documented depths confirm the role of Olho de Mira as a deep, temporary overflow spring connected to the Mindinho depression through phreatic circulation pathways. This work demonstrates the value of technical cave diving as a complementary tool in karst hydrogeological research and provides new knowledge for regional groundwater models in the Estremenho Limestone Massif.

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The role of stylolites as proto-karsts in speleogenesis

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Karst development in carbonate rocks has traditionally been linked to fractures and faults, which are considered the main pathways for groundwater flow and dissolution. Compressive structures, particularly stylolites, have instead be seen as sealing surfaces that reduce porosity and permeability. In this study, we challenge this conventional view by demonstrating that stylolites can play a fundamental and previously underestimated role in the early stages of speleogenesis. We propose that stylolites may act as proto-karst features, capable of initiating localized dissolution, promoting porosity development, and ultimately guiding the evolution of karst conduits.

This research integrates laboratory analyses and field work to explore the relationship between stylolites, fluid–rock interactions, and cave development. A total of fifteen stylolite samples from different geological settings were analyzed using XRD, Fourier-transform infrared spectroscopy (FTIR), SEM-EDS. These samples include both diagenetic and tectonic stylolites. The laboratory work aimed to characterize the mineralogical composition of insoluble residues, the distribution of porosity, and evidence of post-stylolitization fluid circulation.

Microscopic observations consistently reveal that stylolites are enriched in insoluble residues, primarily phyllosilicates (micas, illite, kaolinite, chlorite) and Fe–Ti oxides, which accumulate passively during pressure-solution processes. These residues create strong chemical and mineralogical heterogeneities within monomineralic carbonate rocks. SEM and microstructural analyses show that porosity is generally higher within stylolite seams and at stylolite–matrix interfaces than in the surrounding host rock. Pores often are located along these interfaces, suggesting that stylolites may evolve from initially sealing surfaces into preferential sites for dissolution once geochemical or stress conditions change. Additional mineralogical evidence, including localized dolomitization and the precipitation of minerals such as galena, pyrite, gypsum, and secondary calcite within stylolites, further supports the occurrence of post-formation fluid flow along these structures.

To complement the laboratory data, field investigations were conducted in the Apulia region (southern Italy) and in the Toirano area (northwestern Italy), focusing on the structural control of cave development in different karst and tectonic settings. In Apulia, a scanline survey indicates that approximately 85% of observed stylolites display clear dissolution features, a proportion significantly higher than that observed along faults or fractures. Detailed structural comparisons were carried out in the Grave Rotolo cave, the deepest known cave in Apulia, using orientation data for stylolites, faults, fractures, and cave passages. These analyses show that both primary and secondary cave passages frequently align with stylolite orientations, in some cases more closely than with faults or fractures.

Comparable structural relationships were also documented in the Toirano karst system, where field observations reveal the presence of dissolution and cavities developed also along stylolitic surfaces. The recurrence of these patterns in distinct geological contexts strengthens the interpretation that stylolites exert a direct structural control on early speleogenetic processes, acting as preferential pathways for localized dissolution and guiding the initial development of karst conduits.

Field observations show that stylolites can gradually evolve from tightly closed pressure-solution seams into widened surfaces where dissolution creates micro-voids and small cavities. In later stages, dissolution along stylolites can become so advanced that the original stylolitic morphology is partially or completely erased, resulting in proto-conduits that are difficult to distinguish from fracture-controlled cavities.

Based on these observations, we propose a three-stage conceptual model describing the evolution of stylolites into proto-karst structures. In the first stage, stylolites form as low-permeability pressure-solution surfaces enriched in insoluble residues under compressive stress. In the second stage, micro-porosity nucleates along the stylolite–matrix interface due to free-face dissolution processes driven by chemical contrasts and fluid–rock interactions. In the third stage, interconnected micropores enlarge and evolve into early conduits, allowing focused fluid flow and promoting further dissolution. At this stage, stylolites shift from acting as barriers to functioning as preferential flow paths, effectively becoming proto-karst features.

This study points out a paradox: although stylolites initially act as sealing features, they can be more easily dissolved than sealed fractures because of their polymineralic composition and chemical heterogeneity. The presence of clays, oxides, and other insoluble minerals makes these zones more reactive and favors localized fluid pathway.

Recognizing stylolites as possible initiators of karst processes has important implications for speleogenesis models, hydrogeology, and the characterization of carbonate reservoirs.

In conclusion, our results show that stylolites should not be seen only as barriers but as a path for fluids that can initiate and guide early karst development. This idea suggests that stylolites are important in speleogenetic studies and highlights the value of combining field observations with laboratory analyses to better understand their role in carbonate dissolution and karst evolution.

Dynamically visualize the flowpaths of a tracer or contaminant in 3D

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Recent developments in visualkarsys.com allow the users to simulate and visualize hydrogeological tracing tests, as well as ‘contamination’ scenarios. Input locations or regions must be defined at the top of the 3D hydrogeological model. Users must also assign patterns to these compounds (e.g. small sparkling triangles for chemical compounds, viscous bubbles for oils or hydrocarbons, etc.), colors and behaviors (degradation, dissipation, etc.). The duration of the injection must be defined as well, e.g. short for an accidental spill of a contaminant, or prolonged for a longer spill. During the animation, the tracers and/or contaminants are activated at the desired moment and begin to flow according to the infiltration and flow properties of the 3D hydrogeological model. The user can then see the 3D propagation of the tracer/contaminant through the different zones of the aquifer (ground surface, unsaturated / saturated zones), in real time and assess which parts of the aquifer and which outlets could be ‘impacted’ and to what probable extent (major impact, minor impact).

This module is very useful for assessing in advance the feasibility and prognosis of a hydrogeological tracing test, or for assessing the vulnerability of a hydrogeological system at the conceptual level, as well as for interactively showing to non-hydrogeologists the underground pathways of tracers or contaminants. We hope that this module will help users to assess vulnerability areas and to determine protective measures to be implemented to limit the risk of contamination at the water intake. It should also make it easier to explain concepts to non-specialists and present results in a more explicit/visual way. The applied approach is conceptual and based on empirical values of transport parameters issued from hundreds of tracing tests in karst aquifers.

An integrated tool for generating 3-dimensional karst conduits

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Knowing where and how karst conduits – and therefore flow hydrogeological systems – develop in a rock massif is a recurring concern for hydrogeologists. Applications relating to groundwater exploration and protection, risk assessment during the construction of underground facilities, and prevention of surface collapses often require predictions of where the main conduits are located and their probability of occurrence. In recent years, more or less sophisticated tools, adopting stochastic or deterministic approaches and based on geological geometries and hydraulic principles, have been developed, mainly in the form of Python libraries (Henrion 2011, Borghi et al. 2012, Malard et al. 2015). Although these tools exist, their use often remains ‘complex’ and de facto reserved for academic spheres, as they are relatively tedious to use in applied projects due to time and skill constraints. In light of this, in 2025 the ISSKA decided to implement the KarstNSim library (Gouy et al. 2024) in the visualkarsys.com web service. This recent feature now allows users to generate 3D karst conduit networks online on their own geological and hydrogeological models via a dedicated graphic interface.

Users can modify a few parameters (conduit density, network tortuosity, strength of ‘guidance’ by various discontinuities: faults, overlaps, interlayers, etc.) that constrain the geometry of the conduit network until they obtain one or more scenarios that meet their expectations. This implementation aims to offer a ‘simplified’ tool to the majority of users, providing a limited number of parameters to modify (those with the greatest impact on network geometry) and ensuring optimized calculation times to allow users to ‘test’ different probable scenarios based on their knowledge of the site and their professional experience.

KarstNsim is now a major component of the integrated and explicit approach offered by visualkarsys.com for documenting karst hydrogeological systems. This implementation offers a huge potential in the field of applied karst hydrogeology. Pretty straightforward extensions can now be considered, such as probabilistic prediction of intersecting one or more conduits during tunnel boring, or the possibility of interfacing a hydraulic simulator to model hydraulic heads and flow rates in the conduit network based on estimated or calculated recharge in the catchment area.

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Insight from sediments burial dating on the speleogenesis paradigm

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The classical epigenic speleogenesis model presumes a direct correlation between cave level development and regional base level variations. One could argue that this model implies that the laws of physics are different when water flows at the surface carving deep canyons or underground jumping from one level to another at a lower elevation with the entrenchment of the river. Burial dating of quartz rich alluvium within tiered caves using Terrestrial Cosmogenic Nuclides (TCN, ¹⁰Be and ²⁶Al) suggest a speleogenesis of the center of a large limestone plateau not directly linked to the regional river base level evolution. According to these results and a compilation of others TCN ages we suggest that karstogenesis and latter on speleogenesis are a continuum process, starting from a fundamental heterogeneity during the limestone formation followed by an hypogene phase creating a primokarst composed of passages filled with ghost rock, which will be emptied by the epigene karst dynamics to create cave networks. We propose that these processes initiates speleogenesis and controls the geometry of the networks, which might subsequently be reshaped by a hydrodynamic phase and later biospeleogenesis. These results have implications not only on how the tiered cave levels should or shouldn't be used as geomorphological markers of river entrenchment but also on the water storage that can be important in ghost rock corridors not yet emptied and therefore poorly connected to the springs forming a reservoir with a slow draining.

Tri mlynky Karst Spring in the West Carpathians: Misleading sentinel of climate change?

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Tri mlynky spring (Three little mills in translation; N48.63075°/E17.49687°; 265 m a.s.l.) in Slovakia is a karstic overflow spring situated in the one of the westernmost karst aquifers of the Western Carpathians (Brezovské Karpaty Mts.). The spring is merely recharged by precipitation. Middle Triassic Wetterstein dolomites are outcropping in its 1.454 km² recharge area. Barrier built by thin belt of dark shales keeps the spring some 30 m above the riverbed of the adjacent valley. History of the spring gauging dates back to 1960, together with its tapping by local waterworks. Observations were abandoned in 1966, restored in 1984, and again abandoned in 1992 as the spring completely lost its discharge (17.10.1990) for a two years lasting period. Finding the water discharging again, gauging was restored in 1995. In 2005, Bratislava Waterworks started to be the spring operator, keeping the gauging in the same weekly mode as set since 1960, however data from hydrological year of 2018 (November 2017 – October 2018) are missing. For the periods when the spring was observed, the average discharge value reached 7.87 L/s, with 61.1 L/s maximum and zero values that were observed 229 times (~10% of cases). Groundwater temperature was from 8.0°C to 14.0° with 10.6°C mean value. The “overhanged position” of the spring and its replenishment merely by precipitation make this spring as possible indicator of the climate change impact on groundwater (theoretically...). Simultaneous analysis of precipitation totals, air temperatures and time series of spring discharges, however, has shown strange spring behaviour that makes any conclusions very ambiguous.

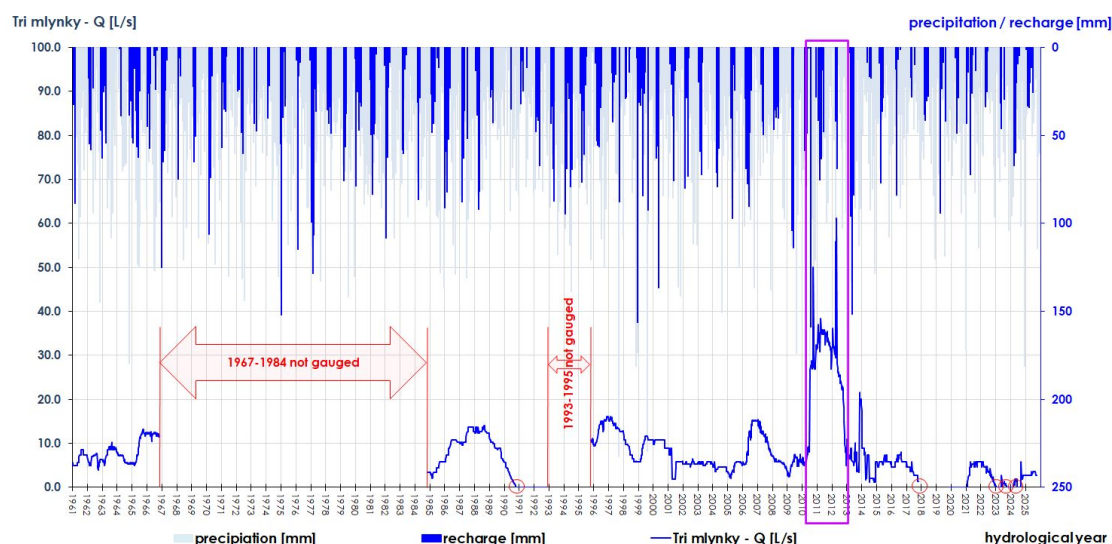


Figure 1. Spring Tri mlynky in Hradište pod Vrátnom – hydrograph of the whole gauged period 1961-2025. Ungauged periods are marked by arrows, dates of discharge loss are marked by red circuits, the period between July 2010 and October 2012 is marked by a violet rectangle.

Time series of air temperatures measured on the nearest, 15 km distanced Myjava station (348 m a.s.l.) with the longest observation history in the region show an increase of 1.37°C in annual means after 2000 (mass curves, Fig.2). In the period of 1961-1999, the air temperature mean

was 8.27°C, in 2000–2025 it was 9.24°C. Throughout the entire observation period precipitation totals seem to be unchanged and differ only in 8 mm between the periods before 2000 (677 mm) and after 2000 (669 mm), see Fig.2A. However, temperature raise has an impact on the effective (unevaporated) precipitation totals calculated by the use of Thornthwaite (1948) formula, and mutual comparison of monthly precipitation totals, potential evapotranspiration and soil retention (field) capacity of 128 mm. Before 2000, effective precipitation annual total was 192 mm in average (28% of precipitation totals), after 2000 it dropped down in 20 mm to 172 mm (in 9%). Based on aforementioned development of water input factors, one should expect similar drop (~9%) in Tri mlynky mean discharge after 2000.

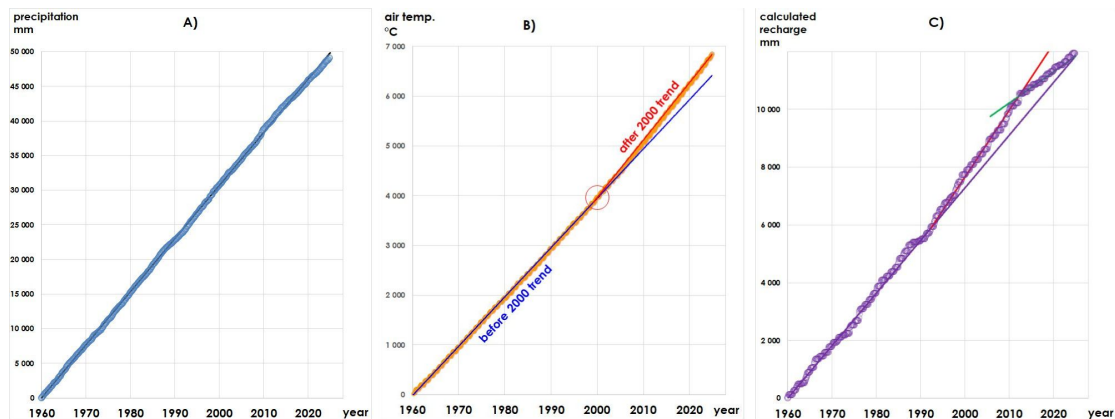


Figure 2. Station Myjava – cumulative mass curves of monthly totals/averages since 1961: A) precipitation; B) air temperatures; C) effective precipitation (marked as “recharge”).

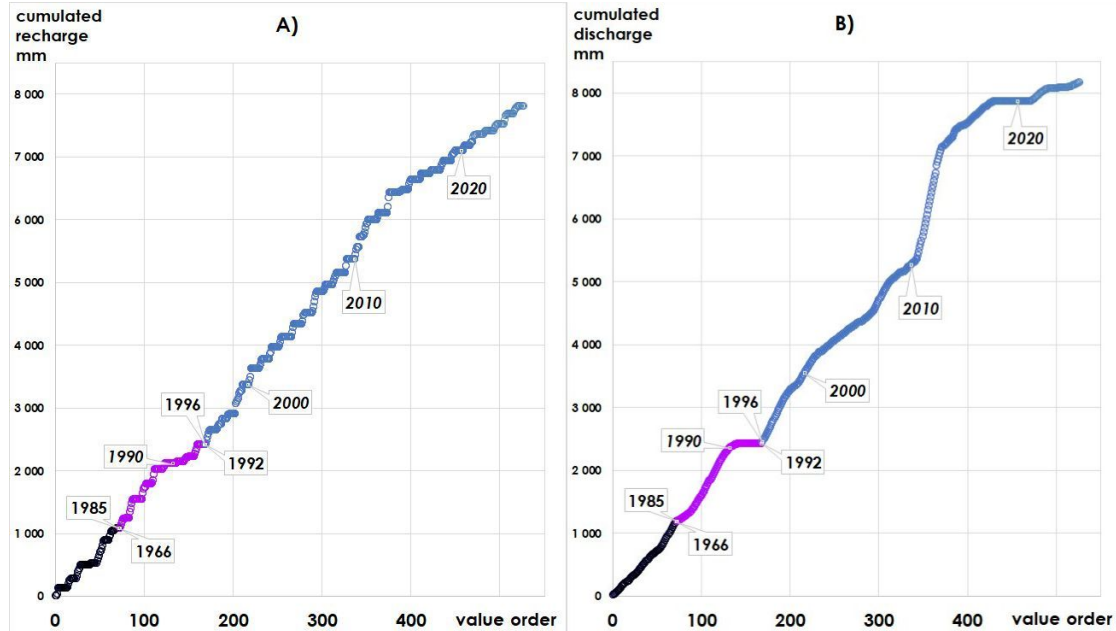


Figure 3. Spring Tri mlynky (1.454 km² recharge area) – cumulative mass curves of: A) discharge in mm in the gauged periods (1960–1966, 1985–1992, 1996–2025); B) effective precipitation in the same time intervals.

In general, the decline in spring Tri mlynky discharge after 2000 met expectations of a decline, but was only in 4% (mean of 8.05 L/s up to 2000; 7.72 L/s after 2000). When analysing individual decades, we may encounter interesting differences: in the 1961–1970 decade with 6

completed years of observations, the average discharge value 7.90 l/s was nearly the same as the overall average (7.87 L/s). There were no measurements in the 1971-1980 decade, but 6 complete observation years in the 1981-1990 (8.35 L/s average) were in 6% of exceedance. The decade 1991-2000 with 7 gauged years had its average of 7.92 L/s (1% higher), but completely gauged decade of 2001-2010 was in 8% lower (7.27 L/s). The greatest volatility can be seen in the last two decades, the latter of which is still ongoing: the 2011-2020 decade with 11.59 L/s was in 47% higher than the overall average, the uncompleted 2021-2030 decade (up to 2025) was in 70% (!) lower with the average discharge of 2.34 L/s for its first five years of gauging.

Closer look at the Fig.1 reveals extremely upraised spring discharge between July 2010 and October 2012, when it reached maximum value of 61.10 L/s, but during the whole period did not fall below 21.10 L/s. This discharge excess was following the heavy rain period in May 2010 (Fig.3). The whole event is supposed to be a consequence of explosive eruption and volcanic ash spreading of the Eyjafjallajökull volcano in Iceland (April – May 2010). May precipitation totals in Myjava station that time were 224 mm (normally 68 mm), and 1009 mm for the whole year (normally 697 mm). Although the precipitation totals were below 600 mm within next two years, the total water volume discharged between May 2010 and October 2012 was 2,324,750 m³, while the calculated effective precipitation for the same 910 days lasting period was only 783,706 m³ (24% of the 3,216,248 m³ precipitation volume, this ratio was also proven by previous water balance studies here, Malík et al. 2025).

It seems that either part of this exceptional precipitation remained unrecorded, or the spring recharge area during such events can be multiplied even in the areal recharge conditions. However, nearly 2.5 years lasting spring response to such recharge impulse underlines the memory effect of the springshed. This effect is also visible on the apparent incoherence of the recharge with spring drying out and recovery during 2017-2025 period (Fig.1).

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Predicting infrequent recharge events in water-limited karstic aquifers

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In water-limited environments, where evapotranspiration exceeds precipitation, groundwater recharge events are typically few and far between. This is because the conditions for recharge to occur typically involve some type of extreme event, such as intense precipitation, very long wet spells, or a compound combination of several climatic factors. While the occurrence of extreme (compound) climate events is expected to be strongly affected by climate change, the consequence on recharge in water-limited regions is yet to be better understood, especially in karstic aquifers. Furthermore, monitoring recharge is challenging in karstic environments because observed water table measurements are not only reflecting recharge, but other phenomena such as water abstraction.

Here we use a unique 10-years record of cave percolation water hydrology using automated drip loggers in two Australian caves with contrasting P-ET. At Daylight Cave, Willi Willi National Park (30.9 S, 152.5 E, 270 asl), in the Macleay River catchment, the hydroclimate is Köppen-Geiger Cfa (temperate, no dry season, hot summer; Peel et al. 2007) with annual P of 1218 mm and an annual ET of 1879 mm (Baker et al. 2024). At Cathedral Cave, Wellington (32.6 S, 148.9 E, 340 asl), in the Bell River catchment, the hydroclimate is also Köppen-Geiger Cfa, with annual P of 620 mm and an annual ET 2231 mm). At both caves we follow the methodology of Priestley et al 2025 and identify recharge events as sudden increases in drip rate. We compare these cave-based records of recharge events to hydroclimate parameters: daily precipitation; daily evapotranspiration; daily soil moisture; and daily river water level at the nearest automatic gauges on the Macleay River and Bell River. We use a predictive method based on the minimization of the Chamfer distance between observed and predicted recharge events. While the Chamfer distance is typically used in computer vision for shape matching, this constitutes one of its first uses with hydrological time series.

We find a relationship between groundwater recharge events and surface water events for the two contrasting karstic sites. The best predictor differs depending on the precipitation regime and the soil thickness. In the Cathedral Cave site, which has bare rock and patchy thin soil cover, the best predictions of recharge are obtained based on streamflow in the nearby river. We hypothesise that overland flow and focused recharge occurs at this site, and the fast surface flows similarly affect the river catchment and the focused recharge above the cave. In the Daylight Cave site that is less arid and has thicker soils, daily precipitation is the best predictor. We hypothesise here that indirect recharge through the soil is the primary process, and precipitation is the better predictor due to the piston-effect nature of recharge processes. Other environmental parameters such as remotely sensed soil moisture are generally less useful in predicting groundwater recharge. The findings at Cathedral Cave are consistent with Kumar et al. (2026) who also reported weaker correlative and causal associations between precipitation and groundwater recharge occurrences at the site.

This research demonstrates that recharge in arid karstic areas, while difficult to observe directly, can be predicted from easily observable parameters related to surface hydrology. This means that it is possible to retrace long-term time series of recharge based on historical hydrological records, or to predict future recharge based on hydrological regimes forecasted by climate models.

Our findings also have implications for water resources management. They suggest that in karstic areas, groundwater recharge is closely linked to surface water. Since both surface and groundwater components are tied, it may be difficult to rely on groundwater to supplement surface water resources in times of drought. Another implication is that floods, while destructive, are needed for recharge to occur, bringing a silver lining to the consequences of future environmental changes.

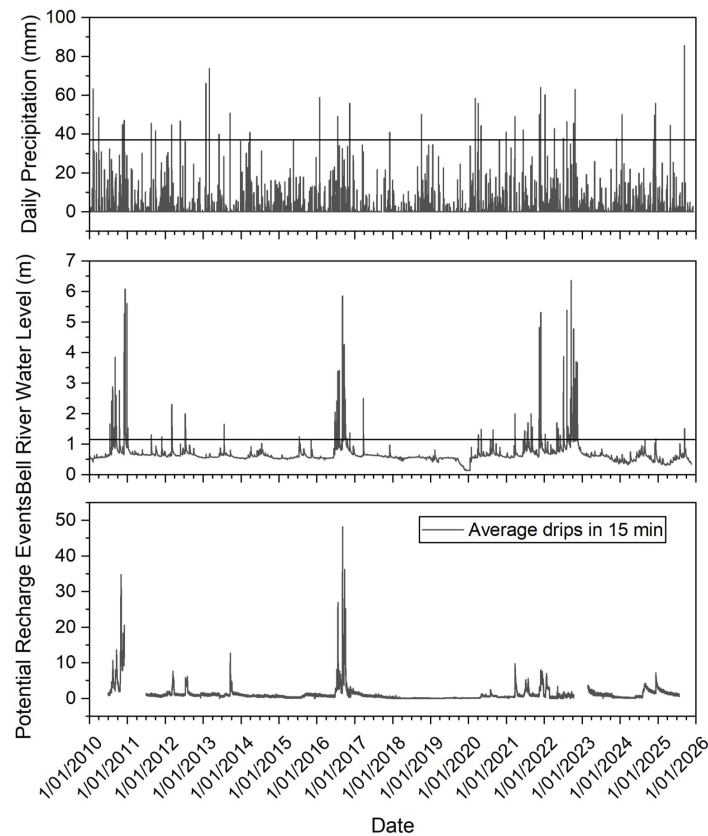


Figure 1. Wellington, NSW. (top) Daily precipitation; (middle) daily Bell River water level; (base) potential recharge events at Cathedral Cave. Horizontal lines are threshold values.

Table 1. Descriptions of the two sites.

Name	Location	Total annual P (mm)	Mean annual T (°C)	Modelled annual ET (mm)	Geology age	Geology type	Vegetation	Surface characteristics	Köppen-Gieger climate classification
Cathedral Cave, Wellington, New South Wales	32.6° S, 148.9° E, ~340 m asl	620	17.2	2231	Devonian	Karstified marmorised limestone	Native open woodland	Gently sloping site, patchy Dermosol soil, with bare rock	Cfa (temperate, no dry season, hot summer)
Daylight Cave, Willi Willi, New South Wales	30.9° S, 152.5° E, ~270 m asl	1218	18.7	1879	Permian	Karstified limestone	Remnant dry and subtropical rainforest	Sloping site, dermosol soil, 10-30 cm thick	Cfa (temperate, no dry season, hot summer)

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Conceptualization of groundwater–surface water interactions in the Mirna catchment using stable water isotopes and radon data

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Karst aquifers are characterized by high heterogeneity, hydraulic connectivity and fast water flow and transport of solutes, making the assessment of groundwater dynamics, residence times and water quality particularly challenging. Understanding groundwater–surface water (GW–SW) interactions is essential in such systems, especially where groundwater resources represent the primary source of drinking water supply. In this context, stable water isotopes and radon, combined with hydrochemical and hydrological data, can provide key insights into flow pathways, recharge mechanisms, residence times, and mixing processes, ultimately supporting the development of robust conceptual models (Cook and Herczeg, 2000).

The Mirna catchment is situated in Istria, Croatia and it represents a complex karst system where groundwater flow and discharge are controlled by geological structures, variable recharge, and hydrological conditions. Several major springs are located in the area: Sv. Ivan, Gradole and Bulaž which are used for public water supply. They are essential for regional water security, particularly during summer when tourism causes the population to quadruple and water demand to rise sharply. The catchment is predominantly composed of carbonate sediments, mainly limestones and limestone breccia with dolomite, accompanied by flysch deposits and Quaternary alluvial silt/clay sediments. Carbonate rocks act as highly permeable aquifers. The catchment is bounded by the Ćićarija and Učka mountains to the north and northeast, and the Mirna River flows towards the Adriatic Sea. Karstification of the carbonates promote rapid infiltration of precipitation and the development of complex subsurface flow pathways. The hydrogeological connectivity between different parts of the catchment remains only partially understood, suggesting the presence of multiple conduits, fracture networks and diffuse flow domains. Spring discharge shows strong seasonal variability, with pronounced contrasts between wet winter periods and dry summers. During prolonged droughts, groundwater storage decreases rapidly, and the capacity of major springs declines, increasing the pressure on public supply systems.



Figure 1. Gradole spring



Figure 2. a) Sv. Ivan spring b) measurement of radon in the spring water

To address these research gaps, this study applies a combined approach using stable water isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$), radon (^{222}Rn), hydrochemistry (major ions, nutrients), and hydrological data to conceptualize GW–SW interactions and recharge dynamics within the Mirna catchment. Stable water isotopes are widely used to track meteoric input, seasonal recharge signatures, elevation-dependent effects, and mixing between waters of different origin or residence times (Gat, 1996; Dansgaard, 1964). In karst, these isotopes are particularly valuable for distinguishing fast event-based flow from slower matrix or fracture storage components. Radon (^{222}Rn) serves as a sensitive tracer of groundwater contribution due to its production from decay of ^{226}Ra in aquifer matrices and high concentration contrasts between groundwater and surface water. Its short half-life (3.82 days) enables detection of recent groundwater inputs and transient exchanges, and has been successfully used to quantify groundwater discharge to rivers and coastal systems (Hoehn and von Gunten, 1989; Burnett et al., 2008). When combined with isotopes and hydrochemistry, radon allows distinction of multiple end-member contributions and temporal recharge modes, and supports evaluation of surface infiltration vs. deep karst conduit activation.

Recent monitoring campaigns indicate that the catchment exhibits a fast hydrological response to extreme precipitation events, characterized by short residence times and rapid changes in water chemistry. Heterogeneous lithological contacts, particularly between carbonate and flysch units, exert additional control on local flow directions and drainage patterns. Climate change projections for the region suggest an increased frequency of heatwaves and drought conditions, potentially exacerbating water scarcity in the future. In this context, the Mirna

catchment becomes a case study in how to manage a fragile resource, urging planners and scientists to pair hydrogeological modelling with persistent monitoring and long-term foresight. It also illustrates the delicate balance between protecting groundwater and pursuing development in a karst environment that offers both possibilities and constraints.

Acknowledgment

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Analysis of regional flow dynamics in the Rio Bueno Sub-Watershed management unit in Jamaica using dye tracing and isotope hydrology methods.

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The Water Resources Authority of Jamaica (WRA) investigated the subsurface flow dynamics of the Rio Bueno sub-Watershed Management Unit of the Dry Harbour Hydrologic Basin in Jamaica. The WRA performed dye tracing exercises between 2016 and 2019 to verify the historical connectivity between various sinking and rising streams in both basins, along with further investigations between 2020 to 2022 using stable isotopes (¹⁸O and ²H) from precipitation, sinks, springs and rivers. Fluorescein, Rhodamine, Eosine and Sulfo-Rhodamine dyes were injected in 5 sinks and charcoal receptors placed at over 20 spring and river sources for dye trace analysis, and stable isotope samples were taken from 46 sources for further analysis. The exercises both reconfirmed historical connections from previous studies, and provided new insights to existing connections, providing further clarity of flow dynamics and delineating previously unknown hydrologic boundaries. This knowledge is important for water resources management, as the rising streams are major sources of water for irrigation, recreation, public water supply and other usage. The WRA continues to investigate other karstic basins via dye tracing and isotope hydrology studies.

Monitoring drip water in the karst critical zone: Insights from the Postojna–Planina Cave System

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The Karst Critical Zone (KCZ) differs significantly from more homogeneous and isotropic systems due to its specific characteristics, particularly the duality of flow and water infiltration. Karst systems are characterized by strong hydrological connectivity between the surface and subsurface; therefore, understanding and investigating their interactions is crucial. When monitoring water in caves, the high heterogeneity in the spatial distribution of drip locations and in flow velocities represents a major challenge. Consequently, measurement methods must be adapted to these specific conditions (Bonacci et al., 2009).

In the south-western Slovenia, above the Postojna-Planina Cave System, an integrated multi-scale ecohydrological monitoring network in the KCZ has been established. The monitoring network includes surface stations in forest measuring soil water content, soil temperature, precipitation, throughfall, solar radiation and wind, as well as cave stations measuring drip water (Ravbar et al., 2026). Based on initial results, several stations were subsequently adapted, and additional measurement stations installed. The current underground monitoring network consists of 12 measurement points, six in each cave. Due to differences in flow characteristics, different drip water monitoring approaches are used. Discharge is quantified either from drip frequency or from absolute pressure measurements of drip water collected in funnels. Measurements of drip frequency and absolute pressure are converted into discharge values using rating curves. Electrical conductivity and temperature of drip water are also measured. Measurements are performed automatically at 30-minute intervals, enabling the detection of rapid and intense changes within the karst aquifer.

Based on descriptive statistics, hydrograph analysis, correlation analysis, and generalized additive models (GAMs), we present the preliminary results on basic characteristics of drip water in Postojna-Planina Cave system.

Drips in Planina Cave are characterised by higher discharges, with mean values of several litres per minute (ranging from 0.13 l/min to 52.74 l/min), whereas in Postojna Cave the average drip discharge is only a few millilitres per minute (ranging from 2.83 mL/min to 63.19 mL/min). Pronounced discharge variability is observed at most drip sites, as indicated by large differences between mean and maximum discharges. In Planina cave the average coefficient of variation of drips is 370.08%. At some drip sites, for example drip N in Postojna Cave where the coefficient of variation is 8.49%, extreme values are less pronounced, resulting in more uniform discharge frequency distributions. The lowest mean discharges typically occur during summer, while the highest values are recorded in autumn.

Hydrograph analysis during precipitation events reveals highly variable drip responses. Drips in Planina Cave respond, on average, within 33.4 h after rainfall onset. Peak discharge occurs, on average, 9.1 h after the initial drip response. Maximum discharges often closely coincide with peak precipitation, and discharge returns relatively quickly to pre-event conditions. In contrast, drips in Postojna Cave generally respond more slowly, on average 52.36 h after rainfall onset. Elevated discharges persist for longer periods, and a return to antecedent conditions may take several days or even weeks. On average, the discharge response lasts 166.53 h.

Correlation analyses provide insight into general hydrological surface–subsurface interactions. Pearson correlation coefficients calculated for 30-minute and daily data between soil water content, precipitation, and discharge indicate very weak correlations. In Planina Cave, stations show moderate to strong positive correlations between mean weekly discharge and mean

weekly precipitation. In Postojna Cave, correlations between mean weekly discharge and mean weekly precipitation are weaker.

Generalized additive models (GAMs) were used to identify complex, nonlinear relationships between independent and dependent variables (Hastie and Tibshirani, 1986; McCullagh and Nelder, 2019). GAMs were applied to model (i) the influence of event precipitation totals on maximum drip discharge and (ii) the influence of average soil water content during rainfall events on maximum drip discharge. Analyses were conducted separately for the active vegetation period and the winter period. For the precipitation–discharge relationship, the best-performing model was obtained for the drip in Planina Cave, where higher precipitation totals lead to higher maximum drip discharges. At the drip station in Postojna Cave, soil water content is a good predictor of maximum discharge during the active vegetation period, while in winter it shows only moderate explanatory power.

Overall, the preliminary results indicate pronounced heterogeneity in drip discharge characteristics between Postojna and Planina Caves, as well as within each cave. In Planina Cave, a more direct hydrological connection between the surface and drip station is evident, with rainfall rapidly infiltrating into the aquifer. In Postojna Cave, preliminary results suggest that drip water is primarily supplied from the karst aquifer catchment area. Drip discharge is therefore probably strongly influenced by antecedent hydrological conditions, with the degree of aquifer saturation determining how quickly and intensely the system responds to precipitation events. Improvements to monitoring stations provide more accurate hydrological measurements, while the expanded monitoring network enables a more comprehensive understanding of the heterogeneity of drip water flow in karst systems.

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Karst porosity – From vugs to caves: Insights from Pleistocene carbonates of the Bahamas to pre-salt carbonates

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Karst systems play a critical role in the productivity of carbonate reservoirs, yet their complex geometry and scale-dependent behaviour pose significant challenges for subsurface characterisation. This study presents a multi-scale investigation of karst-related porosity in carbonate rocks from the Bahamas, with the aim of drawing analogies to the porosity distribution in Brazilian pre-salt reservoirs.

In pre-salt reservoirs, the highly karstified matrix presents significant challenges for direct sampling due to its low mechanical strength and disintegration of cores. Consequently, the use of outcrop analogues is essential for constraining the properties of comparable zones within the reservoir. Additionally, the representativeness of karst features interpreted from borehole data is inherently limited. Thus, a thorough understanding of the physical constraints and spatial dimensions of karst pore systems in analogue outcrops is fundamental for the accurate characterisation of these complex systems.

Using high-resolution microCT imaging and drone-based photogrammetry, we characterised mega- and gigapores in wall-rock samples from Bahamian caves and on carbonate pavements. The microCT results reveal diffuse vug networks in non-stratified grainstones, and well-connected vug porosity along the sedimentary strata in stratified grainstones. These features exhibit morphological similarities to karst structures observed in pre-salt borehole image logs, despite the geological and diagenetic differences between the two settings. Absolute permeability estimations using digital rock simulation also allows us to constrain the expected behaviour of similar zones within the reservoir.

Drone images from carbonate pavements, measuring approximately 20 meters x 70 meters and comparable in scale to geocellular modelling cells, were used to quantify porosity at the outcrop scale. The studied outcrop is in a zone where the epikarst zone is directly coupled with saline water lens. Quantitative analysis of these data revealed extra-matrix porosity values exceeding 21% in these pavements, and the field observations also indicate vertical penetration of the dissolutional process ranging from a few centimetres to at least 20 centimetres —parameters that cannot be obtained from seismic or borehole data.

The geological and petrophysical controls on gigapore and terapore distribution beyond the borehole scale remain one of the greatest limitations in karst modelling in the subsurface. Therefore, these findings may provide valuable parameters for modelling the spatial distribution and connectivity of large-scale pore systems in the pre-salt.

Assessing spring vulnerability in the Luxembourg Sandstones through real-time bacteriological data, fluorescence series and tracer tests

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A karstic spring in the Luxembourg sandstone formation near Luxembourg City was chosen to validate the use of bacteriological real-time monitoring as a tool for characterizing contamination events and evaluate future mitigation strategies. The spring is affected by recurrent intermittent bacteriological events, even after the rehabilitation of its water inflows several years ago. To better understand these intermittent pollution dynamics and trace their origin, automated on-site monitoring of microbial water quality was conducted between 2024 and 2026 using flow cytometry (BactoSense, bNovate) and enzymatic activity (ColiMinder, VWMS) that measure viable bacteria and a proxy of *E. coli*, respectively, in near real-time. In parallel, event sampling campaigns and laboratory analyses were carried out after rainfall episodes of various intensities and durations. Besides routine physicochemical online monitoring signals (turbidity, temperature, conductivity, discharge) fluorescence proxies were also acquired using several field fluorometers involving UV optical ranges, as well as multi-spectral laboratory analyses from selected grab samples. Tracer tests in sink and piezometer started to be implemented in 2025 to track more precisely the origin of microbial contaminations, as inferred from the previous understanding of the microbiological dynamics. Several preferential pathways were found, confirming conduit flows due to karstification of sandstones, thereby also providing a better understanding of bacteriological data. This study is a demonstration of the relevant complementarity of bacteriological, fluorescence and tracing techniques for assessing the immediate vulnerability of a spring, and allowing to plan better protection strategies of karstic drinking water resources. The study also strengthens the idea that more specific microbiological data could also help better targeting artificial tracer experiments for confirming pathways and short-cuts from the surface.

Evaluating the role of rainal variation and a dam reservoir on the resilience of Golabi Karst spring, Iran

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The Golabi Spring is a karst spring in the arid and semi-arid region of Iran, whose average discharge has increased from 500 l/s before to 1300 l/s after the impounding of the Rudbal Dam, which is located upstream of the spring and near the spring's catchment area. This study attempts to evaluate the role of the dam reservoir and changes in the rainfall pattern in the region (i.e., climate change) in the resilience of the discharge of this karst spring. The results reveal that the dam has not only caused changes in the hydrochemistry of the spring water, but also had a significant impact on the increase in the discharge of the Golabi Spring. The hydrograph of the spring elucidates that in natural conditions and before the construction of the dam, the spring discharge and its fluctuations were directly affected by the amount and aerial pattern of rainfall. In such conditions, after a period of heavy rainfall, water infiltration strengthened the spring discharge and discharge increased in a short time after rainfall. However, with the decrease or lack of rainfall, the spring discharge also faced a severe decrease due to the decrease in aquifer recharge. The results show that under natural climatic conditions, the spring discharge experienced severe fluctuations from a minimum of 80 to a maximum of 1000 l/s and was expected to be vulnerable to drought and climate change and have little resilience. However, after the construction of the dam and impounding in 2015, the pattern of spring discharge fluctuations underwent significant changes. Under these conditions, the spring discharge has shown fewer fluctuations and throughout the year, the spring discharge has been measured to be relatively more stable and constant, ranging between 1100 and 1500 l/s. Considering the huge volume of leakage from the Rudbal Dam reservoir, it seems that the Golabi Spring discharge has not decreased much as a result of receiving recharge from the dam reservoir even during periods of low rainfall. Therefore, the dependence of the spring discharge on the rainfall pattern has decreased. As a result, it can be stated that the construction of the dam has not only increased the spring discharge, stabilized the spring discharge, and reduced the fluctuations in the spring flow, but has also contributed increase its resilience to drought and climate change.

LEGO approach to karst conduit network simulation and prediction

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Karst conduit networks are difficult to model because only a small fraction can be directly mapped, yet network structure strongly controls flow and transport. Existing approaches either (i) generate plausible networks by mimicking key controls such as geology and hydraulic gradients (e.g., fast-marching and pseudo-genetic shortest-path methods) [1,2], or (ii) extend observed patterns using stochastic, structure-based simulation [3,4]. More recently, machine-learning models have been used to learn network patterns directly from mapped data and to generate multiple realistic alternatives [5].

We propose a “LEGO-like” way to combine these ideas. Instead of trying to create a full network in one step, we build it from small reusable pieces such as short segments, bends, and junction patterns taken from cave surveys and from fast simulation outputs. A network is then assembled by snapping these bricks together. Geological information guides where connections are plausible, while a data-driven scoring step favors assemblies that resemble real karst networks. This produces an ensemble of completed conduit networks that respects the known information (mapped segments, inlets/outlets) but differs in the unmapped regions.

The main outcome is a practical tool for generating karst conduit networks and predicting their geometry and connectivity. We will present the workflow, demonstrate it on a proof-of-concept case study, present the limitations of the model, and discuss how modular, repeatable building blocks can support reproducible karst modeling for hydrogeological prediction and field planning.

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Spectral graph invariants for the global characterization of karst conduit networks

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Quantitative characterization of karst conduit networks is fundamental for understanding speleogenetic processes, groundwater flow organization, and for validating numerical models of karst evolution. Graph-based approaches have proven particularly effective in this context, as they allow complex three-dimensional cave systems to be represented as networks of nodes and edges. A comprehensive statistical framework for describing karst geometry and topology was introduced by Collon et al. [1], who proposed a set of metrics derived from graph representations of cave surveys, including orientation entropy, branch length statistics, cyclomatic number, and average vertex degree. These metrics are now widely used to describe and compare natural and simulated karst networks. However, most of them are local or combinatorial in nature and only partially capture the global organization, connectivity structure, and functional redundancy of conduit networks.

In this contribution, we propose a complementary framework based on spectral graph theory, aimed at characterizing karst conduit networks through spectral graph invariants defined on various graph-associated metrics and operators. Spectral methods exploit eigenvalues of graph matrices to encode global structural information that cannot be reduced to local counts or shortest-path distances. Such approaches are well established in mathematics and network science and are closely connected to diffusion, transport, and robustness properties on discrete and metric graphs [2], yet they have not been systematically explored in karst geomorphology and hydrogeology.

Following the methodology of Collon et al. [1], we adopt reduced graph representations of karst systems, in which only junctions and extremities are retained as vertices and conduit branches are represented as edges. This reduction removes artifacts related to survey resolution while preserving the essential topology of the network. On these reduced graphs, we investigate families of spectral graph invariants derived from different graph operators, including the adjacency matrix, the combinatorial and normalized Laplacian matrices, and the Moore-Penrose pseudoinverse of the Laplacian. These operators induce distinct spectral metrics, each highlighting different aspects of network organization, connectivity, and transport behavior.

Within this unified spectral framework, we consider invariants related to low-lying eigenvalues, spectral distributions, and eigenvalue-based entropy measures, which provide global descriptors of connectivity robustness, structural heterogeneity, and network complexity. Spectral invariants derived from the adjacency matrix emphasize global connectivity patterns and clustering tendencies, while Laplacian-based spectra characterize how connectivity is distributed across the network. Normalized Laplacian spectra enable meaningful comparisons between karst systems of different sizes and degree distributions, an important feature when working with heterogeneous cave datasets.

Spectral invariants associated with the Laplacian pseudoinverse naturally lead to effective resistance-based measures, including the Kirchhoff index. Effective resistance integrates information from the full Laplacian spectrum and admits a direct physical interpretation in terms of transport efficiency and redundancy. Unlike shortest-path metrics, effective resistance accounts for all possible paths between nodes. In karst systems, low effective resistance is associated with highly interconnected, maze-like architectures offering multiple alternative flow routes, whereas high effective resistance reflects centralized or tree-like networks that concentrate flow along a limited number of conduits. Importantly, networks with similar cyclomatic numbers or average degrees may exhibit markedly different effective resistance values, revealing differences in global organization that are invisible to purely combinatorial metrics.

The proposed spectral invariants are applied to real karst networks previously analyzed using classical statistical descriptors. We compare spectral measures with established topological indicators such as cyclomatic number, connectivity degree, and central point dominance [1]. The results show that spectral graph invariants provide complementary and often more discriminating information about global network organization, redundancy, and transport potential. Beyond descriptive analysis, this spectral framework offers a natural interface with emerging stochastic and data-driven approaches for karst modeling, including recent deep generative models of discrete karst networks [3], by supplying physically meaningful global criteria for model evaluation and comparison.

Overall, this work demonstrates that spectral graph invariants defined on multiple graph metrics offer a powerful and interpretable extension to existing methods for karst network characterization. By integrating geometric, topological, and spectral perspectives within a unified graph-based framework, the proposed approach opens new avenues for comparing natural and simulated karst systems and for linking conduit network structure to groundwater transport processes.

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Noise of groundwater: An analysis of ambient seismic noise potential for detecting karst conduits

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Karst landscapes result from millennia of dissolution processes within carbonate rocks. Over time, these processes develop complex underground networks of conduits and chambers that govern subsurface water flow. Characterising these environments is crucial for groundwater management (for potable or energetic use), civil engineering projects such as tunnel excavation, and the mitigation of natural hazards related to local hydrogeology. Despite their importance, mapping karst networks remains challenging due to their inherent inaccessibility; direct exploration is often limited or impossible, requiring indirect methods to resolve their geometry.

This study proposes a surface-based approach for identifying karst conduits by analysing Ambient Seismic Noise (ASN). We hypothesise that: 1) groundwater flow within karst conduits generates measurable seismic responses at the surface through turbulence and falls; and 2) these signals can be used to locate the conduits.

To test these hypotheses, three controlled water releases (WR) were performed in the accessible Milandre cave system (Jura, CH). An underground waterfall—approximately 3 meters high and located at a depth of 60 meters—served as a source of noise of known position. By using a dam to temporarily block the natural groundwater flow and then instantly releasing the accumulated water head, we were able to identify the transition from a quiescent state to an active waterfall, generating a high level of noise for discrete intervals. The surface response was recorded by nine three-component geophones arranged in three clusters of three around the surface projection of the waterfall (see Figure 1). Spectral analysis revealed consistent and repeatable results across all trials: surface seismic activity significantly increases during waterfall activation, with energy primarily concentrated on the vertical component between 5 and 25 Hz. Particle motion analysis confirmed that, during WR, the wavefield is dominated by vibrations with an axis of motion orientated toward the underground conduit. Furthermore, array processing using beamforming demonstrated that the coherent portion of the signals exhibits back-azimuth and slowness values consistent with the waterfall's location and the medium's physical properties (see Figure 1). This suggests that triangulation is feasible for localising noise sources generated by water turbulence, provided the sensors maintain signal coherency. However, significant attenuation was observed at greater distances, likely due to the high heterogeneity of the medium (voids, fractures, and varying lithologies), particularly within the first meters of soil. Localisation based on amplitude decay supported this interpretation, correctly identifying the general conduit area despite inherent uncertainties in the exact waterfall position.

Building on these findings, we monitored an inaccessible section of the Areuse underground river upstream of its spring at Saint-Sulpice (Neuchâtel, CH). ASN was recorded at Bois de l'Halle, where groundwater from the La Brévine basin is hypothesised to cross the anticline at a depth of approximately 150 m before being rapidly transferred toward the spring through a well-developed conduit network. We deployed 25 geophones, including 21 sensors arranged in three hexagonal sub-arrays. The clusters were distributed across the study area to form an approximately 1 km long W–E–orientated line, based on the working hypothesis that the underground river conduit crosses the area approximately perpendicular to this orientation. All sensors were installed by direct burial in the soil; however, their upper ends remained partially exposed above the ground surface, resulting in not fully embedded sensor coupling. In particular, one cluster was deployed between boulders within a moss-covered deposit, whereas

others were installed on unconsolidated sediments dominated by fine-grained material, with varying thicknesses likely below 1 m in most cases, as well as on compacted ground near a trafficked road. Spectral analysis and Cross-Correlation Functions of the array data revealed a lack of inter-sensor coherence, likely reflecting strong seismic attenuation at this depth combined with heterogeneous site and coupling conditions.

Nevertheless, a single sensor in direct contact with the bedrock showed a strong correlation (Pearson coefficient up to 0.75 at 6.5 Hz) between spectral power and river discharge. This correlation was particularly high within the 3–15 Hz band, a spectral signature similar to the frequencies observed during the Milandre water release tests. This signal was interpreted as seismic energy generated by groundwater flow within the deep conduit. Its detection by this specific sensor was attributed to direct contact with the karstified rock, which allowed the signal to bypass the significant attenuation typical of loose surface soil.

Our results demonstrate that groundwater flow within karst conduits generates a seismic response measurable at the surface, with energy predominantly transmitted in the 3–25 Hz frequency range. While array analysis can provide valuable insights into the positioning of noise sources within karst networks, localising deep flows remains challenging when surface arrays are deployed on loose, unconsolidated soil. Nevertheless, seismic monitoring remains a viable and promising tool for karst exploration. Future surveys should prioritise installing sensors in direct contact with the bedrock to optimise seismic coupling and enhance the detection of ASN derived from subsurface karst dynamics. Finally, analyses should concentrate on the 3–25 Hz range, as this frequency interval demonstrates the strongest correlation with discharge.

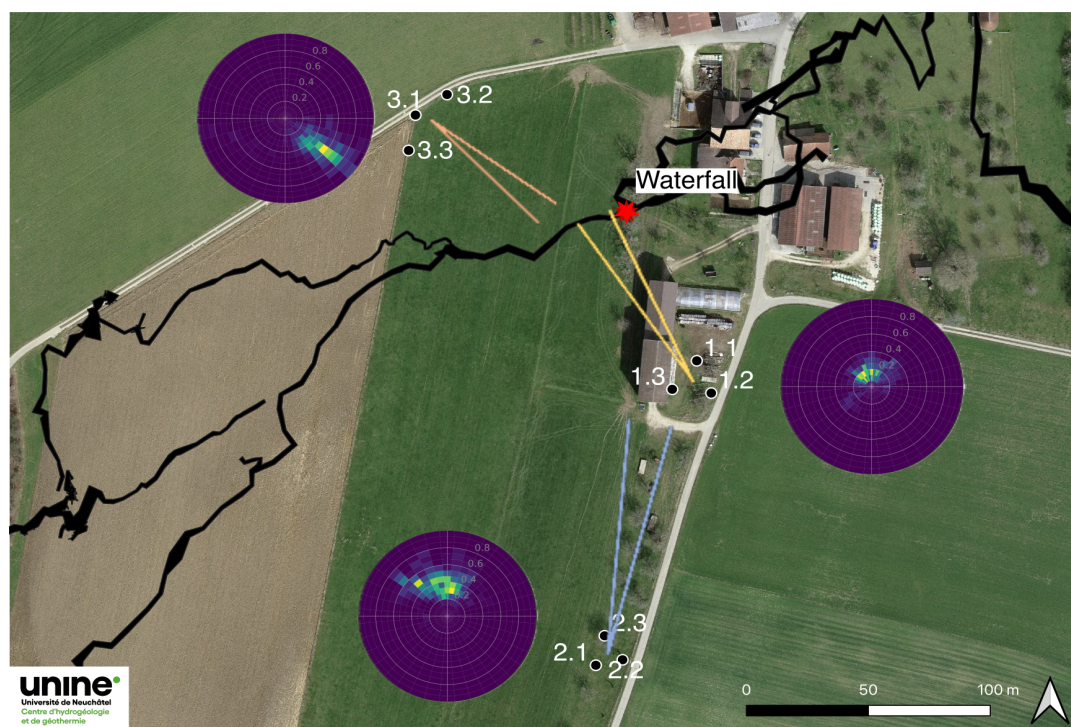


Figure 1. Beamforming results for the first Water Release (WR). The Milandre cave geometry is shown in black. The red star indicates the projected surface position of the underground waterfall. Deployed geophones are shown with black dots. Polar plots for the three geophone clusters represent the back-azimuth (direction of arrival) and slowness of the coherent wavefield. Slowness values range from 0 to 1 s/km (centre to perimeter), corresponding to apparent velocities > 1 km/s. The maximum energy peaks (indicated by coloured lines) align with the spatial position of the waterfall. These results were consistent and reproducible across all WR experiments and show that seismic energy from WR dominated the surface wavefield between 5–25 Hz.

Late Miocene Arctic climate variability recorded by speleothems from North Greenland

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Understanding the sensitivity of the Arctic climate system to past warm climates is essential for improving projections of future high-latitude change. The Miocene represents one of the most relevant geological analogues for near-future climate scenarios, with atmospheric CO₂ concentrations and global temperatures comparable to those projected under high-emissions pathways (Steinthorsdottir et al., 2021). However, terrestrial climate records from the High Arctic remain extremely scarce. Speleothems from caves in eastern North Greenland provide a rare archive capable of recording past environmental conditions during intervals when the region was substantially warmer and wetter than today.

Here we present geochemical and geochronological results from speleothems recovered from caves in eastern North Greenland (Moseley et al., 2020). These carbonate deposits formed during intervals of the Late Miocene when environmental conditions permitted active karst hydrology and cave dripwater infiltration. At present, the region is characterized by polar desert conditions and continuous permafrost, preventing speleothem growth. The presence of extensive speleothem deposits therefore indicates periods of substantially warmer and wetter climate in northern Greenland during the Miocene.

Absolute ages were determined using laser ablation U–Pb geochronology, which enables robust dating of speleothems beyond the temporal range accessible by U–Th techniques. High-resolution stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and trace element analyses were performed along speleothem growth axes to reconstruct Late Miocene environmental variability. Variations in speleothem $\delta^{18}\text{O}$ primarily reflect changes in the isotopic composition of meteoric precipitation and regional temperature, providing a sensitive indicator of Arctic hydroclimate variability. Complementary trace element records provide additional insights into karst hydrology and environmental change. In particular, siliciclastic-derived trace element enrichments capture periods of enhanced detrital input linked to glacial erosion and meltwater transport in the surrounding landscape. In addition, marine aerosol-derived sodium, normalized to detrital elements (Na/(Al+Ti)), provides a proxy for past sea-ice conditions, as sodium in eastern Greenland is largely sourced from sea-ice surfaces and associated marine aerosols. Together, these multi-proxy records allow reconstruction of coupled terrestrial climate, hydrological change, and Arctic sea-ice variability during the Late Miocene (Moseley et al., 2025).

The North Greenland speleothem archive therefore, represents one of the first terrestrial palaeoclimate records from the High Arctic spanning the Late Miocene. By providing direct evidence for significantly warmer and wetter Arctic conditions, these records offer important constraints on Arctic amplification during past greenhouse climates and provide a valuable benchmark for evaluating climate model simulations of future Arctic warming.

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Seawater intrusion in karst aquifers: From conceptual models to realistic scenarios and adaptive management

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Groundwater flow in karst aquifers exhibits distinct regimes that strongly depend on the degree of karstification. This behavior occurs in both inland and coastal environments, where interactions at the freshwater-seawater interface control upwelling and seawater intrusion. Consequently, realistic and optimized predictions require a robust conceptual model. This study establishes a quantitative link between monitoring data and fully density dependent numerical simulations, providing a validated framework, calibrated stress indicators, and operational head thresholds that constrain and justify the subsequent modelling efforts. To reach the goal, multiple complementary datasets were compiled alongside geological maps and borehole logs for the Salento peninsula, southern east Italy. The analysis integrates daily groundwater head records from seven sentinel piezometers, four annual hydrochemical surveys, and a reconstructed time series of pumping and recharge. Daily net recharge was derived from APLIS-based spatial estimates and adjusted for potential evapotranspiration (PET). Initial results reveal pronounced contrast in static head behavior across the domains. Coastal wells display broad, often bimodal head distributions, with recurrent values below sea level near the shoreline, whereas inland wells consistently remain above sea level. In the coastal domain, minimum hydraulic heads are strongly governed by pumping, while inland heads show limited sensitivity to abstraction. The water budget indicates cumulative outflows exceeding inflows, with closure deficits concentrated during periods of intensive pumping. Domain-averaged heads capture these sustained imbalances more clearly than short-term recharge fluctuations. Sensitivity analyses indicate that coastal salinity chemical indicators are primarily controlled by mean head conditions and pumping intensity, whereas inland salinity is largely governed by distance from the coastline and the structural setting. Finally, head-Cl confusion matrices and fitted head-Cl curves define quantitative thresholds, suggesting that maintaining coastal sentinel heads above 3–6 m a.s.l. is necessary to keep Cl concentration within 2,500–5,000 mg L⁻¹, providing operationally relevant management targets.

Quantifying karst aquifer recharge: integration of APLIS method and machine learning techniques

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Accurate assessment of karst groundwater resources using distributed model requires time resolved estimates of spatially distributed recharge, representing the fraction of precipitation that infiltrates and enters the system. Under semi-arid conditions, rainfall is treated as the dominant recharge source, because it represents most of the input and occurs through intermittent event-driven pulses. This contribution presents a leakage-free, physics-informed predictive framework that integrates effective recharge, rainfall, and groundwater-level dynamics to predict annual chloride concentrations and the probability of seawater-intrusion exceedance, with explicitly quantified uncertainty. This work focus on Salento Peninsula, emergent sector of the Apulian region, southeastern Italy. To achieve this goal, the APLIS method was used as a physics-guided prior, extracting both 00site point values and 250 m buffer averages to define the effective recharge. Predictors were aligned with each sampling date to avoid information leakage. Features encompassed multi-scale rainfall and antecedent indices, seasonal fractions, dry-spell duration, heavy-rainfall frequency, and groundwater-head metrics. Targets included annual chloride and a binary seawater-intrusion exceedance label. Ridge regression and gradient-boosted trees were evaluated using leave-one-year-out and band-blocked cross-validation, with uncertainty quantified via conformal/quantile intervals and calibrated exceedance probabilities. Recharge pattern exhibited strong spatiotemporal heterogeneity, with long-term autogenic recharge coefficients ranging from approximately 15% to 83% of precipitation. Temporally, recharge follows a Mediterranean regime, predominantly occurring during a limited number of high-intensity winter events, which may exceed about 120–130 mm per month, reflecting rapid infiltration through preferential flow pathways under wet antecedent conditions. Under cross-validation, the model accurately reproduces chloride concentrations. Predicted values closely match observations across low to moderate salinity ranges, while uncertainty increases at the highest chloride concentrations, as indicated by broader, but generally well-calibrated, 95% prediction intervals, consistent with data sparsity in the extreme upper tail. SHAP (Shapley Additive exPlanation) analysis reveals that electrical conductivity (EC) and total dissolved solids (TDS) are the primary positive contributors to chloride predictions, with bromide providing an additional signal associated with marine mixing. Overall bias is negligible, and increased dispersion is confined to highly saline samples, indicating limited extrapolative influence in that regime. Collectively, these results demonstrate a robust baseline emulator for chloride, with the integration of dynamic hydrologic drivers expected to enhance physical interpretability and reduce uncertainty at elevated chloride levels.

From processes to practice: Deciphering seawater intrusion in karst aquifers for prediction and mitigation

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Seawater intrusion (SWI) has emerged as a global crisis threatening coastal aquifers of at all scales and levels of socio-economic importance. Despite extensive research, a critical knowledge gap persists: the behavior of SWI in karst aquifers remains largely under-represented in both conceptual frameworks and predictive models. Most existing studies either overlook the distinctive hydrogeological characteristics of karst systems or rely on factors and methods that are poorly suited to their inherent heterogeneity of the karst environment. This work addresses that deficiency by explicitly examining seawater intrusion within coastal karst aquifers. This study, critically synthesizes synthesizing the evidence demonstrating that the intrinsic characteristics of karst aquifers constitute a fundamental control on seawater intrusion. Variability in both the degree and spatial extent of karstification among systems exerts a decisive influence on SWI mechanisms, thereby establishing karst development as a primary control. Nevertheless, seawater intrusion may also arise under the influence of secondary co-drivers, which modulate the system responses in the presence of changing environmental conditions and anthropogenic pressures. Conversely, these combined factors enable the systematic classification of seawater intrusion methodologies into two overarching domains: investigative approaches and predictive frameworks. The principal limitations of investigative methods lie in reliably distinguishing paleo-seawater intrusion from recent intrusion, and in resolving depth-dependent processes as well. However, integrating complementary investigative techniques can substantially reduce these uncertainties and help bridge existing knowledge gaps. In contrast, predictive methods are constrained by recurring shortcomings across approaches, including unclear applicability to specific karst typologies, inadequate quantification of uncertainty, and limited integration of heterogeneous data sources. Therefore, priority direction is therefore data–model fusion shifting practice from diagnosis to anticipatory management. Management strategies should be phased in accordance with the severity and diagnostic outcomes of seawater intrusion (SWI) assessment. As salinization advances, more intensive interventions such as hydraulic barriers may be implemented where vertical hydraulic control is feasible. Any such design must explicitly account for heterogeneous layering, barrier crest elevation, and the tailoring of geometry and tie-in depths to site-specific stratigraphy and permeability contrasts.

Perspective of trace element evolution during karstification: Experimental approach

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Experiments were conducted on limestone and dolomite of karst aquifers and different solutions (karst water, rainwater and DDW) to implement the karstification processes. This work tries to address two issues. First, Considering the carbonate dissolution and trace element (TE) evolution in recognizing the influence of different waters on karstification. The TE released from limestone are within the concentrations: Sr (0.2–46), V (0.01–0.83), As (0.01–0.45) and U (0.01–0.65), while those releases from dolomite aquifers are within the ranges of: Sr (0.4–207), V (0.02–2.8), As (0.05–2.7) and U (0.01–2.03) in ppb. The concentrations of TE released from karst water-derived dissolution are more than those released from rainwater-derived dissolution and DDW-derived dissolutions ($U_{\text{karst water-derived}} > U_{\text{rainwater-derived}} > U_{\text{DDW-derived}}$). Second, recognizing the impact of temperature, redox (Eh) and pH variations on release pattern of the TE during dissolution. Kendall correlation analysis was performed for the illustration of this impact. During limestone dissolution, the relation between temperature and release of Sr, V, As and U is mainly inverse and is not significant ($r^2 = 0.1-0.4$). The situation is totally inverse during dolomite dissolution, increasing of temperature is accompanied by increasing of TE and the relation is significant ($r^2 = 0.7-0.85$). In limestone dissolution, variation of Eh is directly proportional with TE and is not significant, except for As ($r^2 = 0.8$). V and As are increases in more oxidizing conditions in dolomite dissolution and U and Sr increases with less oxidized conditions. Generally, TE are releases in less oxidized conditions. Regarding control of pH on the experiments, concentration of Sr, V, As and U increases with the dissolution limestone and dolomite in the alkaline condition ($r^2 = 0.6-0.9$). Dissolution rate of limestone and dolomite are varied and it is not easy to decide which one is faster than the other taken in consideration the various conditions.

Paleoclimate record from the Yelini Cave, central Türkiye

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The stalagmite YL-1 from the Yelini Cave in central Türkiye records the paleoclimate archives of the Marine Isotope Stage (MIS) 5e/5d transition (ca. 130–74 ka). The deposition of the stalagmite started at 117.1 ka and stopped at 114.87 ka. The growth rate of YL-1 is ~0.10 mm/yr from the beginning then varied from 0.04 to 0.12 mm/yr that was greatly controlled by the effective moisture. $\delta^{18}\text{O}$ values of stalagmite YL-1 change from -12.84 to -10.56‰ (VPDB). The $\delta^{13}\text{C}$ values are in the range of -9.63 to -7.89‰ (VPDB). The Hendy Test applied to the YL-1 stalagmite indicated that the change in $\delta^{18}\text{O}$ values along a single lamina do not to exceed 0.5‰ . Therefore, it is suggested that CO_2 separation from dripping water was slow during stalagmite formation and isotopic equilibrium conditions were maintained. The increased or decreased intensity of winter precipitation is the most likely mechanism reflecting the variations in $\delta^{18}\text{O}_{\text{cc}}$ values of the YL-1 stalagmite. $\delta^{13}\text{C}_{\text{cc}}$ of YL-1 indicates C3-type vegetation similar to the other cave records from Anatolia. The modern vegetation is quite scarce at the studied cave site, but the carbon isotope profile of the YL-1 is associated with changes in effective winter precipitation. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the YL-1 stalagmite vary in a narrow range from 0.707946 to 0.707987 that are similar to the host carbonate rock (0.707851). Consequently, the contribution of terrestrial dust (0.7082–0.7086) input is thought to be limited. In the studied stalagmite, both Sr/Ca and Mg/Ca ratios tend to increase from the beginning of deposition up to 116.67 ka despite their low sampling resolution. Sr/Ca ratio attains its maxima at 116.67 ka, which might be related to the increased water residence times in the epikarst. The climatic changes recognized in the YL-1 stalagmite record during the MIS 5e/5d transition generally do not match with other regional records. The lack of a similar climate signal between the YL-1 stalagmite and the $\delta^{18}\text{O}$ record of the So-17A stalagmite from the Sofular Cave is due to Türkiye's northern mountains acting as a barrier, preventing moisture from reaching the inland regions of Türkiye via the Black Sea.

Will karstic flow from inception horizons be the key for the success of geothermal wells in Geneva?

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The «GEothermies» program is a large transversal program launched in 2013, driven by the Geneva State authorities and Industrial Services of Geneva (SIG) which is the Public Utility company. The goal of the program is to lead to a massive and sustainable development of geothermal energy, to substitute at least 20% of fossil energy use for heating purposes.

Since its initial stages, an important dataset has been continuously enriched by the acquisition of new geophysical and geological data (including exploration drilling) involving both academia and local private companies, all participating to precise the geothermal potential of the Geneva basin. In fall 2021, the Canton of Geneva and the Industrial Services of Geneva (SIG) carried out an important 3D seismic survey covering over 180 km² to explore the underground of the Geneva Basin.

In addition to the geophysical exploration, two exploration wells were drilled these last years: the well GGeo-01 at 760 m TVD and the well GGeo-02 at 1400 m TVD. A doublet is planned in autumn 2026 at 1200 m deep. The main targets are the faulted and karstified Cretaceous and Jurassic limestones. We know from the Thônex geothermal well, an ancient exploration well drilled in 1993 at 2600 m MD, as well as from recent GGeo-02 geothermal exploration well that these aquifer units can be hardly cemented and very poorly productive (low primary reservoir properties) away from faults and fractured zones.

The first exploration well GGeo-01 is successful. Artesian water flow of 50 l/s and 34°C is collected from the faulted, karstified lower Cretaceous units at various depths from 460 m to 670 m. The drilling operation in the limestone units was carried out with water circulation, no use of bentonitic mud. Continuous water flow rate measurement and pressure test were done on surface. By this way, we were able to localize from which level water inflows were coming (fig. 1). Moreover, a optic camera and logging pointed out large karstic features in the borehole (fig. 2).

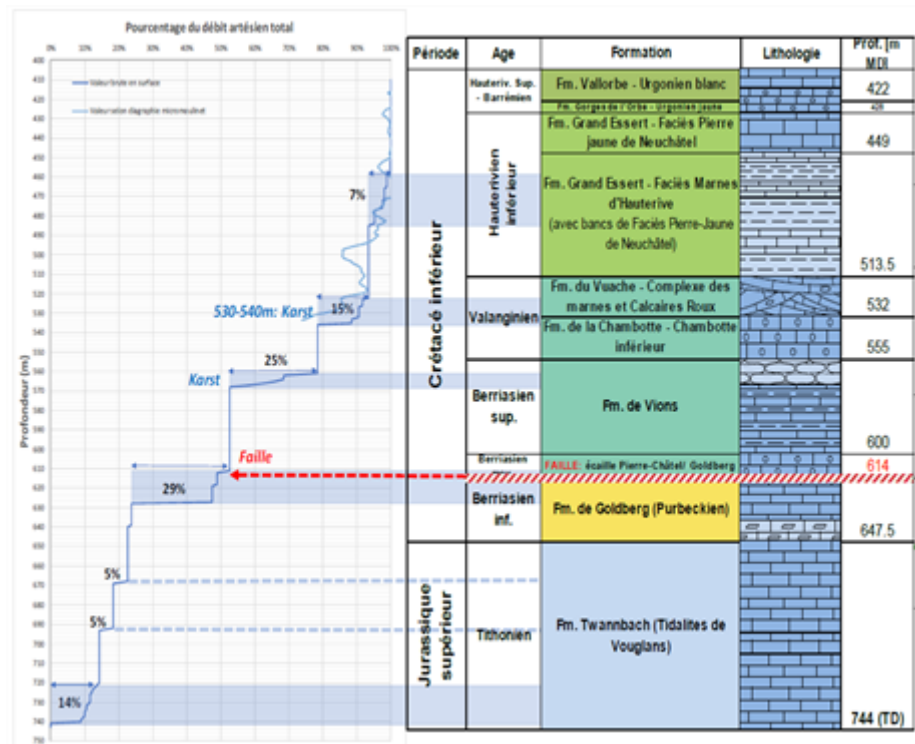


Figure 1. Locations and % of water inflows which are contributing to the total amount of 50 l/s flow rate for GEO-01.



Figure 2. Lateral pipe and rounded blocks at 540 m deep.

To have a clear understanding on the extension of the regional aquifer and its sustainability, hydraulic tests on artesian flow were done for 6 months. Hydrochemical and isotopic analyses, temperature, pressure, flow rate, turbidity were continuously monitored (HGE, 2023a). The well was completely open and the water was evacuated in the waste water pipe. Isotop analysis

of ^{14}C and ^{81}Kr give an average age of 8'000 to 16'000 and 14'000 to 35'000 years old (Guglielmetti et al. 2022).

In this framework, a large field study on the karstified Jura mountains was carried out by the company HGE. Caves and karstic conduits were mapped, with a particular focus on lithology, karstification factors and stratigraphy (fig. 3).

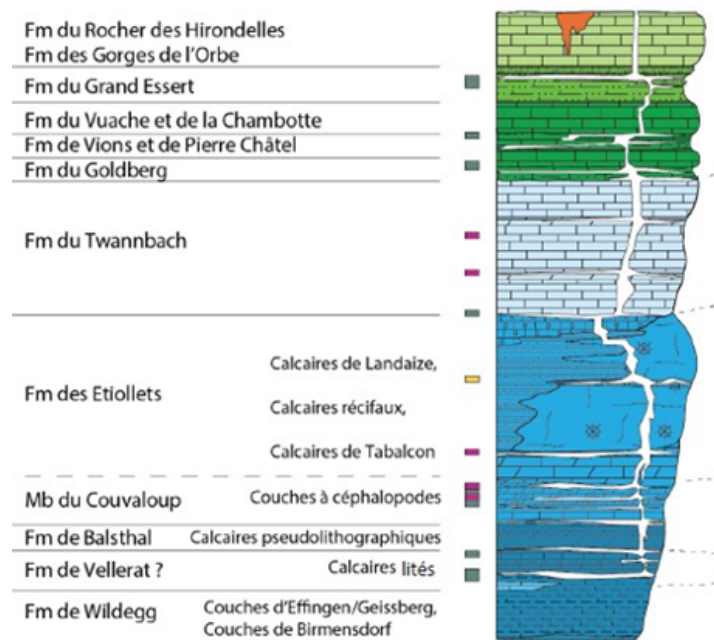


Figure 3. Stratigraphy of the Haut-Chaîne (Jura) near Geneva and location of inception horizons (from HGE, 2023b).

The main results is the strong link between major's inception horizons, karstic features focused horizontally (fig. 4), observed in the Jura Cretaceous and Upper Malm limestone and the productive layers in the GEO-01 well at the same stratigraphic and lithological level. Same observations were done in the Vinzel geothermal well nearby in the Vaud Canton.

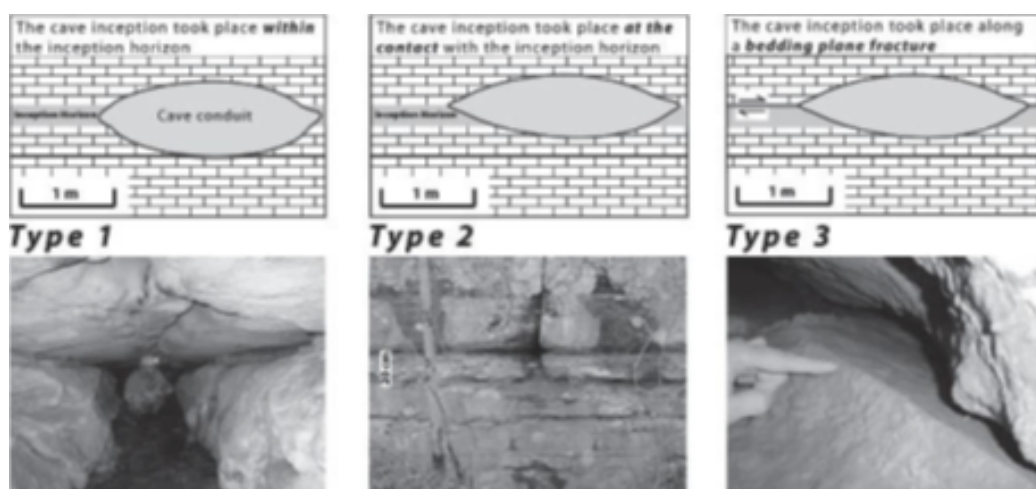


Figure 4. Three types of inception karstic caves (Filipponi et al, 2010).

Thanks to the 3D results, it is possible to map major fractured zones and their adjacent extended seismic degraded zone (SDZ) and some other seismic signature which seem to be related to some large karstic fractured system confirmed by the GGeo-01 well. Our next operations will be drilled in this geological context (fig. 5).

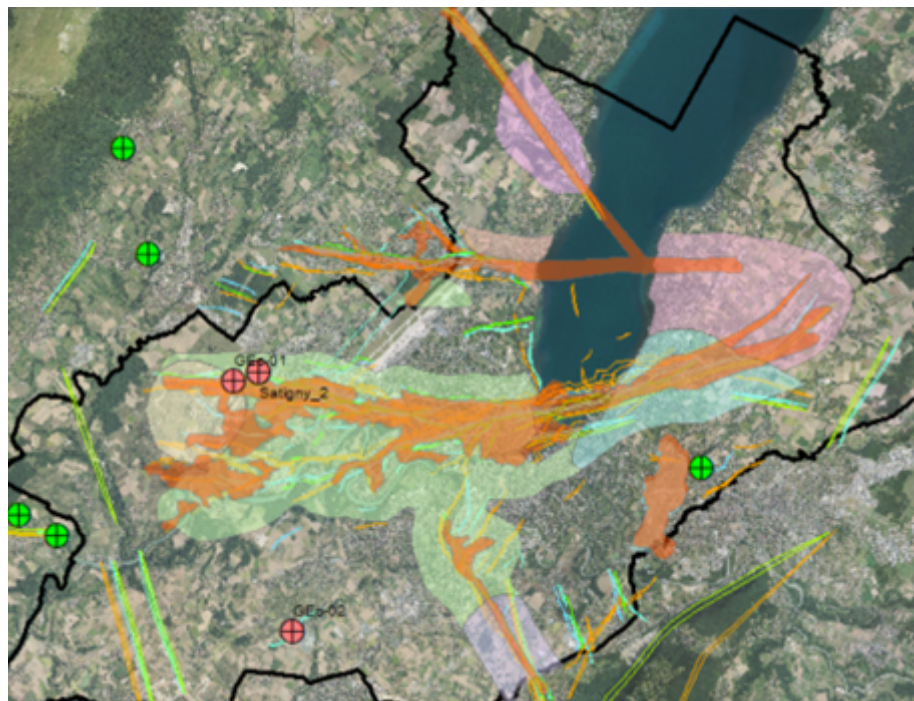


Figure 5. Intersection map between faulted Top Cretaceous and perimeter of district heating network development. The orange color surfaces indicate the presence of SDZ (seismic damage zone) or anisotropy and drive the research for drilling site locations. The productive well GGeo-01 is located on a main fault structure in contrary for GGeo -02 and Thônex. At the left angle of the image is the foothills of Jura Mountain and the right angle is the Salève Mountain.

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From detailed karst groundwater flow models to simplified coarse models: some flow up-scaling issues and methods relevant to karstic environments.

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It is now well known that global warming implies an increasing occurrence of extreme events such as floods and/or droughts. Such events significantly impact groundwater management, particularly in karstic areas. Understanding the response of aquifers to these events is of utmost importance for societal issues. However, past extreme events may be poorly documented, so routine numerical models of aquifers used on a day-to-day basis may not be relevant, as they are not trained on such anomalous data.

The aim of the ERC-funded KARST project is to build a modelling workflow that improves the accuracy of flow models in karst systems, even under extreme forcing conditions. The basic framework relies on a multiscale approach, starting from well-documented karst systems explored by cavers equipped with LiDAR systems, which provide accurate 3D maps of individual caves and, as much as possible, of entire conduit networks. Flow experiments carried out in the laboratory [1], together with CFD simulations on similar geometries, provide improved understanding of flow behaviour in conduits. Geostatistical approaches are then used to build explicit models of conduit networks that can account for missing data within a statistical framework.

The resulting large-scale flow simulations can be carried out using the OpenKARST tool [2], which was developed within the KARST project (<https://openkarst.org/>). Such modelling tools require powerful computing facilities, especially when flow in the porous matrix and surrounding fracture networks is also taken into account.

For practical purposes, it is necessary to build an appropriate proxy that captures the dominant features of the detailed model. Such a proxy may also be useful for estimating the intrinsic uncertainties, which mainly result from incomplete knowledge of the full karst system.

Flow upscaling techniques commonly used in subsurface flow modelling must be adapted to account for the extreme contrasts in flow behaviour occurring in karst systems, where Navier–Stokes-driven conduit flow is coupled with Darcy flow in the porous matrix. Most classical averaging or upscaling methods are irrelevant because they rely on small-perturbation assumptions around a base state, which are not acceptable in karstic environments [3,4]. Connectivity issues, which are fundamentally global properties of the system, therefore become dominant [5]. A promising framework is provided by graph-theoretical tools, which are well suited to capturing connectivity. The main idea is thus to develop methods to construct a coarse graph that captures the dominant flow paths of the system. This is the objective of the present contribution, which addresses several key questions: how can dominant flow paths be identified, and how can an effective coarse flow network be constructed to capture the essential patterns of the detailed network?

In present contribution, starting from the linear Darcean pressurized flow regime, the main approach is to study the eigenvalues/vectors of the Laplacian matrix that is built from the detailed model that represents the connections between vertices linked by edges (The conduits). An adapted k-means method permits to group the vertices independently on their numbering and geometrical proximity. Some methods are proposed to build effective conductivities that may be used in turn at the coarse scale. Randomness of the input data can also be accounted for. Similar works are to be carried out for tracer transport issues.

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The use of analogue modelling to simulate karstogenesis and karst network evolution

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Karst systems represent some of the most significant aquifer networks in the world, accounting for approximately 25% of the global water supply and serving as a critical resource for millions of people. Understanding the geometry of karst systems and the processes that shape their complex networks is essential for predicting groundwater flow and mitigating risks such as contamination and water scarcity. To capture the correct hydrodynamic functioning of karst, realistic representations of karst networks are required. Karst networks are in general represented and generated based on speleological field-map information, providing only information on large conduits (accessible to human-being), on stochastic simulation, or transport models simulating dissolution processes (Jourde et Wang, 2023). However, despite significant advances in numerical modelling, the inherent complexity of karst formation processes limits the ability of traditional models to fully capture the 3D nature and evolution of these systems. Thus, the geometrical representation of complex 3D karst networks is still a challenge.

Analogue modelling, which can produce experimentally complex structures that inherently comply with the mechanics and force equilibrium (Schellart and Strak, 2016), might be worth being explored to represent 3D realistic complex karst networks. Few attempts to simulate karst networks using experimental analogue modelling (Ewers's models, 1982) laid the foundation for experimental investigations. Using salt or plaster plates and water flowing on it, they were able to simulate 2D networks. Core flooding tests (Li et al. 2019, for example) are also used to reproduce rock matrix dissolution and the formation of wormholes. However, these “core flood” models are often dedicated to simulating the dissolution process at smaller scale and in a globally homogeneous media. They are not suitable to simulated large scale (km) karstic networks that interact with lithological facies variations or structural heterogeneities such as faults or fractures, and with different hydrological zones (recharge and discharge). Moreover, the flow regime is forced, and the flow occurs in a totally saturated medium, which is not often the case during the formation of natural karsts.

The objective of this work is to use analogue modelling to create physical experiments capturing the 3D nature and evolution of karst networks. For that purpose, a new experiment set-up has to be defined, incorporating a dissolvable material and a solvent. In order to record the 3D evolution of the experimental model, the experiments are going to be performed in a medical CT-scanner (Coletta et al., 1991). This already proven method offers the opportunity to follow the dynamics of the initiation and propagation of the karst network without being destructive to the model.

A first set of experiments have been conducted to test different materials. The chosen materials should present a good radiological contrast with the solvent (water in most of the cases) and with the created conduits. Materials such as hard caramel, gelatines, sodium polyacrylate or salt grains with different sticking agents have been tested.

The focus will be on two specific materials: salt grains mixed with wallpaper glue and salt grains mixed with cooking oil. Water dripping is poured on the materials in order to simulate water input in the system. These preliminary experiments demonstrate the ability to create conduits in both material, and mimic the dissolution of carbonate rocks (Figure 1). For both materials, the sticking agents (i.e. wallpaper glue or cooking oil) ensure the cohesion of the remaining salt grains. The drawback of the wallpaper glue is its loss of cohesion by forming kind of mud that plugs the pore spaces, when it is fully immersed. This prevents simulating the saturated zone. The cooking oil as sticking agent is thus preferred since the cohesion of the salt grains is maintained even when immersed. The use of cooking oil however requires warm water

to be poured in the model so that dissolution pattern can form. Some tests regarding the effect of water temperature, flow rate and initial porosity as well as the impact of existing structural heterogeneities will be presented.

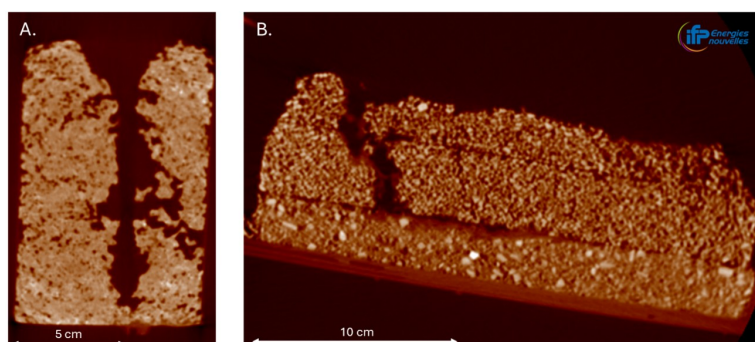


Figure 1. Examples of CT-scan images representing dissolution patterns obtained in A. a mixture of salt grains and wallpaper glue, and in B. a mixture of salt grains and cooking oil.

These preliminary experiments demonstrate the potential for analogue modelling to generate karst geometries, including branching conduits, collapsing caves, flow-path bifurcations, and their evolution through time. First results illustrate the role of preexisting heterogeneities and pores arrangement on karstogenesis, as well as the role of dissolution but also flow erosivity in enlarging the conduits. Further challenges remain to put to scale the obtained models and calibrate the process timing, in order to define the representativeness of the models (namely geometric, kinematic and dynamic similitudes). If representativeness is achieved, analogue models could help to understand the mechanisms and characterize the boundary conditions required for obtaining various kind of karst networks and contribute to improve the numerical simulations for realistic karst network generation.

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Un approccio multidisciplinare per comprendere un ambiente salmastro fragile: il caso studio della Palude del Capitano (Nardò, Puglia – SE Italia)

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La Penisola Salentina (Puglia, Italia sud-orientale) è un'area carsica caratterizzata da una topografia prevalentemente pianeggiante e da un'estesa linea costiera di circa 365 km, delimitata da due mari. La diffusa presenza di rocce carbonatiche solubili ha portato allo sviluppo di tipici paesaggi carsici, che rappresentano le caratteristiche geomorfologiche dominanti della regione. L'area presenta complessi assetti idrogeologici legati alla circolazione delle acque sotterranee e alla loro interazione con l'acqua di mare, inclusa la risalita di acque sulfuree profonde. Numerose zone umide hanno origine dal progressivo sviluppo e dalla coalescenza di molteplici doline, la cui evoluzione a lungo termine ha dato origine agli ambienti allagati attualmente osservati.

Lo studio e il monitoraggio delle doline carsiche costiere sono di primaria importanza, sia per ricostruire i processi responsabili della loro formazione, sia per valutare potenziali scenari futuri legati alla pericolosità geologica. Ciò è particolarmente rilevante nel contesto dello sviluppo antropico in corso e pianificato lungo le fasce costiere. L'area di Palude del Capitano, nel comune di Nardò, è tra i siti di maggiore interesse; comprende una laguna principale e oltre 50 doline, rappresentando un laboratorio naturale ideale per gli studi sul carsismo. Grazie alla sua facile accessibilità, il sito è stato al centro di diverse campagne di ricerca multidisciplinari: indagini disciplinari, tra cui analisi chimiche e biologiche, mappatura geomorfologica, caratterizzazione morfometrica dei sinkhole e identificazione delle connessioni idriche sotterranee tra le principali aree allagate e il Mar Ionio. Il presente studio affronta specificamente quest'ultimo aspetto.

È stata condotta una campagna di campagna dedicata per caratterizzare il quadro idrogeologico della Palude del Capitano: gli sbocchi di acqua dolce sottomarini e costieri sono stati inizialmente identificati utilizzando un drone (UAV) dotato di termocamera. Le acque scaricate da queste sorgenti presentano una temperatura pressoché costante di circa 20 °C durante tutto l'anno, indipendentemente dalle variazioni stagionali delle precipitazioni, mentre le temperature dell'acqua di mare durante il periodo di indagine variavano tra 12 e 14 °C. Questo marcato contrasto termico ha permesso di individuare chiaramente i principali punti di scarico lungo la costa. Sono stati identificati tre sbocchi principali (denominati S1, S2 e S3), tutti con scarico in prossimità della baia nota come Spiaggia del Frascione.

Sono state effettuate prove con traccianti per verificare le connessioni idrauliche tra la laguna principale di Palude del Capitano e le sorgenti costiere identificate. In particolare, in condizioni di bassa marea, è stata iniettata sulforodamina B nel condotto di efflusso della laguna. Sono stati selezionati nove punti di monitoraggio in corrispondenza di sorgenti e condotti carsici accessibili tramite doline. Due di questi siti sono stati monitorati in continuo utilizzando uno spettrofluorimetro GGUN-FL24, con un intervallo di campionamento di 5 minuti, mentre i restanti punti sono stati monitorati tramite campionamento manuale a intervalli di 30-45 minuti.

Il tracciante è stato rilevato per la prima volta sulla costa circa un'ora dopo l'iniezione, indicando un rapido flusso di acque sotterranee verso il mare. Il colorante è emerso inizialmente nella baia del Frascione (sorgenti S1) con una concentrazione dell'ordine di alcune centinaia di ppb e, un'ora dopo, dalla sorgente S3 con una concentrazione massima di 28 ppb. Lo scarico simultaneo da più uscite ha determinato la colorazione visibile dell'intero settore orientale della baia adiacente alla Baia del Frascione.

Un secondo esperimento con tracciante è stato condotto per valutare la connettività idraulica tra la voragine più interna (a circa 800 m dalla linea di costa), il sistema della Palude del Capitano e le sorgenti costiere. In questo caso, la fluoresceina sodica è stata iniettata nel condotto emissario della voragine, mentre ai punti di monitoraggio è stata aggiunta una stazione in prossimità della sorgente della Palude del Capitano. Tutti i punti sono stati rilevati utilizzando strumentazione e protocolli di campionamento identici. Il tracciante ha raggiunto la laguna della Palude del Capitano dopo 3 ore e 41 minuti, corrispondenti a una velocità apparente di flusso della falda freatica di circa 100 m h^{-1} . Le concentrazioni massime del tracciante all'interno della laguna (92 ppb) sono state registrate poco più di 7 ore dopo l'iniezione. Dopo la diluizione e la miscelazione nelle acque lagunari, il tracciante ha continuato il suo percorso verso la linea di costa ed è stato rilevato alla sorgente S1 dopo un tempo di percorrenza totale di 7 ore e 38 minuti e alla sorgente S3 alcuni minuti dopo.

Come ulteriore tecnica di indagine, è stata condotta un'indagine geofisica per testare l'applicabilità della tecnica elettromagnetica multifrequenza utilizzando uno strumento Geophex GEM2. Le mappe di conducibilità risultanti rivelano zone con valori di ECa elevati, interpretati come condotti sotterranei influenzati dalla presenza di acqua salmastra o salina, coerenti con percorsi di interazione attiva tra acqua di falda e acqua di mare.

Modelling of drip water $\delta^{18}\text{O}$ compositions across the karstic caves under different climatic patterns and hydrological conditions

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Understanding how the isotopic signature of precipitation evolves as infiltrating through the soil and epikarst to become cave drip water is crucial for accurately interpreting the paleoclimate information stored in speleothems. But the journey of water from precipitation to cave drip is complex, as it involves various flow paths and mixing processes that can alter the drip water isotopic compositions. For that reason, (robust) models are often needed to decipher the intricate relationship between surface climate and the isotopic signals recorded in cave drip waters, and thus speleothems. However, limited research explicitly focuses on the role of epikarst hydrology and (solute) mixing characteristics across the epikarst, particularly at global scale. There is, therefore, a need for comprehensive knowledge integration with the reliable model applications to identify the role of epikarst hydrology.

In this study, we developed a modelling framework to simulate drip water hydrodynamics and corresponding $\delta^{18}\text{O}$ compositions by adapting the global karst recharge model (the V2Karst model) to incorporate drip-specific source apportionment. By coupling this model with the StorAge Selection (SAS) function, we characterized age-selective mixing and transport processes of water from soil and epikarst storages to drip locations. This approach allows for the simulation of different flow pathways and subsequent modification of meteoric precipitation $\delta^{18}\text{O}$ values during its travel through the soil-epikarst system.

By applying the integrated methodology into six cave sites under different climatic and hydrological conditions, we test the model in (reasonably) simulating drip water hydrology, and its isotopic compositions based on their site-specific conditions. We then identify the consistent patterns and regional differences in the factors that control drip water isotopes. While the approach still requires better estimates for the model parametrization, our modelling framework allows for a more comprehensive understanding of the flow and transport pathways, as well as storage dynamics across the epikarst and their influence on the isotopic composition of drip water. From this perspective, there is an opportunity to enhance our understanding of cave drip hydrology and mixing processes at cave sites, which will help to test and develop more robust interpretations of speleothem $\delta^{18}\text{O}$ records, ultimately improving our ability to predict the impacts of future climate change on karst water resources.

ERT and interpretable machine learning integrated prediction of karst soil and epikarst thickness in a peak cluster-valley catchment, Southwest China

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The soil weathering rate of karst carbonate rocks is very low, resulting in scarce and thin soil layers. Under the subtropical monsoon climate, a well-developed epikarst zone is formed in the upper part of the vadose zone, with abundant fractures and pores filled with soil. The karst hillslopes surface bedrock is exposed, forming a mosaic soil landscape with soil. However, traditional profile surveys make it difficult to quantitatively determine the spatial distribution of soil and the epikarst zone with high precision; additionally, complex lithological conditions and strong spatial heterogeneity of carbonate rocks further limit the accurate quantification of soil thickness (ST) and epikarst thickness (EkT).

Therefore, this study investigated the soil-epikarst structures and their spatial distribution at different topographic locations (including different hillslope positions, ridges, saddles, and valleys) using Electrical Resistivity Tomography (ERT, 5268 sampling points) in a peak cluster-valley catchment in Southwest China. Furthermore, an interpretation method was established, where the application of revised inflexion points in 1D resistivity vertical profiles for improving ST and EkT characterization accuracy was assessed, with interpretations validated against borehole data.

Results showed that between hillslopes, the average ST ranges from 0.42 to 0.52 m, and the average EkT ranges from 3.38 to 4.58 m. The average ST in the valley (3.23 m) is significantly greater than that on hillslopes (0.49 m). Although there are some scattered, fragmented areas with EkT exceeding 20 m in the valley, both the average and median EkT in the valley (3.77 m and 2.98 m) are slightly smaller than those on hillslopes (3.93 m and 3.63 m).

This study integrated high-density ERT observations with a 1-m UAV LiDAR DEM and interpretable machine learning to predict karst soil and epikarst thickness. Important topographic controlling factors were screened out by machine learning, including those affecting ST (i.e., slope position (SP), relative elevation (RElev), slope gradient (S), slope roughness (SR), hillslope shape (HS), slope aspect (SOS), profile curvature (PrC)) and those affecting EkT (i.e., plan curvature (PLC), profile curvature (PrC), flow length (FLU), flow direction (FLD), aspect (A), relative elevation (RELE)).

Moreover, machine learning has made it possible to predict the spatial distribution of soil and the epikarst zone in the catchment with high precision, thereby providing structural information for studies such as soil erosion investigation, hydrological models, and material transport in porous media.

Keywords: karst, epikarst zone, soil thickness (ST), epikarst thickness (EkT), electrical resistivity tomography (ERT), machine learning, Southwest China

Assessing the thermal impact of show-cave visitors on non-visited passages

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Side passages in show caves may be exempt from the direct influence of tourist visits. However, heat emitted by visitors can still be transported into these passages and stored in the surrounding cave walls. We study the heat budget in Brezimeni Rov which is a side passage of Postojnska Jama, Slovenia. This passage is a major ventilation pathway connecting the cave with the surface above. The study is based on a time series of airflow velocity and temperature measurements in a segment of the passage, as well as on a numerical model that combines airflow, advective heat transfer within the passage, heat exchange between air and cave walls, and heat conduction in the surrounding rock. To assess the influence of tourism, we compare results from periods when the cave was closed to visitors due to the COVID-19 pandemic with periods before and after the COVID crisis.

Visits of Postojna Cave consists of a train ride along Stara Jama passage, marked with a dotted blue line in Fig. 1, and a pedestrian visits throughout the main touristic part marked with a red line in the same figure, while Brezimeni Rov is inside a dotted box. Tourism affects the heat balance through the energy inputs of human metabolism and lighting, which are more intense in the main touristic part visited on foot than in the passages traversed by train. Effects are proportional to the number of visitors, which is higher during the summer months. Dominant airflow direction during summer is from Brezimeni Rov and from the main touristic part through Stara Jama toward the cave entrance, marked Ω in Fig. 1, opposite in winter. Air current in Brezimeni Rov is stronger in winter than in the summer.

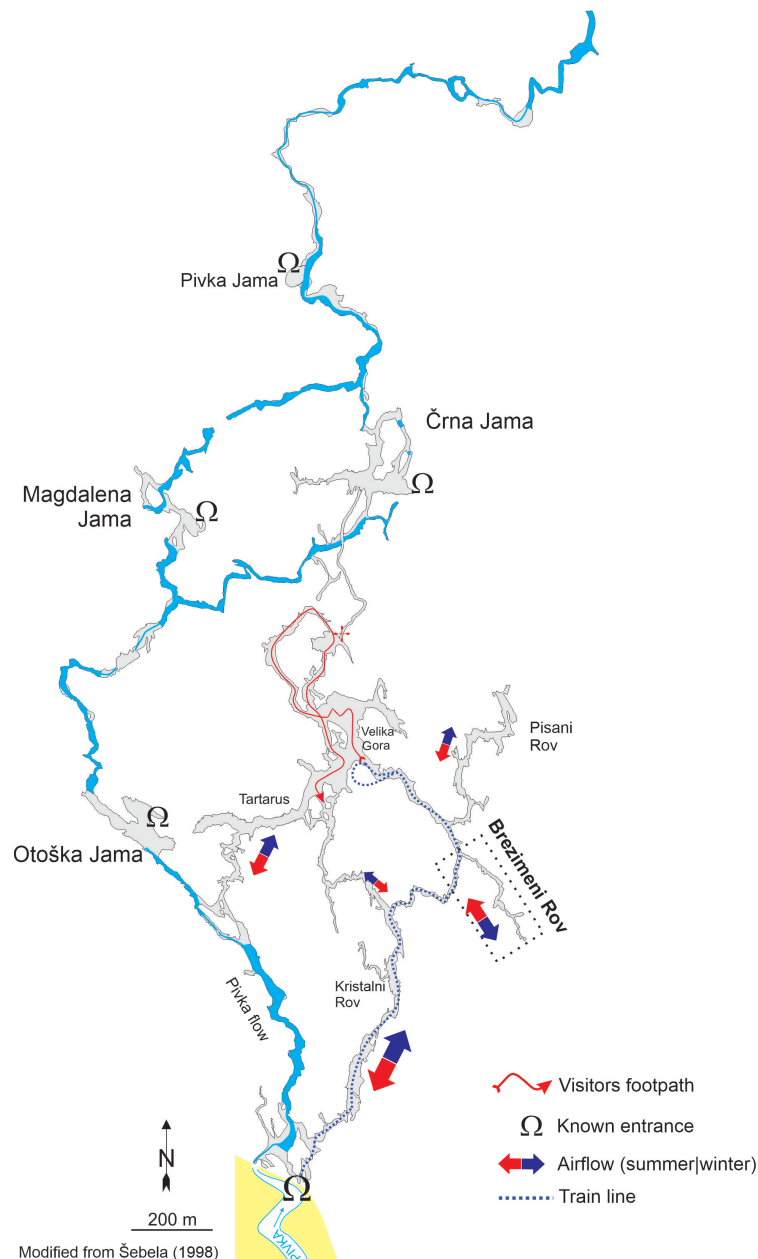


Figure 1. Map of Postojna Cave. Tourist railway, tourist footpath, Brezimeni rov passage, typical ventilation direction, and cave entrance are marked.

Based on the position and airflow directions of the passage, one would expect thermal influence of tourism on Brezimeni Rov to be small, and not observable by standard temperature monitoring. During summer ventilation regime, air from the touristic parts of the cave does not enter the passage at all. In winter, the air entering Brezimeni Rov encounters the passage along the train tracks but not the main touristic part of the cave, therefore being exposed to a minor part of the influence of a relatively small number of tourists.

However, the observations show that during absence of tourism due to COVID in 2020, the temperature in Brezimeni Rov decreased significantly (Fig. 2), demonstrating that it indeed is influenced by tourism to an important amount. This leads us to two conclusions regarding heat in caves on yearly timescales:

- Heat efficiently spreads along cave passages on long distances. The lights and the part of the railway closest to the measurement station are 200 m away from the station along

the passage, while the main touristic part is 600 m away. The heat causing the observed temperature change must have traversed these distances.

- Heat in caves can be efficiently stored and released. Summer temperature in Brezimeni Rov during the COVID crisis is lowered relative to the usual summers, even though the air introduced by summer airflow is unaffected by tourism. The effect of tourism on summer temperatures thus requires storing the heat across seasons.

We propose the following hypothesis: heat generated in the central part of the cave, where tourists spend most of their time, is advectively transported toward the main entrance during summer, with part of this heat being stored in the cave walls along the transport pathway. During winter, when airflow reverses direction, part of the stored heat is transferred back to the air, which exits to the surface via Brezimeni rov. Consequently, the air entering Brezimeni rov in winter is warmer following summers with higher tourist visitation.

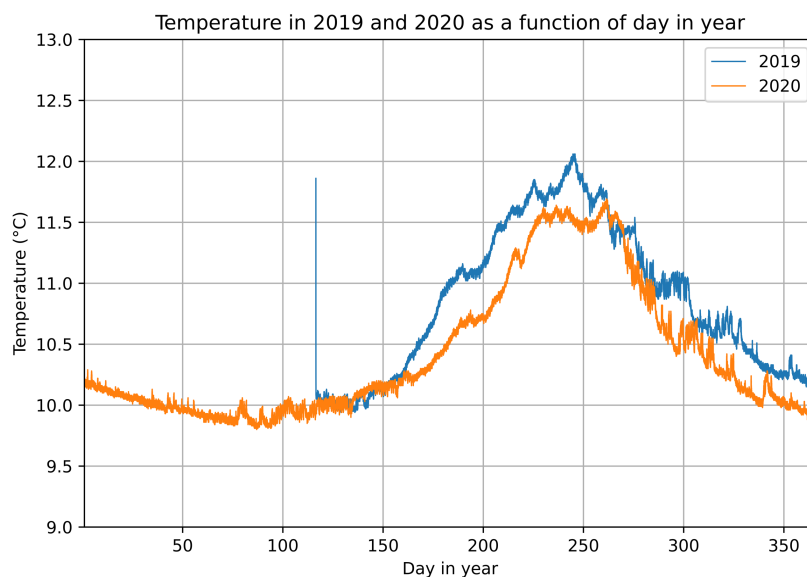


Figure 2. Temperature throughout the year at the station in Brezimeni Rov passage for 2019 and 2020.

The demonstrated ability of heat to efficiently travel along caves over long distances requires the heat not to be lost from caves into the rock massif. We explore heat transport along Brezimeni Rov with a numerical model that combines airflow, advective heat transfer within the passage, heat exchange between air and cave walls, and heat conduction in the surrounding rock, and is constrained by temperature and air current measurements. The match between the model result and the measured temperatures is good, it improves when the passage geometry is resolved better, and the values of the fitted model parameters are reasonable. This indicates that the heat is governed by the processes included in the model.

An intriguing question is, where does the heat liberated from tourists in Postojnska Jama travel, and where and when does it leave the system (or generally, where does heat introduced into a cave end up after a certain time). We demonstrate that conduction through the rock, advection by fluids such as air, and exchange between the phases all have an important influence. There is a fundamental difference between conduction and advection though. When two points are coupled by conduction, they affect each other symmetrically, a heat source at either one would affect the other. In contrast, advection works in the direction of the current – an upstream point affects the downstream points but is not affected by them. As a consequence, defining the heat flow as a result of advection comes with additional challenges compared to conduction.

Coupling stochastic conduit generation with flow and transport models to assess observational constraints on karst conduit inverse problems

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One central objective of hydrogeological modelling is to propose probable reconstructions of the groundwater flow field in space and time for a given aquifer [Kiraly 2003]. These rely on geological and structural information, sparse field observations and hydrological tests, and therefore often confront non-unique and underconstrained inverse problems, especially in karstic contexts.

Here, we ask how different types and combinations of field observations constrain ensembles of plausible karst conduit configurations generated from geological and structural attractors. Using a synthetic-data framework on a known system, surveyed conduit geometry provides a reference to evaluate which observations are sufficient to meaningfully reduce structural and hydraulic uncertainty.

In karstic aquifers, flow is commonly conceptualized as high-permeability conduits embedded within a low-permeability matrix. In the absence of speleological and diving surveys, conduits cannot be uniquely identified and are therefore represented as ensembles of plausible configurations.

Stochastic conduit generators can rapidly simulate plausible networks from anisotropic least-cost rules, applied to 2D or 3D maps of attractors [Borghiet al. 2012, Fandel et al. 2020, Gouyet al. 2024, Miville et al. 2025]. Such networks can then be used in flow and transport simulations. Because our main objective is to compare the information content of conduit-dominated observations (in particular tracer time scales and event-scale dynamics), we focus on Discrete Conduit Network (DCN) models [Rossman et al. 2010, Kordilla et al. 2025].

Previous studies have coupled stochastic conduit generation with flow and transport models to investigate parameter sensitivity in synthetic experiments [Borghiet al. 2016], estimate discharge uncertainty on the Gottesacker alpine karst system [Fandel et al. 2020], and rank geometries using a trial and error method on tracer data on the Baget pyrenean karst system [Sivellev et al. 2020]. Rather than assessing whether a given parameter set can be retrieved, we compare how different observation types condition the space of plausible conduit configurations and parameter combinations.

We apply this framework to the Lirou, a kilometer-scale overflow system of the Lez watershed (southern France), where surveyed conduit geometry provides a reference for evaluating observational constraints.

Structural and hydraulic parameters are sampled using space-filling designs to explore a broad uncertainty range. Conduit ensembles are generated using stochastic generation based on fixed boundary conditions (inlets, outlets) and geological or structural attractors (faults, stratigraphic or topographic gradients), using a stochastic fracture generation model derived from fault-related fracture statistics [Boura et al. 2025]. Generated conduit networks are then used as inputs for flow and transport simulations.

For each synthetic experiment, subsets of field-like observations (discharge, piezometry, conduit head, breakthrough tracer curves) are extracted and used to constrain model ensembles through statistical comparison. We investigate how combinations of observations constrain conduit ensembles and which data types most effectively reduce structural and hydraulic uncertainty.

Results will be interpreted in light of the relative weight of structural priors versus hydrological observations in shaping the conduit ensemble, viewing inverse solutions as conditioned ensembles rather than optimal models, with particular attention to parameter compensation and equifinality. The availability of long-term hydraulic and tracer data on the Lirou system enables initial comparison between synthetic experiments and real-world observations, and the framework is designed to be transferable to other instrumented karstic systems (Baget, Cents-Fonts, etc.).

This work provides a framework to compare the information content of commonly collected karst observations, framing conduit inverse problems in terms of information gain and ensemble conditioning, and offering a transferable methodology for instrumented karst systems where direct conduit surveys are unavailable.

The response of the karst hydrosystems of the Jura Mountains to climate change: an integrated water - carbon approach

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In the context of the increasing impacts of climate change on the socio-ecosystems of the Jura Mountains, karst hydrosystems play a pivotal role within the Critical Zone. Beyond their importance as a regional water resource, they may also contribute to the sequestration of atmospheric and soil CO₂ through limestone dissolution (Gaillardet et al., 2018; Fig. 1).

Hence, and in light of ongoing and projected hydroclimatic changes (Fig. 2), this project aims to quantify water and carbon fluxes across multiple timescales at four sites in the Jura Mountains: three karst sites belonging to the French SNO Karst network and one peatland site from the SNO Peatlands network, located above a karst aquifer. These sites are distributed along an altitudinal gradient and are therefore representative of the diversity of karst environments across the Jura Mountains. The specific objectives are to develop rainfall–discharge models for all sites and to identify the mechanisms controlling inorganic carbon concentrations and fluxes, in order to model their future evolution under projected climate scenarios.

The future development of karst hydrosystems in the Jura Mountains is likely to be governed by two main groups of mechanisms: (i) a temperature-induced increase in microbial activity within the infiltration zone, leading to higher soil CO₂ concentrations and enhanced karstification intensity; and (ii) a seasonal redistribution of water discharge, with decreasing summer flows and increasing winter flows, thereby modifying the temporal patterns of karstification.

To evaluate these hypotheses, we are currently analyzing concentrations and fluxes of dissolved inorganic carbon (DIC, estimated from electrical conductivity) together with water discharge data that have been monitored continuously since 2014 at a 30-minute time step. These data will be compared with a range of hydrological and meteorological variables to identify pluriannual, seasonal, and event-scale trends using statistical and machine-learning approaches. Combined with projected climate simulations (Climate Model Intercomparison Project and/or DRIAS-Eau), this dataset will ultimately be used to derive future trajectories of water and carbon fluxes up to 2100, and to explore their potential generalization at the scale of the mountain range.

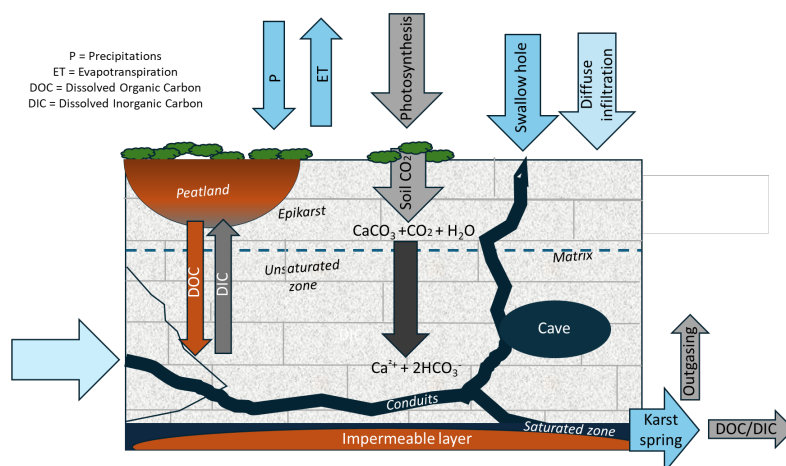


Figure 1. Conceptual representation of water and carbon fluxes in karst hydrosystems of the Jura mountains, including conduit and matrix flow and surface hydroecosystems such as peatlands.

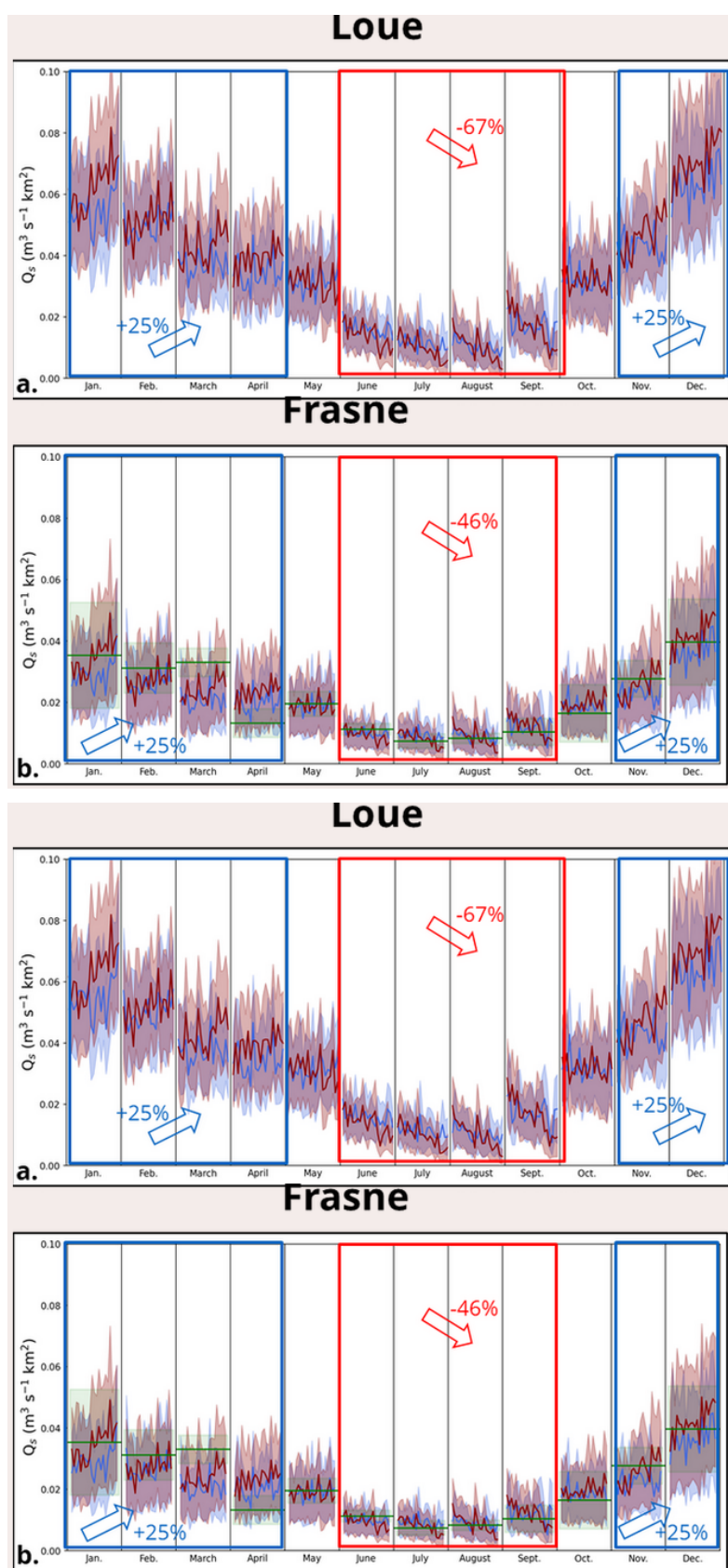


Figure 2. Example of projected discharge simulations based on precipitation data from CMIP climate models for a karst hydrosystem (the Loue river at Vuillafans) and a karst-fed hydroecosystem (the Frasne peatland) over the period 2020-2100.

Contrasting behavior of Eastern Asian and Mediterranean karst aquifers revealed through a unified, physically based recession model

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Karst aquifers supply drinking water to hundreds of millions of people but remain among the least understood freshwater systems, due to their strongly heterogeneous conduit–matrix structure. Spring recession analysis is widely used to infer karst storage dynamics. Yet, most existing models either treat different parts of the hydrograph separately or rely on empirical formulations with limited physical interpretability.

Here we derive a unified analytical model for karst spring recession by combining turbulent conduit flow, represented by a Forchheimer-type relationship, with linear drainage from a porous matrix. The resulting governing equation:

$$dQ/dt = -\alpha Q^n + \gamma e^{-\lambda t} \text{ (Equation 1)}$$

simultaneously describes nonlinear conduit depletion and delayed conduit–matrix exchange. The parameters (α , n , γ , λ) are directly linked to aquifer properties, reflecting conduit drainage efficiency, flow nonlinearity, and the magnitude and timescale of matrix drainage. We apply the model to hourly discharge records (2013–2023) from climatically and geologically contrasting karst systems in monsoon-influenced southwest China and Mediterranean central Italy. Event-based calibration shows that the unified recession model reproduces complete recession limbs and consistently outperforms a classical dual-reservoir benchmark. Beyond goodness of fit, the inferred parameter patterns reveal systematic regional contrasts: the Chinese spring exhibits higher nonlinear exponents ($n = 2$) and larger α , indicating strongly turbulent, conduit-dominated drainage with short memory, whereas the Italian spring is characterised by $n = 1$, smaller α and negligible γ , consistent with large, slowly draining matrix storage. Mapping events in the (n , $S = \gamma/\lambda$) parameter space delineates distinct functional regimes of karst aquifers that can be related to differences in drought resilience and baseflow support. The unified recession model thus provides a diagnostic tool for inferring karst aquifer functioning from discharge data alone, supporting water resource assessment and climate impact studies in data-scarce regions.

Large-scale evidence of microbially-mediated carbonate dissolution across different aquifers

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Introduction

The relationships between groundwater chemistry and microbial functioning in aquifers remain poorly understood, as do the reciprocal interactions between groundwater pollution and microbial activity. In this study, we investigated more than 60 groundwater sites in central and southern Italy, integrating geochemical, isotopic, and microbiological data to identify key biogeochemical processes controlling water–rock interactions.

Study area and methods

The main study area is the Sacco River Valley (central Italy), which hosts multiple hydrogeological complexes, including Quaternary alluvial deposits, Pleistocene volcanic products and travertines, Miocene flysch sequences, and Meso–Cenozoic carbonate formations.

Groundwater samples were collected from wells and springs between November 2024 and December 2025, together with in situ measurements of physical and chemical parameters (Cisternino et al., 2026; Preziosi et al., 2026). Laboratory analyses included major ions, trace elements, dissolved organic carbon (DOC), and stable isotopes ($\delta^{13}\text{C}_{\text{DIC}}$, $\delta^2\text{H}$, and $\delta^{18}\text{O}$).

The groundwater microbial community was characterized by assessing the total cell counts (flow cytometry), the heterotrophic respiration potential (Biolog MT2™ and Ecoplate™ assays), and the phylogenetic profiling through 16S rRNA gene amplicon sequencing.

Results and discussion

Most samples belong to the Ca-HCO_3 hydrochemical facies with near-neutral pH values. Approximately 30% of the sampled sites showed reducing conditions, associated with higher salinity, and elevated concentration of iron, manganese, and arsenic.

Most $\delta^{13}\text{C}_{\text{DIC}}$ values ranged between -20‰ and -10‰, indicating that groundwater was predominantly influenced by biogenic CO_2 derived from microbial respiration. A limited number of samples displayed less negative to slightly positive $\delta^{13}\text{C}_{\text{DIC}}$ values, associated with field evidence of dissolved gases, suggesting localized interaction with deep geogenic CO_2 sources.

Statistical analyses revealed significant positive correlations between heterotrophic respiration and Ca^{2+} , electrical conductivity, HCO_3^- , Mg^{2+} , SO_4^{2-} , $\delta^{13}\text{C}_{\text{DIC}}$, and dissolved iron, whereas a weaker negative correlation was observed with redox potential. Multivariate analyses further discriminated sample groups related to redox conditions and salinity, the latter being positively associated with heterotrophic microbial respiration.

The same pattern was verified in an independent dataset from the Murgia karst aquifer (southern Italy), a coastal carbonate aquifer system affected by seawater intrusion, which was sampled between 2019 and 2021 at 50 sites during four campaigns (Masciale et al., 2021; Salvadori et al., 2025).

In both datasets of Sacco River valley and Murgia karst aquifer, the microbial respiration measures correlate with the observed values of dissolved calcium, more evidently above approximately 100 mg/L of Ca^{2+} concentration.

The microbial community composition indicated the dominance of heterotrophic activities at either aerobic or anaerobic conditions. Heterotrophic microorganisms can mineralize organic carbon and produce CO₂, which generates carbonic acid, promoting calcite dissolution. In addition, under anoxic conditions, microbial fermentation can produce organic acids, which may be even more effective at the water-rock interface.

Conclusions

Our results provide large-scale field evidence that microbial activity may play a relevant role in promoting carbonate dissolution in groundwater systems. The reproducible relationship between heterotrophic respiration and calcium concentration, observed across hydrogeologically distinct aquifers, highlights microbial metabolism as a potentially important control on groundwater geochemistry and water–rock interactions.

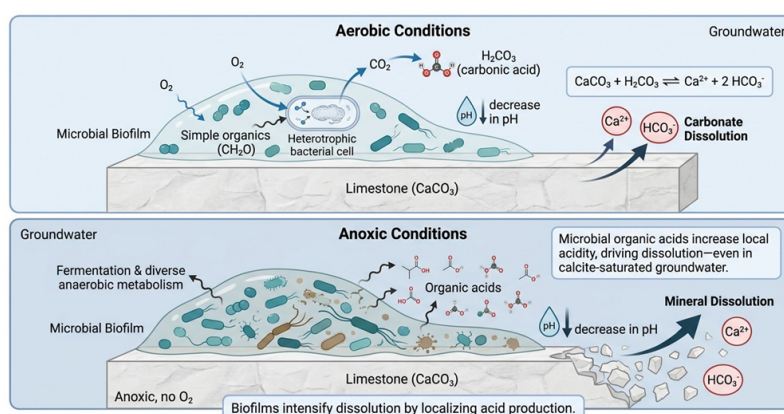


Figure 1. Microbially mediated calcite dissolution under aerobic and anaerobic conditions (generated by FigureLabs)

Acknowledgements

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Connectivity and structural controls on preferential flow and transport in karst-like network models

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Karst systems are characterized by strong structural heterogeneity, complex connectivity, and preferential flow pathways, leading to highly nonlinear flow and transport behavior. Understanding how structural organization and connectivity control flow localization, velocity contrasts, and solute transport remains a key challenge for the characterization and modeling of karst aquifers.

In this work, we investigate the impact of network structure on flow and transport using pore network models as conceptual representations of karst-like and fractured-porous systems. Large ensembles of synthetic networks are generated with controlled variations in coordination number, throat size and length distributions, and overall connectivity, mimicking different degrees of structural organization and channelization. Single-phase flow and advective-diffusive transport simulations are performed for each network, and metrics characterizing preferential flow and transport behavior, such as velocity and flow-rate distributions, dispersion coefficients, spatial moments, and breakthrough curve characteristics, are extracted.

To systematically identify the dominant structural controls, we use interpretable machine learning as an analysis tool applied to the ensemble of simulation results. By relating flow and transport metrics to geometric and topological descriptors of the networks, the approach allows us to quantify the relative importance of connectivity, heterogeneity, and network organization, as well as their interactions, in controlling preferential flow paths and anomalous transport. The results provide mechanistic insight into how karst-like structural features influence flow and transport behavior and highlight the potential of network-based and data-driven approaches to support conceptual understanding and modeling of karst systems.

Hydrogeological monitoring and modelling of the alpine karst system of Tsanfleuron (Switzerland)

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About 40% of the European Alps consist of carbonate rock outcrops by area. The mountain chain is home to many well-developed karstic aquifers which experience elevated annual recharge and these in turn are key suppliers of renewable water resources for many large urban centres, like Vienna (Goldscheider, et al. 2025). The main alpine karst springs fall almost exclusively under pluvio-nival regimes, with a few also partly recharged by glacier melt. Throughout the 21st century, the Alps will likely experience a temporal shift of precipitation maxima, from summer towards winter and precipitation will also likely fall more often as rain rather than snow (Gobiet et al., 2014). In addition, the frequency and intensity of flood or drought events are both expected to increase. The change in runoff characteristics will be detrimental to water supply because, in rural and touristic alpine regions, water consumption increases dramatically during the summer period, coinciding with predicted discharge minima. Various recent studies in alpine karstic environments highlight the key role played by snowmelt dynamics on karst aquifer recharge e.g. Rispal, et al. (2025, in review), while others provide frameworks to include snow cover data in multi-objective calibration routines (Di Marco, et al., 2021).

The well studied Tsanfleuron karst aquifer is in many ways a poster child for karst aquifers in high mountain regions, as it is fed to varying degrees by rainfall, snow- and glacier melt. It is located in the Diablerets massif in the Swiss Alps, at elevations ranging from about 1500 m above sea level (a.s.l.) to 2900 m a.s.l.. The catchment is comprised of three distinct geomorphic zones: one of carbonates overlain by the retreating Tsanfleuron glacier (above 2600 m.a.s.l.), one of recently uncovered carbonates lacking top soil where karst features are only lightly expressed (between 2300 and 2600 m a.s.l.), and one of limestone pavements comporting karrenfields, sinkholes and varying degrees of soil cover. The timber line is located between 1800 and 1900 m a.s.l.. The upper limit of tree growth is 2100 m a.s.l., whilst soil is absent above 2300 m a.s.l. Therefore, snow melt directly on bare karst to be the dominant process by which during winter to spring, the Tsanfleuron karst aquifer is recharged at present.

The so-called shallow aquifer consists of an up to 100 m thick sequence of mid-Cretaceous “Urgonian facies” limestone, underlain by marly layers. Deeper carbonate aquifers are connected to the shallow Urgonian aquifer by extensive faults. In this well studied aquifer, extensive dye-tracing campaigns have enabled the identification of the main known outlets are the Glarey spring, providing drinking water to the community of Conthey (VS), with a discharge varying between 30 -200 L / s. Others include the main spring of the Sarine River, several springs along the Lizerne valley to the south (Gremaud et al., 2010). The Audon springs (BE), of which very little is known (Salamin, 2023), lie at the base of carbonate outcrops from the same tectonic nappe as the shallow Urgonian aquifer and may provide an additional outflow for northern rim of the Tsanfleuron carbonate aquifer.

Salamin (2023) modeled the total discharge at Glarey using a combination of a simple reservoir approach, calibrated on the long-standing data from the Glarey spring and some sporadic monitoring efforts on its overflow estavelle, whilst recharge originating from glacier melt was estimated using a mass-balance balance model. These efforts yielded a satisfactory estimate of spring discharge dynamics into the future under a broad swath of climate scenarios for the 21st Century, where total water availability either increased or decreased depending on the chosen scenario (Salamin, 2023). Some uncertainty remained on the plausibility of the maximal discharges forecast using extreme climate scenarios. Whilst these preliminary models accounted for snow accumulation, the parameters of the accounting routine were optimised on observed discharge values alone, in contrast to some newer methodologies highlighting the benefit of multi-objective calibration on satellite-derived snow cover products (Di Marco et al. 2021).

To address these shortcomings, we present the renewed monitoring set-up including the total outflow consisting of the Glarey spring and its overflow estavelle since October 2024, as well as outflows at the Sarine River, and the Audon springs (Figure 1). We also describe some

preliminary results from in-cave monitoring of the epi-phreatic zone of one major cave of the area. We briefly highlight new insights from the calibration of reservoir models coupled with the CEMA-Neige snow-accounting routine on the total Glarey spring and estavelle discharge measurements and snow cover fractions obtained from the MODIS satellite imagery.

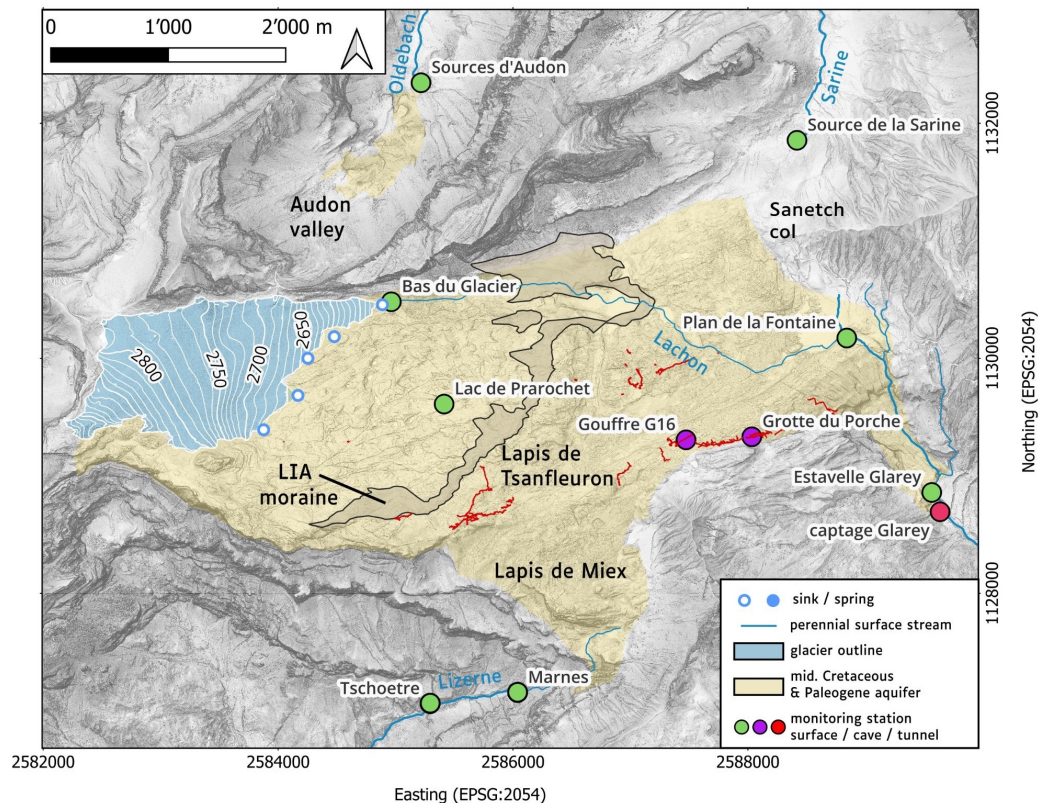


Figure 1. Map of Tsanfleuron catchment and monitoring framework, updated from Gremaud et al. (2010). Swiss Alti3D digital elevation model, Swisstopo. Tsanfleuron glacier model from CREALP, October 2025, light plane photogrammetry. Cave outlines courtesy of Groupe de Spéléologie Rhodanien (GSR), Société Spéléologique Genevoise (SSG), Spéléo-Club Jura (SCJ), & Groupe Spéléo Lausanne (GSL) (2024)

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Deployment of a low-cost automated cumulative collector for cave stream and drip waters in an alpine cave (Switzerland)

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High resolution sampling of natural environmental tracers like stable isotopes or major ions, from precipitation or surface waters is useful in calibrating tracer-aided runoff models (Tunaley et al., 2017), but data collection is often labour-intensive. When repeated manual sampling is not possible due to terrain remoteness, the protocol often necessitates the deployment of reliable, rugged, weatherproof automated samplers. This usually comes at a high initial cost and requires maintenance (Tauro et al., 2018).

Most available devices make use of peristaltic pumps to distribute sample water in airtight bottles (e.g. Hartmann et al., 2018). Their cost is relatively high (several thousand euros) and they require high-capacity accumulators to function. To automate the sampling of cave stream water in the shallow vadose zone of a remote cave, as well as that of sub-weekly integral rainfall samples, we assembled a simpler, low-cost (< 1000 EUR) device, using the bill of materials and building instructions published by Michelsen et al. (2019).

The sequential sampler is comprised of a funnel designed originally to collect rainfall, or dripping water. The funnel distributes event (rain) water through LDPE tubing to sample bottles is normally done passively by gravity. However, we adapted this design by using fiberglass wicks immersed in the notched box. This tube connects to the distribution unit, actuated by a stepper motor. This moving rotor piece allows the sequential filling of 18 different thick walled 500 mL bottles, as well as the venting of bottle air by way of a 15 m air-filled tube. Bottle caps are bored and fitted tightly with two cable grommets, connecting to the distribution and venting tube, respectively. The tube-dip-in bottle design with a venting tube is the principal mechanism by which evaporation losses in the bottles are prevented, and thus post-sampling isotopic shifts in the bottles minimised (Natali et al, 2024). The distribution tube extends almost all the way to the base of the sampling bottle, and in addition, by choosing narrow diameter bottles, only a small amount of rain is required to effectively decouple the sample from the atmosphere.

We present preliminary results from the deployment of this low-cost automated sampler in a remote alpine site. We installed a cave stream collector in Grotte du Porche (46.31526° N, 7.28271°E), a hydrologically active cave of Tsanfleuron (Switzerland). We first calibrated the stage-discharge relationship of a rectangular box with a v-notch, installed it in a cave together with a pressure-conductivity-temperature sensor (Figure 1).

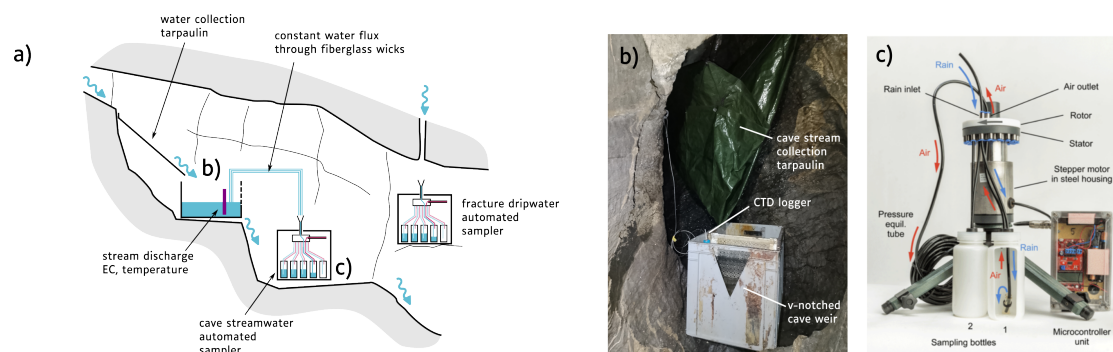


Figure 1. a) Sketch of in-cave monitoring set up for cave stream gauging and automated sampling of stream and drip samples, b) cave weir at Grotte du Porche and c) choice of design for the sequential cumulative sampler, reproduced from Michelsen et al. (2019)

We will extract the water from the v-notched box by threading fiberglass wicks in LDPE tubing and dip one of the free ends into the box, while the other end is suspended over the drip-water collection funnels. Through capillary action, water from the box travels through the wicks and drips into the automated sample collector. After initial tests we will install several wicks in parallel to achieve drip rates sufficient to consistently fill over 50 % of the bottle volume and thus prevent evaporative losses. While automatic samplers equipped with peristaltic pumps selectively extract a chosen volume of water during a short period (seconds), our sampling design will effectively sample the average stream water composition over a period of hours to days. Using this timeseries of cave stream water samples together with repeated but lower frequency snowpack characterisation protocols, we will explore the timing and damping of the snow melt signals travelling through the conduits of a shallow karst aquifer.

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Relationship between landscape evolution and karstification: The example of the Muschelkalk in Northern Württemberg (Germany)

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Introduction

In hydrogeology, aquifers are often described as temporally static systems with unchanged characteristics. However, a closer look at landscape evolution over geological time scales reveals that aquifers are dynamic systems that undergo continuous transformation. This study examines the Muschelkalk karst aquifer system in northern Württemberg, highlighting the interaction between landscape evolution and karst development.

Geological setting of the muschelkalk

The Muschelkalk represents the middle unit of the Germanic Triassic. Its thickness reaches of 200–240 m (Rausch & Simon 1988; Rausch et al. 1995). The Lower and Upper Muschelkalk are primarily composed of limestones with interbedded claystone layers, whereas the Middle Muschelkalk is dominated by evaporitic deposits, including gypsum, anhydrite, and halite.

Landscape evolution and karst development

The study area lies within the South German cuesta landscape (*Süddeutsches Schichtstufenland*). Previous studies have demonstrated that the cuesta escarpments retreated progressively towards the southeast, transitioning through a series of distinct evolutionary stages (Simon 1987, 1997; see Fig. 1). This stepwise retreat of the escarpments formed the structural foundation for the development of the Muschelkalk karst aquifer, which can be divided into three main stages.

As the escarpments retreated over time, the karst aquifer system underwent significant changes. The uniformity of the aquifer's development across large areas was facilitated by the alignment of the cuesta positions with tectonic synclines or river valleys. These regions, which remained stable for extended periods, provided the conditions necessary for the continued evolution of karst features.

By considering the landscape evolution, it is possible to assign temporal brackets to the various stages of karstification. Due to the spatial proximity of the three evolutionary stages within the current cuesta landscape, it is possible to observe all stages of karstification in the present day. These stages, which originally occurred sequentially over time, are now spatially juxtaposed, providing a unique opportunity to study the temporal evolution of karst aquifers in one region.

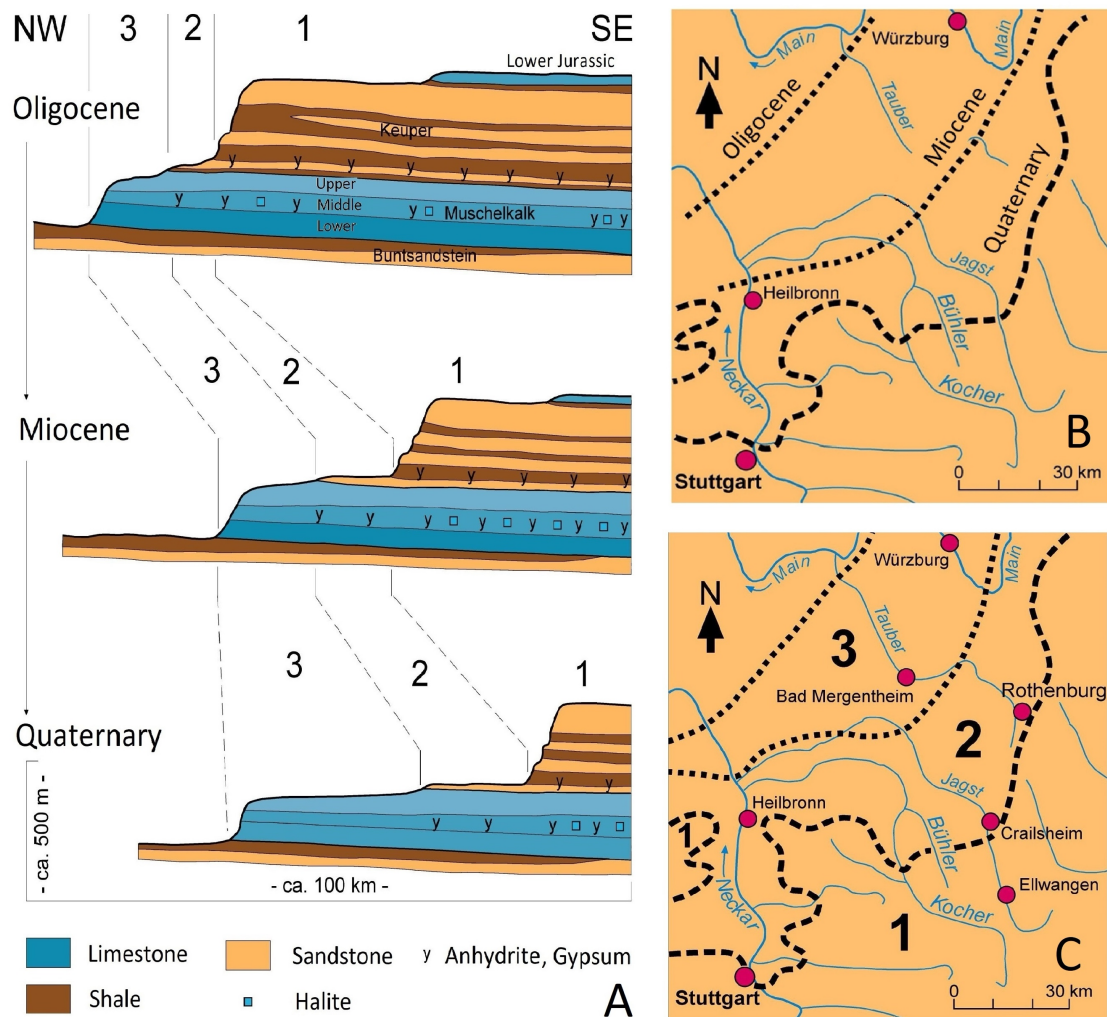


Figure 1. A & B: Landscape evolution and spatial distribution of the cuesta escarpments from the Oligocene to the Quaternary. C: Current subdivision of the aquifer system into areas 1 to 3. (adapted from Simon 1997; Rausch & Simon 1998).

The initiation of karstification in the Upper Muschelkalk dates back to the Oligocene. The processes that alter the Muschelkalk rocks after their consolidation are karstification and dissolution of the evaporitic rocks. Both processes occur over different time scales. Karstification in the Upper Muschelkalk is significantly accelerated due to the rapid leaching of the evaporitic rocks. As a result of the dissolution of the salt deposits in the Middle Muschelkalk, the total thickness of the Muschelkalk decreases to 150 to 190 meters. This implies that the Upper Muschelkalk sinks by approximately 50 meters in the stratigraphic column, which strongly influences the degradation of the limestones in the Upper Muschelkalk, thereby accelerating the karstification process.

Spatial zoning of the muschelkalk aquifer system

In the study area, three spatial zones can be identified (Fig. 1 C) that lie next to each other and correspond to different stages of aquifer genesis.

In Area 1, the Muschelkalk is still covered by approximately 200 to 300 meters of Keuper strata, so karstification has not yet occurred. The northern and western boundaries of this area correspond to the present-day boundary of the Keuper cuesta. The hydrogeological conditions

of the aquifer in this area have been described in detail by Rausch & Simon (1998). Karstification of the Upper Muschelkalk has not yet taken place here, except in locally highly tectonically disturbed areas.

Area 2 is predominantly occupied by the Gäuflächen (Hohenloher Ebene, Kraichgau). In this area, the Upper Muschelkalk is intensely karstified. Karstification intensified significantly with the onset of dissolution of the salt and sulfate rocks and remains an active process. Surface depressions, sinkholes, caves, and disappearing streams are characteristic karst features. The halite of the Middle Muschelkalk has been completely dissolved, while the sulfate rocks are still undergoing intense leaching. The Lower Muschelkalk shows no signs of karstification.

Area 3 extends to the northwest up to the present-day Muschelkalk cuesta. The land surface in the southern part is still formed by the Upper Muschelkalk, which is locally covered by rocks from the Erfurt Formation. The valleys are incised into tectonic uplifts, reaching into the Upper Buntsandstein. The Lower Muschelkalk is intensely karstified. While karstification also continues in the Upper Muschelkalk, the peak of karst development has already passed. Cavities here are largely sealed.

Conclusion

The conclusion emphasizes that aquifers, like the Muschelkalk in northern Württemberg, evolve over geological time scales and are dynamic systems rather than static ones. This dynamic nature is highlighted by the example of distinct hydrogeological areas in a cuesta landscape, which can be understood in relation to the sequential stages of aquifer formation, similar to Walther's Law of Facies in sedimentology (Rausch et al. 2023).

The concept of aquifer genesis has broader implications for aquifer characterization. It provides insight into spatial zoning of aquifer parameters, groundwater chemistry, and the modeling of groundwater systems, particularly for long-term predictions. This is especially relevant for applications such as climate change projections and the safety assessment of long-term geological storage sites, like those for radioactive waste.

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Integrating surface and subsurface monitoring to assess recharge processes in a karst critical zone

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Karst aquifers are highly sensitive to changes in precipitation patterns, vegetation cover and soil properties, yet the combined effects of these factors on infiltration, soil water storage and recharge remain insufficiently understood, particularly within the unsaturated zone. This study addresses these gaps by integrating detailed surface observations of vegetation and soil properties with high-resolution hydrological monitoring at the surface and in caves below. The objectives were to (i) assess the influence of vegetation cover, soil properties and geomorphological setting on soil moisture dynamics and effective precipitation and (ii) identify the conditions under which different parts of the karst critical zone respond to recharge.

The research was conducted in the Postojna–Planina karst region in southwestern Slovenia, an area included in the eLTER and LifeWatch research network and infrastructure. A comprehensive monitoring network comprising 15 sites was established, including 10 surface sites representing different vegetation types and geomorphological settings, and 5 underground sites monitoring individual cave drips in Postojna and Planina caves. Continuous measurements of precipitation, throughfall and other meteorological variables, soil moisture, and drip discharges have been performed at 30-minute intervals since October 2020. Field observations were complemented by water balance calculations performed with the BROOK90 hydrological model and by simulations with a soil water balance model to estimate effective precipitation (P_{ef}) under different vegetation scenarios.

Preliminary results indicate that different vegetation types strongly modulate the distribution of throughfall. During intensive rainfall events, throughfall is more concentrated beneath natural forest regeneration than in large canopy gaps due to canopy interception and drop coalescence, resulting in larger droplets and locally increased precipitation inputs. This effect is particularly pronounced during the vegetation growing season, when leaf area and interception capacity of canopies are highest. Soil moisture dynamics, in turn, are further shaped by seasonal variations in vegetation development, reflecting differences between the vegetation dormant and growing seasons. Soil moisture values are generally higher during the vegetation dormant season and tend to increase with soil depth as evapotranspiration effects diminish downward in the soil profile. In contrast, during the growing season, vertical differences in soil moisture are more pronounced due to evapotranspiration and enhanced root water uptake. Vegetation type further modulates these vertical patterns. Natural forest regeneration and mature forest canopies exhibit stronger soil-moisture gradients between shallow and deeper soil horizons than large canopy gaps, reflecting intensive soil moisture uptake, particularly by young trees. This pattern is further supported by modelling results, which show that evapotranspiration strongly reduces P_{ef}, with the highest losses occurring in forest regeneration sites during the growing season.

Site-specific deviations, however, highlight the influence of local geomorphology. In a doline with dense natural forest regeneration, upper soil layer remains wetter than deeper soil horizons owing to shading by canopies and reduced surface evaporation, while deeper soil layer experiences stronger soil moisture depletion due to intensive rooting and the presence of preferential flow paths along rocks and roots. This is also confirmed by model results, which show the lowest P_{ef} in dolines covered by forest regeneration and the highest in large canopy gaps. In addition, soil-moisture responses to precipitation in dolines may be more attenuated than at other sites.

Consistent with soil moisture patterns, drip activity in caves is markedly higher during the vegetation dormant season, although individual drips respond heterogeneously to precipitation

events. Not all drips react to the same precipitation events, reflecting differences in antecedent soil moisture conditions, precipitation characteristics, degree of karstification, and cave ceiling thickness. On average, 20–34 mm of precipitation is required to trigger a drip response. Drips in Planina Cave are more sensitive to precipitation, responding after 9–15 hours, whereas those in Postojna Cave react after 26–36 hours and require longer or more intense precipitation. During the growing season, up to six times more precipitation is needed to induce a dripping response, and reaction times are longer.

Modelling at the catchment scale, independent of our plot-scale monitoring sites, suggests that reduced canopy interception resulting from vegetation cover change, and the associated reduction in evapotranspiration, can increase P_{ef} and groundwater recharge by approximately 5%, providing complementary insights to our field observations. The results of this study highlight the critical role of vegetation–soil–unsaturated zone interactions in controlling recharge dynamics in karst systems and demonstrate the value of integrated surface–subsurface monitoring within karst critical zones.

Numerical investigation of flow and transport in karst aquifers considering conduit network structure and conduit–matrix Interaction

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Karst aquifers exhibit complex flow and transport behavior due to the coexistence of discrete conduit networks and a surrounding fissured and fractured rock matrix. Understanding the interaction between these domains and assessing the influence of conduit network geometry are challenging in numerical karst modeling, particularly for solute transport processes.

In this study, we use the discrete–continuum model MODFLOW Conduit Flow Process (CFP, version 2 [1]), including its implemented solute transport capabilities [2], to investigate transport dynamics in karst systems. The focus is on the combined effects of conduit network patterns, conduit parameters, and conduit–matrix interaction on flow and transport behavior. To allow systematic and comprehensive model investigation, solute transport functionality has been implemented in the Python-based pre- and post-processing library CFPy [3]. This enables a comprehensive and scalable script-based workflow for designing, executing, and evaluating coupled flow and transport simulations.

The Python-based workflow further allows coupling with PyKasso [4] to generate stochastic conduit network realizations. This provides a flexible framework to investigate the effects of different conduit patterns, including variations in network density, connectivity, and spatial organization. Based on this setup, a systematic parameter study is conducted that considers not only transport-related parameters but also structural characteristics of the conduit networks.

The presented approach allows systematic investigations about how conduit network geometry, conduit parameter, and conduit–matrix transfer processes affect transport characteristics in karst systems. This provides additional insights and information for karst system characterization. The methods provide a flexible and process-based numerical framework for investigating structural and parametric controls on karst transport processes and supports advanced analyses in karst hydrogeological research.

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Equivalent parameters for the Darcy-Weisbach equation in conduits of varying diameters

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The most frequently used equation to model flow in fully saturated karst conduits is the Darcy-Weisbach equation. It relates the head loss to the discharge through the conduit via a friction factor. The estimation of this friction factor depends only on two physical parameters, the diameter of the conduit and its relative rugosity. Among the different empirical and theoretical formulas proposed for the estimation of the friction factor, the Churchill (1977) equation is one of the most convenient. All this theory is well established for pipes of constant diameter, and it is widely employed in codes used to model groundwater flow in karstic systems such as CAVE (Liedl et al 2003), Modflow-CFP (Reimann & Hill 2009) or OpenKARST (Kordilla et al. 2025).

But real cave conduits and networks have varying diameters. Accounting for this decimeter scale spatial variability can rapidly become cumbersome and imply heavy numerical computations at the scale of a catchment. To simplify and accelerate the numerical models, an approach consists in replacing 1D parts of the network having conduits of varying diameters with an equivalent 1D conduit of constant diameter as shown in Figure 1.

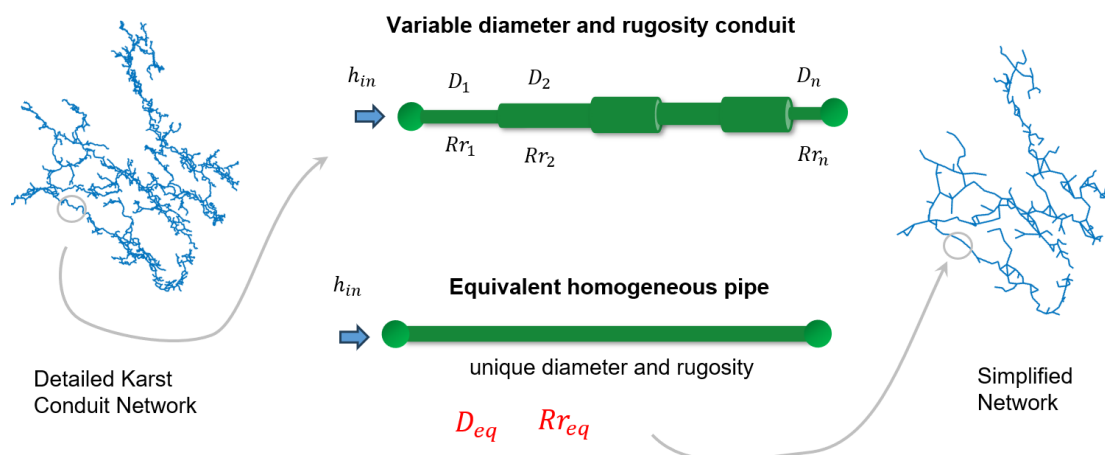


Figure 1. Principle of the 1D upscaling procedure: within a complex network, one dimensional branches having variable diameters and rugosities can be replaced with equivalent homogenous pipes.

In this presentation, we show that the equivalent diameter can be computed as a power average of the distribution of the local diameters for the laminar regime as was previously reported for example by Liedl et al. (2003). For the fully rough turbulent regime, an equivalent rugosity can also be computed analytically, it involves a mean of the local diameters raised to a power of 5. The transitional regime between laminar and turbulent flow occurs over a broad range of equivalent Reynolds number. The departure from the laminar regime occurs at a critical Reynolds that can be estimated simply from the minimum diameter within the section of variable diameters.

Assuming a simple linear relation between the equivalent Reynolds number and the friction factor in the transition between the laminar and fully rough turbulent regime allows to provide an estimation of the friction factor for the whole range of possible Reynolds number for a conduit of varying diameters.

This simple approach is tested on synthetic karstic networks generated following the method proposed by Hendrick and Renard (2016). We show on these networks, that one can replace all the 1D parts of the network having variable diameters by equivalent homogeneous 1D parts and obtain the same total fluxes through the network over a complete range of laminar to turbulent flow at the scale of the full network. The computational speedup obtained with this approach can reach up to three orders of magnitude depending on the flow conditions and variability of the conduit diameters.

The future steps of this work are to account for the partially saturated and transient regimes.

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LuKARS 3.0: A framework for simulating flow and transport in karst environments

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Karst water resources play a vital role in global water supply, providing drinking water to 10–25% of the world's population. Karst systems exhibit complex hydrological behavior, with fast-flow pathways and highly variable storage capacities. Hydrological models are essential for effective water resource management. However, modelling of karst systems is still a difficult task due to the heterogeneity of these systems and the uncertainties in karst structure.

LuKARS, a semi-distributed hydrological model for karst systems, addresses some of these challenges by allowing the consideration of multiple hydrotopes (i.e. distinct landscape units characterized by similar land use and soil types and thus by homogeneous hydrological properties) within a catchment. Despite its low computational cost, LuKARS faces challenges in the context of sensitivity analysis and uncertainty quantification due to its large number of parameters. Compared to the original version of LuKARS (Bittner et al., 2018), which was used in this study as a benchmark for the evaluation of the code performance, the newly developed version of LuKARS 3.0 (Richieri et al., 2025) allows much shorter computational times, which was achieved primarily using the Numba Python library. The results showed a reduction in runtime of approximately 99.39% (from 1.14 seconds per test run down to 7 milliseconds), for the same model structure. In addition, LuKARS 3.0 allows an easy implementation of the model on clusters and a flexible model structure characterized by an arbitrary number of hydrotopes (Fig.1 a) as well as by the possibility of activating/deactivating different model compartments, i.e., epikarst, matrix and conduit.

In this study, we leverage the low computation time of LuKARS 3.0 to apply Morris' sensitivity analysis method (Morris, 1991), demonstrating its comparability to dimensional reduction techniques like the active subspace method (Teixeira Parente et al., 2019). The efficient runtime also facilitates the investigation of combined parameter and structural uncertainties. We calibrate different model structures for the Kerschbaum spring in Austria, with parameter estimation and uncertainty quantified via the GLUE method (Beven and Binley, 1992).

Finally, we developed a flow and transport model by coupling LuKARS 3.0 with IPhreeqc (Charlton and Parkhurst, 2011), a special module of the geochemical modeling code PHREEQC (Parkhurst and Appelo, 2013), specifically designed to interface with other software programs including Python. We implemented a simple complete mixing model based on the internal fluxes of the flow model and on inverse modeling (Fig.1 b). To account for uncertainties, we used the posterior distribution of the selected best-performing model structure based on spring discharge as input for the mixing model. Our hypothesis is that assessing uncertainty based solely on flow model performance may not accurately capture transient transport processes, and that a combined uncertainty analysis of both flow and transport is necessary.

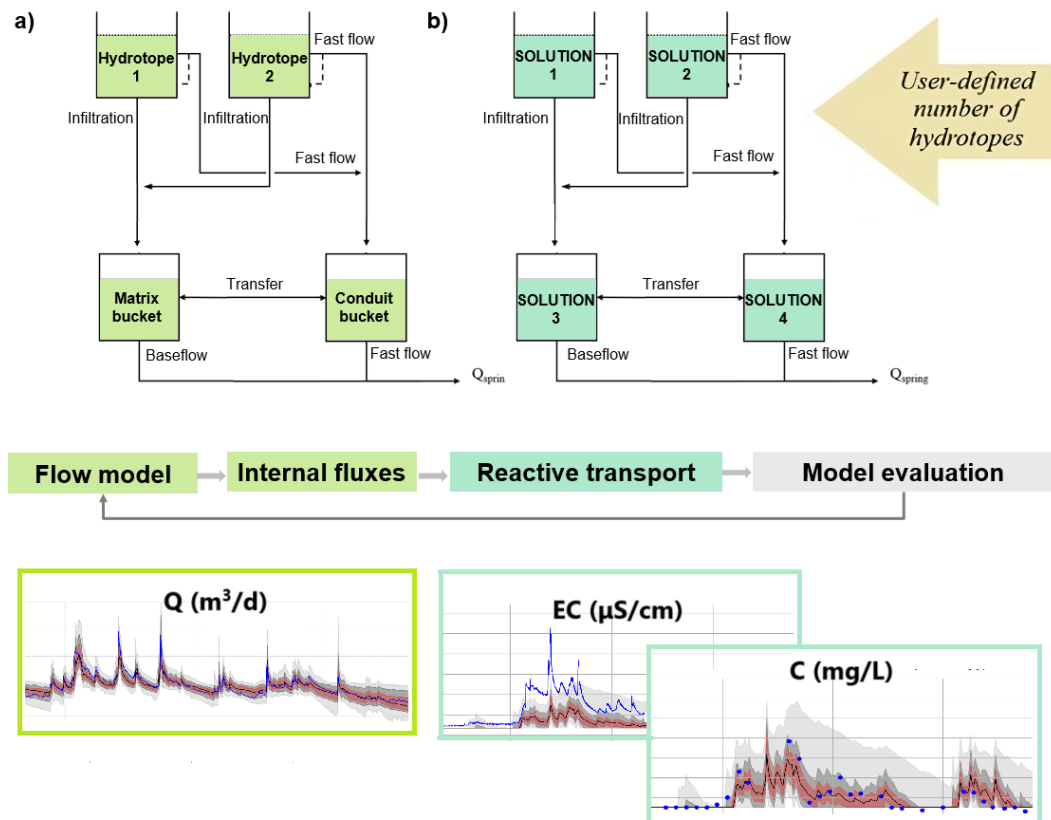


Figure 1. A schematic representation of the hydrological LuKARS 3.0 flow model and b of its coupling with IPhreeqc.

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Structural controls on groundwater flow: Linking fault kinematics to hydraulic properties in the Fontaine de Vaucluse Karst System

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Their hydraulic behavior of karst aquifers is strongly controlled by geological heterogeneities. In this context The Fontaine de Vaucluse aquifer (South of France) with a catchment area exceeding 1,100 km² provides an emblematic example of a large and structurally complex karst aquifer, where groundwater flow is tightly controlled by geological heterogeneities inherited from tectonic processes.

In this study, we investigate how sedimentary facies and tectonic structures jointly control the spatial organization of karst features. Faults, one of the main structural heterogeneities in karst systems, are three-dimensional objects with complex geometries. Their hydraulic properties are closely linked to their formation mechanisms and reactivation history. To assess their impact on fluid flow in carbonate karst environments, we conducted a field-based structural analysis. This static approach enabled us to characterize the development and structuring of these fault zones. Our methodology involved: (i) A structural mapping of the system based on lineaments identified from LiDAR data and satellite imagery; (ii) detailed analysis of 65 representative outcrops to determine fault-zone structural characteristics. It includes size and nature of core zones (CZ), fracture density and organization within damage zones (DZ) and cementation patterns. We also identified kinematic indicators: fault dip and orientation, slickensides, calcite deposits in rock shelters, cross-cutting relationships, and fault interactions.

In parallel, the spatial distribution of surface karst morphologies was analyzed through the construction of a GIS-based inventory of dolines, combined with an existing database of karst cavities. The resulting dataset includes 3,992 karst objects and reveals strong spatial heterogeneities in karst development across the catchment. The analysis points towards clear relationships between karst morphology distribution, sedimentary facies, and fault networks, emphasizing the role of tectonic inheritance in guiding karstification processes, from surface morphologies to deep flow pathways.

Based on this dataset, we reconstructed the formation and reactivation history of the faults and evaluated the local impact of these structural heterogeneities on fluid flow. The results can be grouped into two main aspects:

1. General aspects: The hydraulic behavior of the studied faults is largely controlled by their mode of formation and reactivation history. Our work highlights a strong relationship between kinematics and the lithological nature of the CZ. To a lesser extent, they also demonstrate the importance of the relationship between displacement amplitude and CZ composition. This type of fault structures will surely impact the structuration of karstic conducts, behaving as either a barrier or a drain.

2. Regional Aspects: This study improves our understanding of the regional geodynamics. It establishes a link between five major tectonic phases, three main fault orientation families and three distinct periods of fault formation. Our results also demonstrate the significant role of the Pyrenean orogeny in structuring the Monts d'Albion, whereas the Alpine orogeny was mainly responsible for the reactivation of major fault zones and possible karst network reorganization.

These integrated structural and geomorphological works provide the basics for ongoing works involving the construction of a numerical geological model, which will be used to model flow behaviors within the Fontaine de Vaucluse aquifer, ultimately improving the assessment of the resource vulnerability under future climate change scenarios.

From geological evolution to present-day hydrodynamics : an integrated approach applied to the Dévoluy karst aquifer

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Karst aquifers are widespread and constitute a major groundwater resource, yet their functioning is challenging to interpret due to the complexity of their geological framework and the resulting flow pathways. Understanding present-day hydrodynamics therefore requires reconstructing the aquifer's evolution and assessing how geological inheritance controls groundwater circulation.

The Dévoluy karst aquifer (French Alps) provides an ideal case study. The massif is well-delimited, with a quasi-unique outlet, and exhibits a complex polyphased geological history, making it suitable for reconstructing both its geological framework and hydrological functioning.

The karstic aquifer's evolution was reconstructed from sedimentary organization, structural analysis, geomorphological observations and dating of karst sediments and speleothems. The carbonate succession is relatively homogeneous, with minor facies variations; stratigraphic heterogeneities are limited, with local silica-rich layers forming the main contrasts affecting reservoir properties. Tectonic structuration from the early Cenozoic to the late Miocene formed a syncline cut by a major thrust in its central part, while largely post-tectonic uplift led to progressive valley incision and partial isolation of the massif. Karstification developed during incision from the late Miocene to the Quaternary, forming successive networks and progressively organizing drainage toward a single outlet at the northern edge of the massif, the Gillardes springs.

The present-day system was studied at multiple scales. At the sample and outcrop scale, fractures dominate permeability. Conduit development at the km scale is controlled by the interaction of stratigraphic discontinuities and faults with successive hydrologic base levels. At the aquifer scale, the synclinal geometry organizes flow toward the outlet while major faults such as the central Dévoluy thrust influences connectivity and compartmentalizes the reservoir. Hydrologic modeling further shows that snow accumulation and melt govern recharge dynamics in this highly reactive alpine system.

This study demonstrates that reconstructing geological signals across scales is essential for understanding karst aquifer functioning. By combining geological and hydrogeological observations, this approach provides a transferable framework linking system evolution, karstification, and present-day flow, and can be applied to other complex karst systems to assess the influence of geological inheritance and climate-driven recharge.

Assessing surface facilities hydraulic impacts with a surface/groundwater flow coupled model

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Deep geological disposal project (Cigeo, see Andra 2025 for more information) carried out by Andra (French national agency for radioactive waste management) will include surface facilities (shaft and ramp areas) that should be constructed over fissured and karstified Barrois limestones. Karstic aquifers are well known for their complex interactions between surface water and groundwater in addition to the high flow velocity in karstic networks which may leads to a high vulnerability of the water resource.

Andra and BRGM (French geological survey) have designed a major program which aims to assess and model flow and transport in the Barrois limestones to quantify the Cigeo project hydraulic disturbances on the local water resources. At the same time and strongly linked to this program, a Barrois limestones hydrogeological model have been developed at regional and local scales with the newly developed CS2par code (see Kerrou *et al.*, 2026a for more details about the code development and validation) which sets up and uses a fully coupled model of surface water flow (diffusive wave equation) and groundwater flow (Darcy and Richard's equation). This model, based on hydrogeological models at larger scale, was calibrated in transient flow regime using hydraulic heads time series monitored near surface facilities and river flow rates monitored 10 km to the north (see Kerrou *et al.*, 2026b for more details about the model construction). Evolution of hydraulic heads and river discharge rates were well reproduced, especially in the ramp area where calibration data are concentrated. Surface flow calibration will be improved by using data coming from monitoring stations recently installed in nearby rivers. Nevertheless, the model is well enough calibrated at the ramp area scale to give robust insights of how surface facilities will impact surface and groundwater flows. Therefore, the model was operated to evaluate the hydraulic impacts that will be induced by future surface facilities which is the final step of the complete methodology to understand surface and groundwater flows behaviours in the studied area.

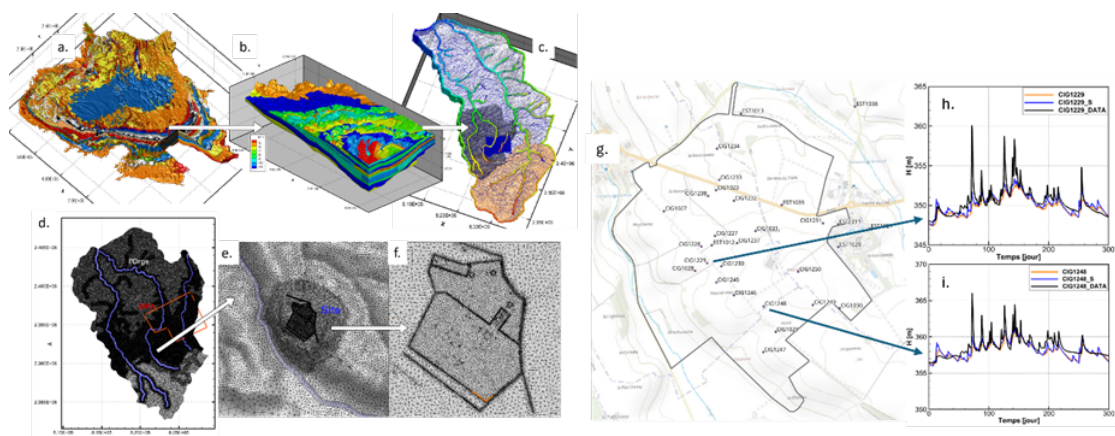


Figure 1. Hydrogeological models from Paris basin scale (a.) to the ramp zone scale (e. and f.). Barrois limestone hydrogeological model scales are shown in c. (regional) and d. (local); g. Monitored piezometers of the ramp zone; h. and i. simulated hydraulic heads in subsurface layer (blue) and in a specific layer where flow concentrates (orange) compared to measurements (black).

Natural field of the future ramp area will be reshaped with surface earthmoving that will change surface hydraulic conductivity and could create new recharge areas of karstified and transmissive limestone layers observed at the subsurface. The ramp area design also includes protection structures to prevent nuclear installations from flooding due to rising groundwater levels, and those structures could impact surface and groundwater flows dynamics. Both (earthmoving and protection structures) have been implemented in the finite element mesh, their impacts on surface water and groundwater flows have been evaluated in high and low water periods and compared with initial state.

For instance, results have shown that surface earthmoving generate the most important impacts on surface water and groundwater in low water periods. Protection structures preventing flooding by groundwater rising limit the hydraulic disturbance spatial extent but generate groundwater rising inside the ramp area despite a well distribution of groundwater drains.

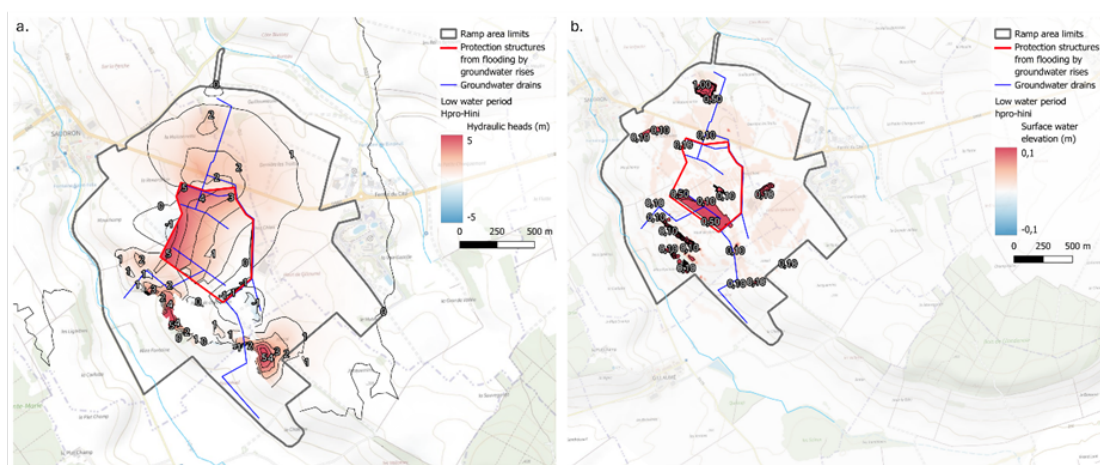


Figure 2. Surface and groundwater flows coupled model results during low water periods, results are differences between a project situation (surface earthmoving with protection structures) and the natural state. Positive values mean a rise of hydraulic heads or surface water elevation due to ramp area construction; a. impacts on groundwater flow in a specific limestone layer, b. impacts on surface flow.

The strength of the surface and groundwater flows coupled model is that all surface evolutions that will take place during the Cigeo project works could be implemented in the model to assess their impacts. Results from the current version and the next improved version (with new river data for calibration) of this couple surface / groundwater flow model supports surface facilities design studies and the next impact studies of the Cigeo project.

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Physics based modeling of speleogenesis in openKarst - preliminary results

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Predicting flow and water quality in karstic environments is a challenging task due to the complex structures and high heterogeneity of karstic reservoirs. openKARST is a Python-based open-source flow and transport simulator in karst networks (Kordilla et al. 2025). It employs the Saint-Venant hydraulic equations to compute transient flow in complex networks, including dynamic free surface or pressurized flows under laminar and turbulent conditions. To represent complex karstic networks, openKARST uses a graph-based numerical framework. Although real networks suitable to field access can be mapped, most often only the geology and main faults are known, without any detailed information about the conduit network topology.

The general objective of the research presented in this poster is to create a new tool based on openKARST, which will allow karstic networks to be created by simulating the speleogenesis processes. In a second step, we want to employ it to extract the statistical features of the simulated networks at a scale that is usually not accessible by caving exploration.

Here, we provide an overview of the main speleogenesis phenomena and modeling approaches that were proposed in the scientific literature so far. It includes a synthesis of the equations that govern speleogenesis through the dissolution of limestone in groundwater enriched with CO₂ (e.g. Buhmann and Dreybrodt 1985, Groves and Howard 1994). It also summarizes the usual simplifications of equations and numerical models of dissolution that can be applied along a 1D fracture or pipe (e.g. Dreybrodt 1990, Leidl et al. 2003) or for 2D and 3D modelling (e.g. Kaufmann 2016, Wang et al. 2020).

The poster then presents how these equations can be implemented within openKARST to establish a physics-based model for the large scale simulation of speleogenesis, as well as the first tests comparing the resulting simulations with previously published studies.

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Hydrochemical and lumped-parameter modelling tools to reduce uncertainty in groundwater/surface water assessment in alpine karst catchments: The case of Sierra de Segura massif (SE Spain)

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Knowledge of surface water-groundwater interactions in karst regions is crucial for enhancing the characterization of aquifers and the estimation of its water resources. This is particularly relevant in Mediterranean mountain areas, whose aquifers act as the source of many rivers that sustain biodiversity and economic and social developments (Xanke et al., 2024). However, the lack of specific -quantitative- information on the temporal and spatial variability of water resources limits its management. A good example is the Sierra de Segura, an extensive (3000 km²) mid-height (1.000 to 2136 m a.s.l.) carbonate massif in SE Spain, where ungauged catchments support headwater of two of the most relevant rivers in the Iberian Peninsula (Guadalquivir and Segura). This research aims to evaluate the applicability of combined hydrological, hydrochemical, and numerical modelling tools to decouple groundwater contribution to total river outflows. To do this, a data set including in-situ flow-rate and physico-chemical measurements, major ions, TOC, and $\delta^{18}\text{O}$, from four gauging stations (GS-1 to GS-4 in Figure 1) was gathered during five hydrological years (2020/21–2024/25). Based on dataset, the temporal and spatial contributions of surface water and groundwater to the total streamflow in two rivers (Segura and Zumeta) were assessed using: (1) a hydrochemical mixing model combined with a Recursive Digital Filter -RDF- (Lyne and Hollick, 1979); and (2) the KarstMod bucket-style numerical model (Mazzilli et al., 2019).

During the study period, mean streamflow in Zumeta River progressively increases from 0.26 (GS-1) to 0.66 m³/s (GS-2), and from 0.64 to 1.21 m³/s in Segura River (GS3 and GS4, respectively). Accordingly, total mean value of water resources measured in the area was 78.44 hm³/year: 20.70 hm³/year in GS-2 (Zumeta River) and 57.74 hm³/year in GS-4 (Segura).

For the hydrochemical mixing model, two end-members were selected as they represent the extreme chemical signatures of the hydrosystem: groundwater from carbonate aquifers and the surface runoff. NO₃⁻, SO₄²⁻, Cl⁻, TOC, deuterium excess -d-excess-, and $\delta^{18}\text{O}$ were used to compute a mass balance at each monitoring site. These parameters were selected as they can be treated as conservative tracers under the studied conditions, and have distinctive values at each end-member. Results were compared against field-measured samples for validation. In general, R² values higher than 0.85 were obtained for Cl⁻, TOC, d-excess, and $\delta^{18}\text{O}$ (Table 1). From these correlations, a set of groundwater fractions was derived, with average values ranging from 58 % in GS-4 (Zumeta River) to 81 % in GS-1 (Segura River), which were used to optimize the Base Flow Index, a parameter of the RDF that allow the hydrographs to be decoupled. The statistical results are summarized in Table 1. Accordingly, values for groundwater component range from 18.10 to 29.35 hm³/year (Segura) and 6.41 and 17.97 hm³/year (Zumeta) (Table 1).

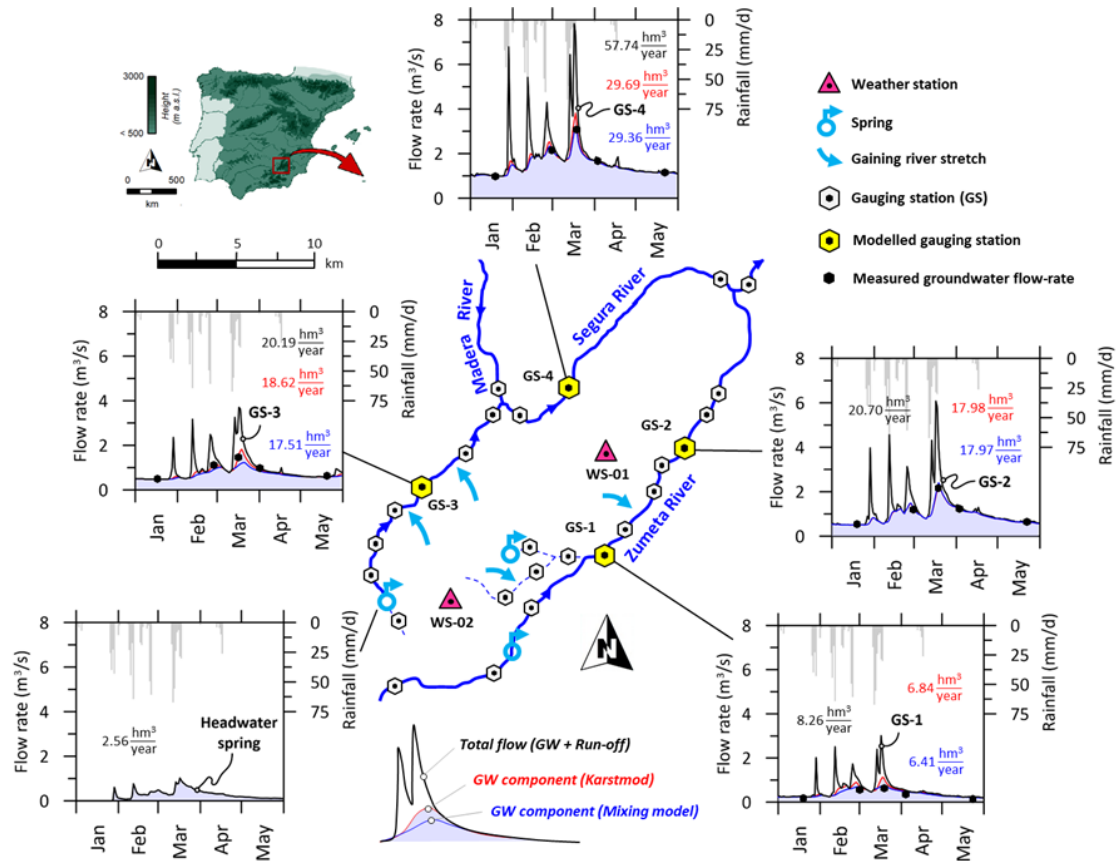


Figure 1. Sketch of Segura and Zumeta rivers for a representative period (Jan–May 2024). Hydrographs include the total water resources (black), and the calculated flow components derived from the hydrochemical (blue) and KarstMod (red) methods.

Table 1. Observed - modelled correlation coefficient (R^2), Baseflow Index (BFI), and modeled groundwater results obtained by the hydrochemical mixing model (left) and KarstMod (right). Objective function is defined as $W_{OBJ} = 0.6 \text{ KGE} + 0.4 \text{ BE}$.

Hydrochemical mixing model						KarstMod model					
River	Parameter	GS-1	GS-2	GS-3	GS-4	Stage	Objetive function	GS-1	GS-2	GS-3	GS-4
Segura	NO ₃ ⁻	-	-	0.48	0.53	Calibration	BE	-	-	0.98	0.98
	SO ₄ ²⁻	-	-	0.73	0.75		KGE	-	-	0.94	0.87
	Cl ⁻	-	-	0.98	0.87		W _{OBJ}	-	-	0.96	0.91
	TOC	-	-	0.92	0.90	Validation	BE	-	-	0.83	0.76
	d-excess	-	-	0.97	0.95		KGE	-	-	0.92	0.86
	δ ¹⁸ O	-	-	0.89	0.67		W _{OBJ}	-	-	0.88	0.82
Zumeta	NO ₃ ⁻	0.56	0.43	-	-	Calibration	BE	0.77	0.73	-	-
	SO ₄ ²⁻	0.78	0.71	-	-		KGE	0.81	0.84	-	-
	Cl ⁻	0.99	0.89	-	-		W _{OBJ}	0.79	0.80	-	-
	TOC	0.99	0.92	-	-	Validation	BE	0.78	0.87	-	-
	d-excess	0.95	0.90	-	-		KGE	0.83	0.83	-	-
	δ ¹⁸ O	0.92	0.89	-	-		W _{OBJ}	0.81	0.85	-	-
BFI (%)		81	67	73	58						
Runoff factor (%)		19	33	27	42						
GW discharge (m ³ /s)	Max.	0.76	2.41	1.23	3.18						
	Avg.	0.20	0.57	0.56	0.93						
	Min.	0.08	0.19	0.47	0.84						
Annual Resources (hm ³ /y)		6.41	17.97	17.51	29.36						

The KarstMod model was conceptualized as two interconnected structures (Figure 2): the first one simulates conduit and matrix flow due to recharge by rainfall and snowmelt in headwaters (GS-1 and GS-3). The second part also reproduces diffuse groundwater inflows and run-off in the gauging stations GS-2 and GS-4. Both modules were calibrated and validated to optimize the objective function $W_{OBJ} = 0.6 \text{ KGE} + 0.4 \text{ BE}$. The model shows high performance ($\text{KGE} > 0.8$; $\text{BE} > 0.7$) during both calibration and validation steps. According, groundwater fraction represents 81% of the flow at the headwaters of the Segura River (annual groundwater resources of $18.62 \text{ hm}^3/\text{year}$) and 62% downstream ($29.69 \text{ hm}^3/\text{year}$), whereas in the Zumeta Valley is 87% ($6.84 \text{ hm}^3/\text{year}$) and 69% ($17.98 \text{ hm}^3/\text{year}$), respectively. Full results dataset is listed in Table 1.

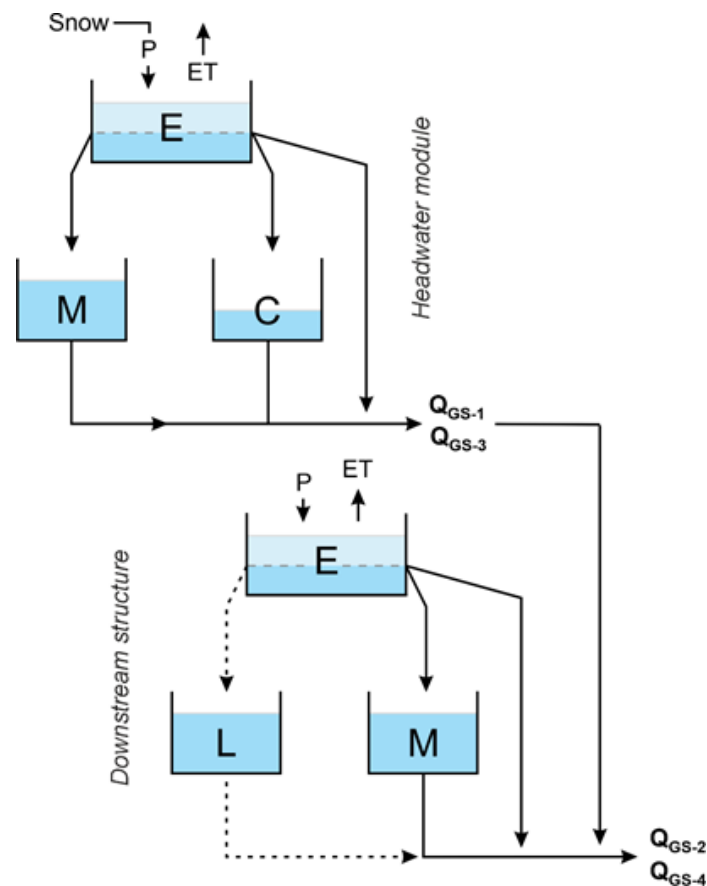


Figure 2. KarstMod structure scheme. Dashed lines indicate flow components for the Zumeta model. P: Precipitation, ET: Evapotranspiration, E: Epikarst, C: Conduits, L: Long-term flow-paths, M: Matrix and Q_{GS} : simulated flow.

The physically meaningful separation of baseflow from a river hydrograph remains an unresolved problem in hydrology, especially in carbonate regions with highly variable hydrodynamic conditions, such as the pilot site. This complexity was addressed using an integrated framework that combines field hydrochemical data with RDF. This approach yields a more robust hydrodynamic conceptualization of the karst system, reducing the uncertainty and ensuring results consistent with numerical modelling. Consequently, both simulations (mixing model and KarstMod) produced near-identical baseflow series and similar groundwater resources. Despite the strong correlation of both methods with field data, differences of 0.43 and $1.11 \text{ hm}^3/\text{year}$ persist in the respective valley headwaters simulations (Figure 1). This partly reflects the distinct mathematical formulations of the approaches and, consequently, more effective capture of the flashy conduit-flow response by KarstMod; whereas the mixing model tends to smooth the discharge peaks as tracers require time to be equilibrated chemically. These

discrepancies are particularly evident during high-water conditions, when the physical characteristics of each catchment constrain the flow response: active fluvial dynamics with strong groundwater dependence (Segura) vs higher groundwater residence times (Zumeta). In this sense, the geomorphological/hydrodynamic setting, soil-rock-groundwater interactions, or a combination of these processes are responsible for the different hydrodynamical evolution and, ultimately, the surface water/groundwater interaction dynamics.

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A model of the evolution of the water resource availability at the Glarey karstic spring in the glaciated Tsanfleuron watershed

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The Glarey spring is one of the main outlets of the Diablerets massif. The commune of Conthey in Valais taps it for its drinking water supply. This spring drains most of the Tsanfleuron lapiaz located at altitudes ranging from 2,000 to almost 3,000 meters. The upper part of the catchment is covered by a glacier. The region is subject to heavy precipitations. Much of this precipitation falls in the form of snow. However, this substantial snowfall cannot compensate the melting of the Tsanfleuron glacier. Its disappearance threatens to upset the hydrological regime within the watershed. The objective of this work is therefore to evaluate the possible evolution of the water resources at the Glarey spring.

The research approach involves the collection of novel field data and the construction of a model able to forecast the impact of climate change scenarios. The model includes two main components. The hydrological component models the evolution of the Tsanfleuron glacier based on mass balance computations and provides watershed-wide chronicles of rain, snowmelt, and glacier melt. These chronicles are the input of the hydrogeological model that estimates the discharge rate at the Glarey spring. This component of the model includes a production function, representing the infiltration through the epikarst while considering the effects of evapotranspiration, and transfer function representing the hydraulic behavior of the endokarst. The model was calibrated using actual measurements and was then used to forecast future discharge using the CH18 climate scenarios. This allowed to obtain a range of possible evolutions from 2020 to 2090.

The results show a large variability and uncertainty in the long term forecasts depending on the climate scenarios. All the models predict the complete melt of Tsanfleuron glacier. But the impact on the discharge rate at the Glarey spring is less drastic, most of the models indicate a change in the temporal distribution of the discharge.

**Updating the multi-decadal climate trend impact on a large karst spring flow:
the case of Caposele Spring (Southern Italy)**

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The Caposele Spring is one of the main karst water sources in the Southern Apennines and one of the largest springs in Italy. It is characterized by a long historical series of flow measurements, making it particularly suitable for studying the relationship between groundwater availability and climate variability. This work analyzes the temporal variations of the spring flow in relation to observed climate trends reflected by specific climate and hydroclimatic indices. The analysis is based on multi-decadal historical series of flow, compared with precipitation and temperature data from the recharge area. Trends are assessed using nonparametric statistical tests, while the spring hydrological response is investigated through the analysis of recession curves and seasonal and multiannual variability. The correlation between flow and climate conditions is examined using standardized drought indices, such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI).

The results update the historical trend on a longer time series analysis respect to previous studies, highlighting the significant relationship between periods of prolonged rainfall deficit and reductions in spring flow. Delayed responses, resulting from data analysis, are found to be consistent with the storage and drainage characteristics of the karst system. Moreover, the results help to detect potential increasing sensitivity of the spring to climate anomalies, particularly during long-term droughts. The study contributes to the understanding of the effects of climate variability and change on karst water resources and provides useful insights for the sustainable management of large karst spring catchments in a context of increasing climate pressure, such as the Mediterranean area.

The karst vadose zone – Infiltration dynamics and storage

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The karst vadose zone has been demonstrated to act as an important compartment in the storage and recharge infiltration process particularly in karst regions characterised by thick unsaturated zones. In semi-arid regions of the Eastern Mediterranean, very wet years have shown to have prolonged effects of elevated groundwater discharge as well as elevated groundwater levels, compared to long-term average hydraulic conditions.

The above prolonged storage effects can generally be attributed either to delayed groundwater discharge or the sustained infiltration processes in the matrix of the vadose zone.

Research focussed on the analysis of the geohydrological processes in the field, i.e. the analysis of spring discharge and groundwater hydrograph records, both for humid-temperate as well as semi-arid conditions, the analysis of water tracers (Krypton and T/He; trace organics) as well as the coupled modelling of saturated / unsaturated flow, employing a double-continuum approach.

Our findings show that in less maturely karstified aquifer systems, the contribution of delayed seepage from the vadose zone can reach up to 40% of total spring discharge which is of particular importance in regions with prolonged drought periods, expected for semi-arid environments. The analysis of the tracer information allowed the discrimination of the process of delayed discharge, in particular Krypton tracer analysis demonstrated the extended residence time of infiltrating water in the vadose zone.

Water level in observation wells simulated from fracture and matrix water heads outputted by dual-continuum hydrogeological models

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This work deals with the simulation of flows in fractured porous reservoirs, and more specifically the issue of modelling the hydrogeological processes in a way that takes into account the effect of the very existence of observation wells on the evolution of piezometric heads.

For densely fractured porous reservoirs, it may be appropriate to model the fractured porous medium as two distinct media, each one with its own hydrodynamic parameters and linked to the other by a water exchange term (*Warren and Root, 1963*) (*Gerke and van Genuchten, 1993*).

This representation is particularly suitable when water exchanges between the matrix medium and the fracture network are slow compared to the dynamics of the overall water flow in the system, and, at the same time, when the capacitive effect of the matrix medium cannot be neglected in these overall dynamics.

Such an approach introduces a significant number of parameters, which need to be calibrated as accurately as possible. The parametric adjustment process requires field data, such as piezometric records from observation wells, spring discharge rates or solute concentration records (from observation wells or at springs).

In this context, the problem is as follows: do observation wells in fractured porous aquifers measure water head in the fracture network, water head in the matrix reservoir, or some combination of both? One can assume generally that observation wells measure fracture water head, because matrix permeability is negligible compared to fracture network permeability (*Delay et al., 2017*) (*Robineau et al., 2018*).

Nevertheless, this reasoning may be invalid for observation wells poorly-connected to the fracture network (*Jazayeri et al., 2011*). Yet, the possibility of such a poor connection at given depths has never been implemented, to our knowledge, in a physics-based manner when comparing matrix and fracture water heads simulated by dual-continuum models to on-field data.

To fill this knowledge gap, a physically based, easy to calibrate, open-source postprocessing tool, “POWeR-FADS” (Program for Observation Well Representation in Fractured Aquifer Dual-continuum Simulations), has been developed. It introduces as parameters well geometry and the altitude of the lowest interception of the fracture network by the well, assuming that, when the water head in the fracture network is below this altitude, the borehole is no more directly connected to the fracture network.

From these, POWeR-FADS nonintrusively postprocesses time series of matrix and fracture water heads at the borehole, as simulated beforehand by any planar, bidimensional dual-continuum hydrogeological model (that do not explicitly take into account the existence of the borehole), to calculate water exchanges inside the observation well and thus the evolution of water level in the well.

Synthetic test cases show that POWeR-FADS makes it possible to simulate peculiar behaviors that are similar to patterns actually observed by the authors in on-site observation wells of a fractured porous carbonate aquifer: flat sections in observed piezometric records, delayed but sharp rises at the beginning of recharge events or inflexion points accelerating the drawdown velocity during the recession phase.

The benefit of this tool is that it allows these singular behaviors to be reproduced, thereby enabling better calibration of dual-continuum models, reducing the risk of overfitting.

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Seasonal trends in continuous spring temperature and discharge data from karstified and fissured rocks in Switzerland

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Continuous water temperature data of 15 springs in karstified carbonate rocks and of 15 springs in fissured rocks of the Swiss National Groundwater Monitoring NAQUA were processed and evaluated grouped by season. Springs in the Jura, on the Plateau, and in the Alps were studied. Some karst springs in the Alps are recharged in summer by glacier melting water. While some springs in fissured crystallin and clastic rocks show an overall increasing trend for groundwater temperature over the last 25 years – similar as gravel aquifers in river valleys – such a tendency is not observed at springs in karstified carbonate rocks. The increasing tendency of the groundwater temperature at springs from fissured rocks can be attributed to climate change. In karstified rocks, mixing of waters from the different parts of the aquifer might mask a possible increasing trend in temperature. Furthermore, the groundwater temperature data were compared with the NAQUA continuous measurements of spring discharge, electrical conductivity and turbidity, and with air temperature and rain amount. A correlation between water temperature and electrical conductivity was observed. But the water temperature at springs in karstified rocks does not follow the increasing tendency of air temperature. The results from Swiss aquifers are also compared with observations made in the neighboring countries. The challenges of online monitoring in karstified rocks on a national level are also discussed.

Control of geological structure on karst development and groundwater circulation in Jinci Spring Basin, northern China

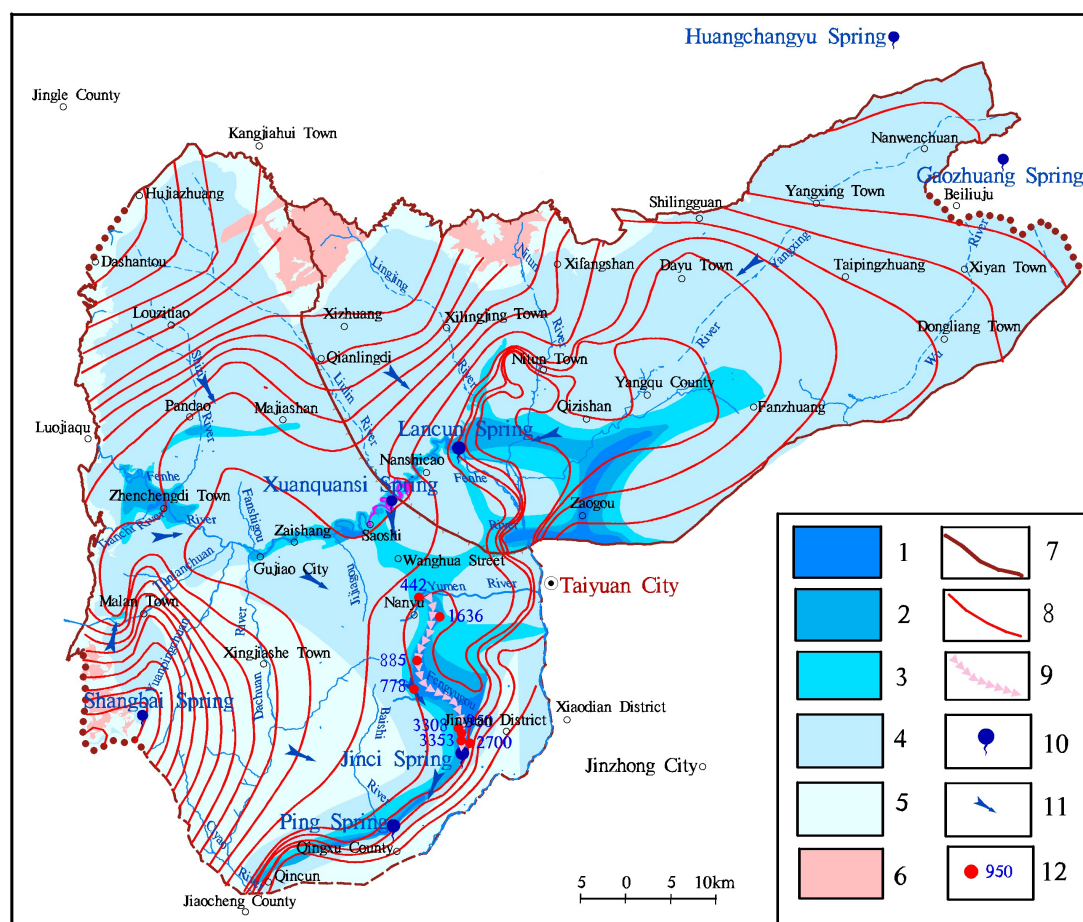
Haoyong Shen, Yongping Liang

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Jinci Spring is a typical large karst spring in northern China, consisting of Nanlao, Shengmu, and Shanli springs. It discharges at the foot of Xuanweng Mountain in the western hills of Jinyuan District, Taiyuan City, Shanxi Province, with a catchment area of approximately 2,713 km². The spring flow was about 1.99 m³/s in the 1950s but dried up in 1994.

The karst aquifer in the basin is primarily composed of Cambrian and Ordovician carbonate rocks. Geological structure is the key factor controlling karst development and groundwater circulation. The overall structure is an NNE-trending, asymmetric compound syncline, uplifted in the north and plunging southward. Controlled by the Malan and Shiqianfeng synclines, the burial depth of carbonate rocks in the central-western part exceeds 500 m, with a deep burial zone (>1000 m) formed in the synclinal core. Karst development here is extremely weak, as evidenced by intact drill cores with minimal dissolution features, specific well yields mostly below 2 m³/d·m, and generally poor water yield potential. In contrast, the central zone (Zhenchengdi–Gujiao–Wangfeng–Mingxian–Jinci Spring) exhibits intense karstification. Numerous karst collapse columns, mostly elliptical or irregularly circular with long axes of 30–50 m, have been discovered during coal mining in the overlying Carboniferous–Permian strata. The youngest strata found within these columns belong to the Triassic, indicating significant subsurface dissolution. Furthermore, boreholes in the Wangfeng horst and along the eastern marginal faults reveal 1–3 m high karst caves, and a 4.3 m high cave was encountered near the Jinci Spring, representing areas of strong karst development and highly conductive hydrodynamic conditions.

The structural framework governs the zonation of karst water circulation. The northern carbonate outcrop area serves as the main recharge zone, where single-well yields are generally below 500 m³/d, groundwater chemistry is of the HCO₃–Ca·Mg, and total dissolved solids (TDS) are below 350 mg/L. The central and eastern parts act as the runoff–convergence zone, with single-well yields reaching 1,000–10,000 m³/d, groundwater chemistry transitioning to the SO₄·HCO₃–Ca·Mg, and TDS increasing to 500–900 mg/L. The southeastern part is the discharge zone, featuring main discharge points such as Jinci Spring and Pingquan Spring, where groundwater chemistry becomes the SO₄–Ca·Mg and TDS rises to around 1000 mg/L. Additionally, based on groundwater yield potential, δD , $\delta^{18}O$, and ^{14}C data, a strong karst groundwater runoff belt has been identified along the path Nanyu–West of Baijiazhuang Coal Mine–Longshan–Mingxiangou–Jinci Spring.



1. Extremely water rich area($q>5000\text{m}^3/\text{d}\cdot\text{m}$); 2. Strong water rich area($q=3000\text{--}5000\text{m}^3/\text{d}\cdot\text{m}$); 3. Medium water rich area($q=1000\text{--}3000\text{m}^3/\text{d}\cdot\text{m}$); 4. Weak water rich area($100\text{--}1000\text{m}^3/\text{d}\cdot\text{m}$); 5. Poor water rich area($q<100\text{m}^3/\text{d}\cdot\text{m}$); 6. Non carbonate distribution area; 7. Karst groundwater system boundary; 8. Karst groundwater level contour line; 9. Karst groundwater strong runoff zone; 10. Karst spring; 11. Karst groundwater flow direction; 12. Karst groundwater borehole (the number represents the water inflow with a depth reduction of $1\text{m m}^3/\text{d}$)

Forty years of research progress at the Guilin Yaji experimental site: vegetation-driven karst critical zone research and prospects

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karst critical zone is a vital interface for global carbon and water cycles, and its structure and processes represent a frontier and challenge in global earth science research. This paper systematically reviews the research progress at the Yaji Karst Experimental Site across three core areas: karst hydrology, karst soil geochemistry, and carbon sink effects, with a focus on clarifying the coupled driving role of vegetation restoration within these domains. Research findings indicate that early hydrological studies have advanced from lumped "black-box" models to the refinement of process identification and simulation. Currently, there is an urgent need to integrate active regulatory modules of vegetation on interception, evapotranspiration, and runoff components, moving toward a new paradigm of "vegetation-water-rock" coupling. The understanding of karstification driving mechanisms has evolved from the binary coupling of soil carbon geochemical behavior and microbial catalysis to the clarification that vegetation constructs a ternary synergistic driving system of "vegetation-soil carbon-microorganisms" through carbon source supply and microenvironment regulation. Studies on the karst dynamic system theory and carbon sink effects have highlighted the coupled regulatory value of vegetation, confirming that vegetation significantly enhances carbon sink intensity and stability by optimizing carbon source supply and water transport. Vegetation has transformed from a passive response factor to a core driving factor connecting the three major research directions. Future research should focus on the in-depth coupling mechanism of "vegetation succession-karst dynamics-carbon sink function", and achieve the expansion from point-scale mechanisms to area-scale effects through the integration of multiple technologies. This will provide a scientific basis for ecological restoration and carbon management in the karst regions of southern China.

Spatial characterization of surface karst in the Canadian Rockies using SLAM LiDAR and photogrammetry

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Karst aquifers in the Southern Canadian Rockies represent a critical water source and storage mechanism, characterized by complex fracture networks that control recharge pathways and conduit development expressed at both the surface and subsurface. This study presents an applied geomatics approach to quantitatively characterize the three-dimensional morphology of two large surface shafts near Burstall Pass in Kananaskis Country, approximately 100 km west of Calgary, Alberta. These shafts are representative of dozens of similar features on the Burstall Plateau that collectively form a major recharge catchment for the underlying aquifer, with many occurring within large depressions interpreted as remnant sinkholes.

A multifaceted survey methodology integrating portable laser scanning, GNSS control, and photogrammetric reconstruction was employed to generate high-resolution 3D models of the subsurface karst geometry. Advanced SLAM (Simultaneous Localization and Mapping) laser imaging techniques were deployed in a challenging alpine environment to capture vertical and overhung geometries inaccessible to conventional surveying methods. The larger feature is an elongated shaft approximately 9m long, 3m wide, and exceeding 30m in depth, while the smaller sinkhole has a $\sim 1\text{m}^2$ opening and extends nearly 20m below surface. A SLAM-based handheld laser scanner was repeatedly lowered into the openings and integrated with stationary surface scans and oriented photography to produce georeferenced 3D models with approximately $\pm 10\text{mm}$ precision.

Tracer analysis has previously demonstrated hydraulic connectivity between this aquifer and a discharge stream located 15km to the north and more than 600m lower in elevation. By providing quantitative geometric characterization of key surface inputs, this work contributes to improved understanding of alpine karst recharge processes and demonstrates the value of applied geomatics techniques for karst hydrogeological investigation [1].

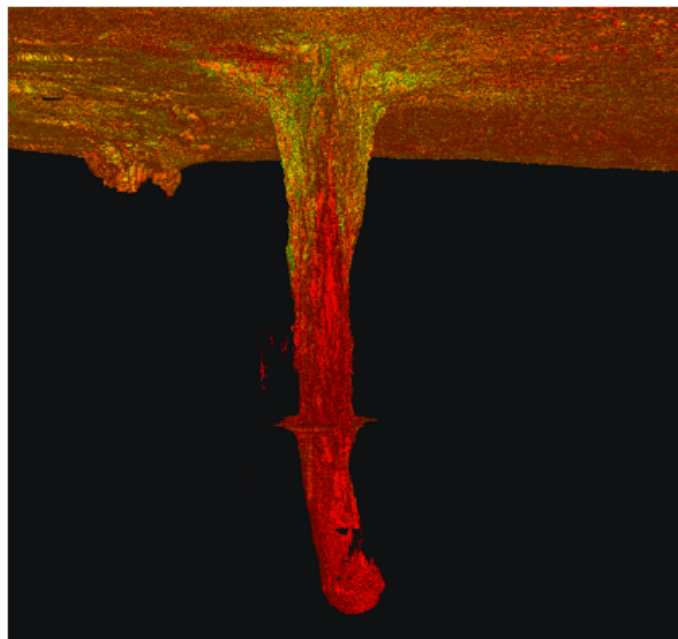


Figure 1: Point cloud image of surface karst showing both fracture and bedding plane dissolution features. Karst dimensions are 9m x 3m x 30m. Color represents the intensity of the signal return with intensity decreasing with depth.

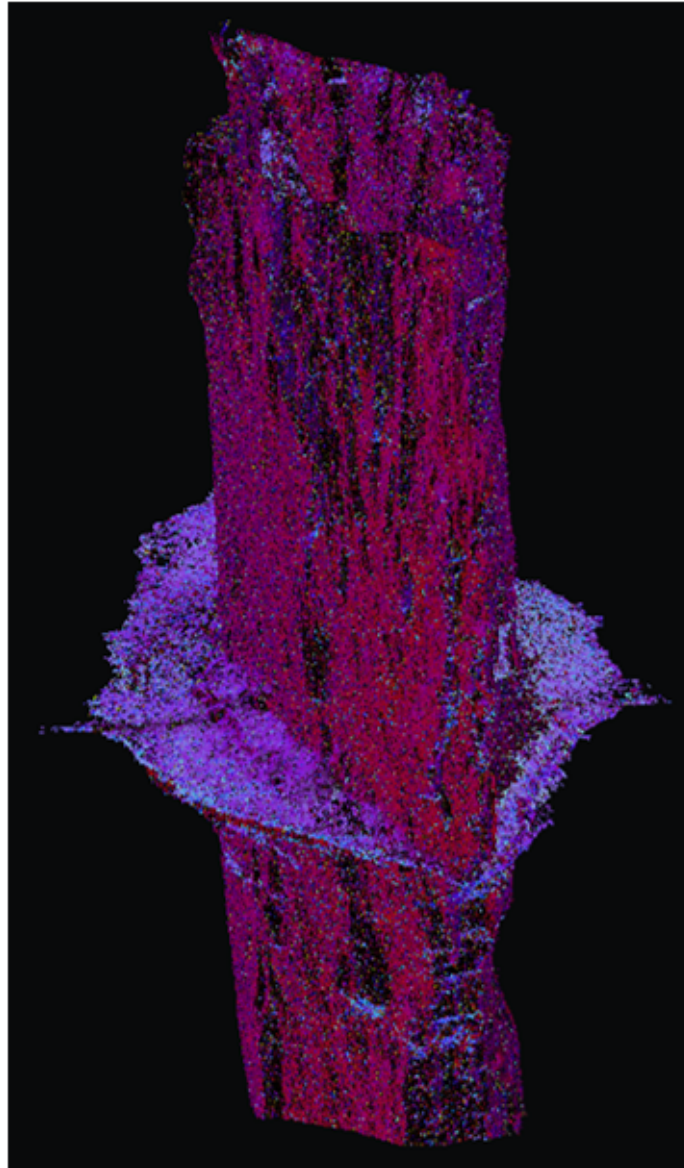


Figure 2: Image of bedding plane dissolution feature located approximately 15m below the surface. Point color represents the normal vector to the surface, highlighting the difference between horizontal and vertical facets.

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When the karst systems are known: A virtual laboratory for benchmarking lumped models

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Groundwater models are important tools when studying and managing karst water resources. There, and especially when we aim at obtaining system understanding through models, it is not just important to get right answers (e.g., good agreement between simulations and observations), but we have to get these answers for the right reasons (i.e., because the underlying processes are realistically reflected in our model). For lumped models, which reflect the karst system in a spatially aggregated manner, this problem has been addressed before, e.g., via model evaluation using multiple system signatures, such as spring discharge and solute concentrations, during model calibration. Because the conduit network and general geological structure are largely unknown in most cases, lumped model (structural and process related) realism beyond a model's ability to simulate system signatures is often impossible to assess. To better understand karst system functioning for groundwater resources management lumped models are still vital tools, making it necessary to study karst systems and corresponding lumped models on the basis of completely known systems. To tackle this challenge, we develop a virtual laboratory for karst groundwater modelling. This virtual laboratory facilitates (1) the generation and simulation of synthetic karst systems, together with system signatures such as spring discharge, using state-of-the-art spatially distributed numerical modelling and (2) the subsequent simulation of karst system signatures using lumped models. This virtual laboratory makes the generation of synthetic karst systems more accessible to a wider hydro(geo)logical community, taking a step towards more realistic process representation in lumped karst models in the future. Building on our previous work, the virtual laboratory allows for the stochastic generation of conduit networks using pyKasso [1] and their subsequent embedding and simulation with the spatially distributed discrete-continuum model MODFLOW CFPv2 [2] via the CFPy package for the Python programming language [3]. Lastly, the virtual laboratory allows for the application of a range of lumped models to the synthetically generated data. We demonstrate the capabilities of the virtual laboratory for a number of cases, show upcoming development goals, and discuss opportunities for future applications.

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Coupling flow and transport in hydrological modeling of karst environments

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Lumped parameter hydrological models (LPHM) has been widely developed in karst hydrology during the last decades. Such models aim to simulate the transfer function of a karst system by estimating spring discharge from meteorological forcing (precipitation, evapotranspiration). Identifying the suitable LPHM structure remains challenging in karst environments as a consequence of (i) a high heterogeneity and anisotropy of the flow behavior, (ii) a limited access to the internal structure of the host aquifer and (iii) the lack of informative content of piezometric measurements (when available). LPHM constitute a powerful tool to simulate karst spring discharge with parsimony but may lead to model structure equifinality, meaning that several LPHM structures can reach satisfactorily predictive performance. Such situation leads to one question: *do my model works for good reason ?* Then, auxiliary observations can be used to evaluate the consistency of the spring discharge simulations with different kind of field observations such as piezometric head measurement (Mazzilli et al., 2011), surface flow (Cousquer and Jourde, 2022), gravimetry (Mazzilli et al., 2013) or air excess (Sivelle et al., 2022).

In this study, we evaluate the added value of considering major ions concentration time series for the calibration of LPHM over the Toulon spring (supplying drinking water for Périgueux city, France) and the Lez spring (supplying drinking water for Montpellier city, France). To do so, we developed a flow and transport model derived from the LuKARS 3.0 model (Richieri et al., 2025) by coupling LPHM with IPhreeqc (Charlton and Parkhurst, 2011). The LPHM parameter estimation is performed using a Bayesian inference framework implemented with PyMC3 (Salvatier et al., 2016). We hypothesize that including major ions time series in the LPHM calibration support the model structure selection by including flow and transport processes understanding through hydrogeochemistry.

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Recharge to the Confined Aquifer of the North Coast Karst Belt of Puerto Rico

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The two main aquifers associated with the North Coast Karst Belt of Puerto Rico provide water for industry, agriculture, and municipalities of the north coast of the island (Figure 1). Tertiary-age geologic formations associated with both aquifers consist largely of limestone. A marly limestone unit of the Cibao Formation separates the two aquifers. Significant karst features such as mogotes (conical hills) and sinkholes (dolines) are common where these units are exposed at the surface (Figure 2). There is some apparent fault or fracture control for the escarpment that marks the western edge of the Lares Limestone where the Río Grande de Manatí has cut deeply into the Tertiary formations.

The surface and subsurface geologic units within the North Coast Karst Belt consist largely of Oligocene to Miocene-age sedimentary formations overlain by semiconsolidated to unconsolidated Quaternary deposits. This study focuses on the Cabachuelas Cave Preserve in the municipality of Morovis. The principal karst forming geologic unit in the study area is the Oligocene-age Lares Limestone. The Lares sits conformably on the San Sebastián Formation which consists of sandy limestone and consolidated and unconsolidated sand.

The elevations of the bottoms of the deepest sinkholes follow a line that dips to the north at about 1.6 degrees (Figure 3). This provides for a minimum thickness of the Lares Limestone of 15 m above the top of the San Sebastián Formation. The alignment of the bottoms of the sinkholes suggests that a bedding feature is limiting downward migration of the sinkholes. This could be due to a lower permeability bed in the limestone. Evidence for this is some streams that flow short distances across the bottom of some of the sinkholes before entering the subsurface.

The position of the contact between the Lares Limestone and the San Sebastián Formation is based on field observations and the geologic map of Berryhill (1965). The dip of the contact is estimated to be about 2.2 degrees to the north.

Other than the incised valley of the Río Grande de Manatí to the west of the site, there is no evidence of discharge of groundwater that infiltrates the subsurface within the zone of mogotes and sinkholes. The stratigraphy of the area suggests that groundwater flow is primarily through the lower portion of the Lares Limestone (Figure 3). The lower permeability of the underlying San Sebastián Formation would limit the amount of water that could pass through that formation. Down dip (north), the recharging water spreads into the limestones of the Cibao Formation which overlies the Lares Limestone.

This study shows that the Cabacuelas karst area is a significant source of water to the unconfined aquifer to the north that is used extensively by industry, agriculture, and municipalities. A better understanding of this water source could lead to better protections for water quality and could avoid the contamination by industrial activities of the unconfined aquifer.

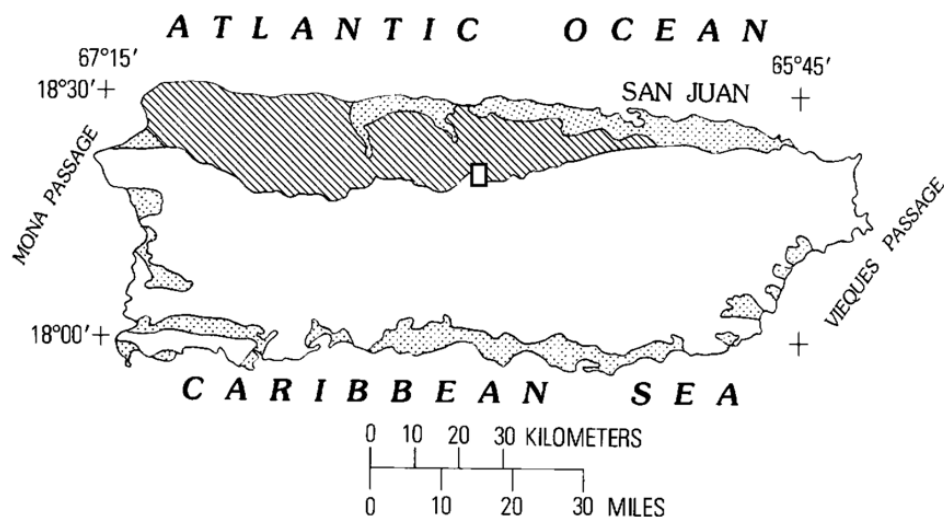


Figure 1. Location of the study area (rectangle) within the North Coast Karst Belt of Puerto Rico (dark shaded area) (figure modified from Monroe, 1980).

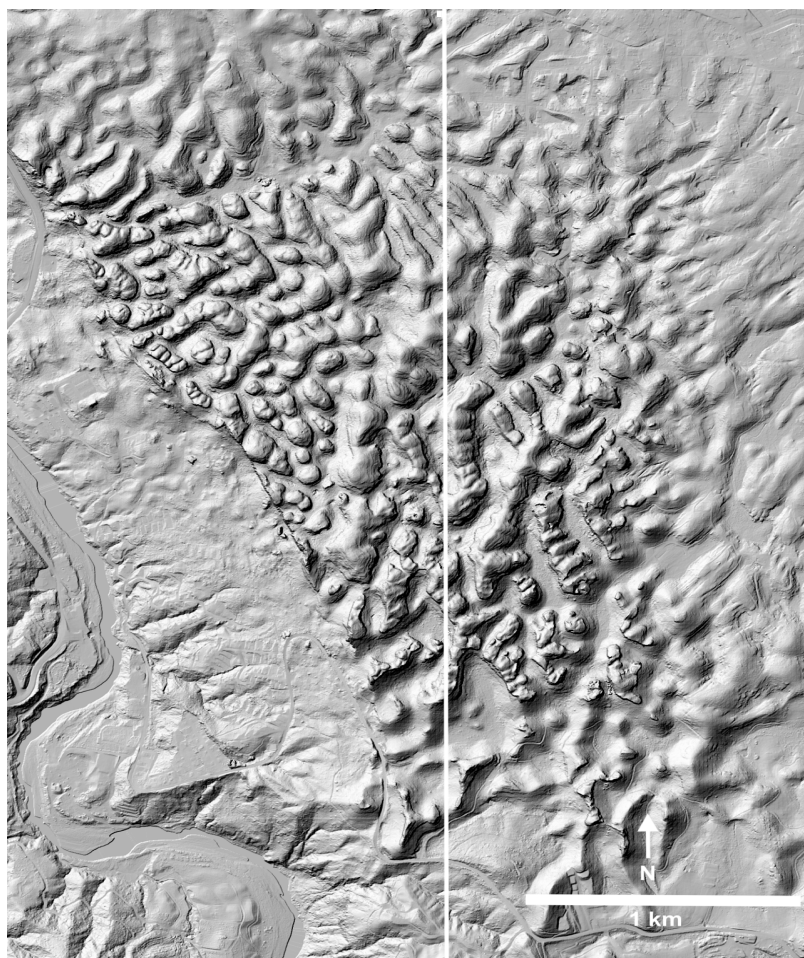


Figure 2. Digital elevation model (DEM) of the Cabachuelas area in the municipality of Morovis, Puerto Rico. The vertical white line represents the cross section presented in Figure 3. The DEM is based on lidar data from NOAA (2018).

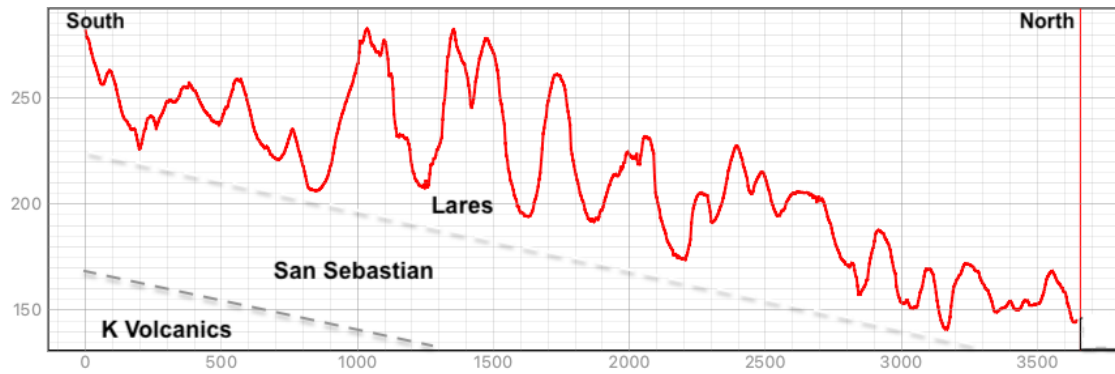


Figure 3. North-south cross section based on lidar data, geologic maps (Berryhill, 1965; Monroe, 1980), and field mapping. Values are in meters.

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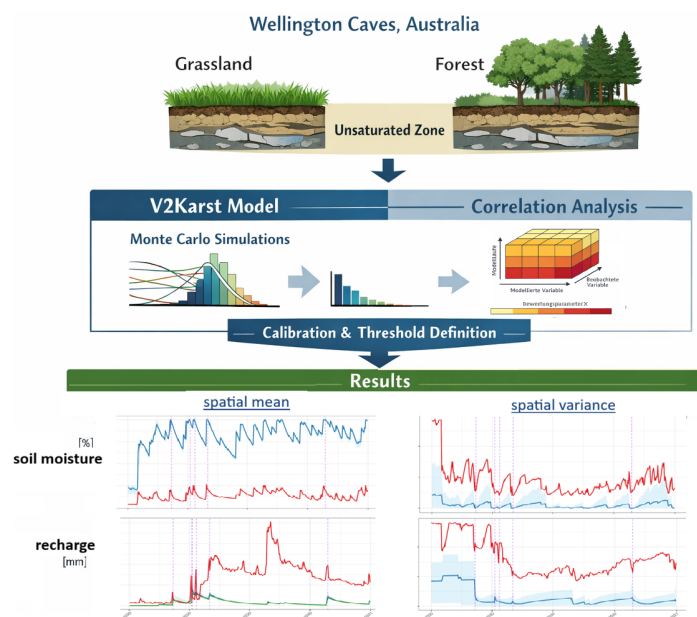
Evaluating the semi-distributed V2Karst model through a systematic correlation analysis: Dynamics of soil moisture and potential groundwater recharge at Wellington Caves (New South Wales, Australia)

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Karst systems are distinguished by their pronounced spatial heterogeneity and nonlinear processes in the unsaturated zone. This characteristic complexity renders high-resolution simulations of groundwater recharge a challenging endeavour. The objective of this work is to determine whether the semi-distributed model V2Karst successfully captures the dynamics of soil moisture and potential groundwater recharge in terms of spatial means and variances for different land uses (i.e., grassland and forestry) on the plot scale for the Wellington Caves (New South Wales, Australia). To address this aim, a Monte Carlo ensemble was subjected to multifactorial evaluation through systematic correlation analysis. Based on these findings, a set of threshold values was derived for an enhanced calibration strategy that incorporates modelling uncertainty. The findings demonstrate a highly effective reproduction of the temporal dynamics of the spatial mean of soil moisture in both land uses (Pearson's $r > 0.8$), in addition to site-specific differences in their spatial variance ($r_{\text{Grass}} > 0.9$; $r_{\text{Wood}} > 0.6$). For recharge processes, the time series of spatial variance is consistently reproduced using cross-correlation ($\text{CCF}_{\text{Grass}} > 0.75$; $\text{CCF}_{\text{Wood}} > 0.8$), while the spatial mean demonstrates only limited agreement with the averaged drip time series ($\text{CCF}_{\text{Grass}} > 0.6$; $\text{CCF}_{\text{Wood}} > 0.5$). The behavioural parameter sets identified based on the threshold criteria – four for grassland and two for forestry (with overlaps) – focus on the following ranges: $a = 0.02\text{--}1.52$ (–), $V_{\text{soi}} = 123\text{--}873$ mm, $V_{\text{epi}} = 309\text{--}645$ mm (forestry up to 543 mm) and $K_{\text{epi}} = 30.4\text{--}47.9$ days. The interpretation of these results is partially limited by the restriction of the evaluation to a period of one year and 250 model runs, as well as by incommensurabilities between point drip data and area-related epikarst outflow. The study signifies an important methodological step towards small-scale, event-based calibration of V2Karst, emphasising the significance of metrics for characterising spatial variance and temporal dynamics in the evaluation of potential groundwater recharge. The work contributes towards the long-term development of the understanding of karst groundwater resources in the context of changing climate and land use conditions.

Keywords: karst hydrology, groundwater recharge, soil moisture, systematic correlation analysis, uncertainty-informed model evaluation



Czech Hydrometeorological Institute and its hydrological research of karst areas

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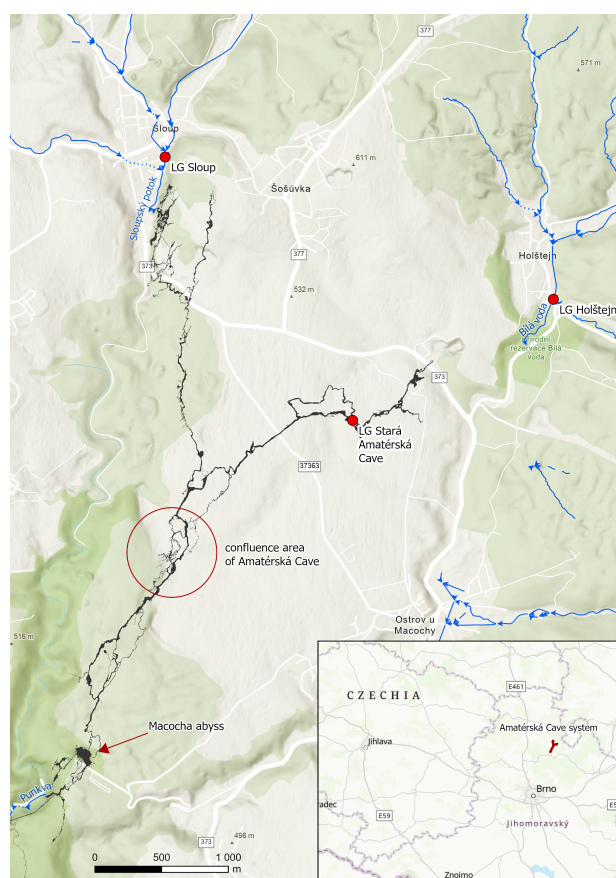
Since 2009, our team of hydrologists from the Brno branch of the Czech Hydrometeorological Institute (hereinafter CHMI) has been continuously monitoring the underground flow of the Punkva River in the Amatérská Cave system in the Moravian Karst. We are thus continuing the work of our predecessors from the CHMI, who at the turn of the 1960s and 1970s contributed to securing hydrological knowledge during the dramatic discovery of the Punkva cave system – Amatérská Cave (hereinafter AMJ) – which today has 50 kilometers of known passages. The Punkva river originates in the central part of the AMJ cave system at the confluence of two streams – Bílá voda and Sloupský potok, which have created a maze of passages with a specific hydrological regime in this part of the cave (map). This was the impetus for our research – to describe the hydrological conditions of the Punkva confluence area, or, to put it more dramatically, to find the source of Punkva (Lejska et al. 2016a). Therefore, since 2009, we have installed pressure probes at more than 30 locations in this part of the cave and its wider surroundings to measure water level fluctuations at ten-minute intervals. Some of the probes also allow data to be transmitted to the internet using transmission cables up to 1 km long. 3D mapping of the AMJ confluence area using a terrestrial laser scanner has proven to be very useful for understanding karst hydraulics, due to the levelling of underground levels with the highest possible accuracy of approx. 1 cm. We began this high-precision mapping in 2013 in cooperation with the Institute of Geonics of the Czech Academy of Sciences, and today we have a 3D model of the AMJ confluence area with a length of more than 3 km. Repeated 3D mapping of cave passages in the AMJ system is used to assess the movement of gravel sediments after flood events (Lejska, Kuda, Špinarová 2025).

In 2018, a pressure probe with data transmission to the internet was installed in the Stará Amatérská Cave (hereinafter STAM). STAM is part of the AMJ cave system, which, from a hydrological point of view, represents the drainage inflow of Bílá voda into the AMJ confluence area. Because the nature of the cave passages at the site of the installed probe is also favorable for hydrometric measurements, we also evaluate the flow regime of the underground stream of Bílá voda here, which proves to be very beneficial in terms of the methodology of evaluating the flows themselves... The winter hydrological regime of Bílá voda is not affected by the freezing of the stream in the karst underground, which is otherwise a common phenomenon on surface streams not only in the Moravian Karst, but throughout the Czech Republic. Since we have been measuring the flow rates of Bílá voda above its underground sinkhole – the limnigraphic station Holštejn – since 1968, we have a tool for understanding the logic of freezing and thawing of ice on surface streams and its use for improving the CHMI methodology used to evaluate winter flow rates.

The Moravian Karst is an amazing natural laboratory for research into karst hydrology. In addition to the confluence area in the central part of the AMJ, monitoring water levels in the drainage part of the AMJ in the cave passages draining the Punkva river to its outlet in the world-famous Macocha abyss, also offers great research potential. Analysis of the measured data from the October 2020 flood wave in this part of the cave yielded very interesting results in terms of the hydraulics of flood water passage through the drainage parts of the cave system – changes in the direction of water flow, the function of estavelles and underground passages acting as dry polders (Lejska et al. 2021).

Recently, in cooperation with the Czech Speleological Society (CSS) and the Czech Geological Survey (CGS), we have been participating in expeditions to karst areas in the Balkans. In 2024, we provided bathymetric measurements of the world's largest underground hydrothermal lake, located in Albania, for an expedition led by the CSS. Bathymetric mapping was performed using ADCP sonar, commonly used at the CHMI to measure the flow rates of larger watercourses. The result of this measurement is a contour map created in a GIS environment of

Lake Neuron, which is 200 m long, 40 m wide, and up to 7.5 m deep, located in the Atmos abyss (Audy 2025). In 2025, in cooperation with the Czech Speleological Society and the Czech Geological Survey, we began hydrological research of the Mrtvica river in its karst canyon in the Maganik mountains in Montenegro. The Mrtvica river drains the Vranštica cave system, which is the drainage part of the system connected to the 1,160 m deep Iron Deep abyss discovered by Czech speleologists. Our task here is to describe the hydrological regime of the Mrtvica springs, which means monitoring water level fluctuations, including evaluating the flow rates of Mrtvica at several locations in its catchment area. To this end, we have so far installed three small improvised limnigraphic stations and carried out several hydrometric measurements. This karst area represents a real challenge for us, both in terms of testing measuring instruments and procedures in more demanding conditions, and subsequently in terms of developing not only new procedures but also new measuring techniques.



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Current status and future perspectives of the IAH Karst Commission's MIKAS (Most Important Karst Aquifers' Springs) Project

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Project MIKAS (Most Important Karst Aquifer's Springs, <https://mikasproject.org/>) was launched at the annual meeting of the Karst Commission (KC) of the International Association of Hydrogeologists (IAH) in June 2022, during the EUROKARST conference held in Malaga. Its aim is to identify, promote and create a base for the protection of the most important karst springs at the global, as well as at the national level. It is supported by the IAH Council and four continental-level sponsors. The project's Advisory Board (AB) is composed of Karst Commission members and previous Commission chairs, who have continental/regional responsibilities and coordinate the work of national experts.

The AB members prepared a set of Guidelines, which include selection criteria for the two established groups, MIKAS (the list of globally important springs) and NIKAS (nationally important springs), as well as a Spring Survey Form. The selection criteria are historic, aesthetic, economic, scientific and ecological.

At the end of 2025, the MIKAS project involved more than 100 national experts from six continents. To date, their expertise helped evaluate more than 250 springs in 65 countries, of which more than 160 belong to the MIKAS group. The tentative deadline for data collection is September 2026 and it is expected that by then approximately 80 countries will have been covered by appropriate expertise. The total number of countries with some karst occurrence is around 150, but not all of them have important springs. In certain cases, karst is of limited extension or even mostly confined. For some countries, in which important karst springs are present but no local expertise has been identified, AB members have collected and presented basic data in two categories: 1. Springs with insufficient data, or for which there is only a preliminarily survey, and 2. MIKAS/NIKAS candidate springs requiring further study. The former category provides a higher level of confidence and includes consultations with local or international experts who possess knowledge regarding the concerned country, whereas the latter relies solely on available literature and internet data and require confirmation that water has originated in karst aquifer.

The AB is preparing the Code of Practice aiming to highlight the importance of springs on the MIKAS and NIKAS lists, to defend them from possible devastation, and to advocate that any further intervention considers their internationally recognized status. The concept of protecting selected springs does not imply prevention of their further use. The projects for their development, whether or not they are already tapped out, should require only sustainable and precautionary approaches in water management. As a final action, a proposal for standardised informative plates with emblems of the IAH Karst Commission, MIKAS and the local responsible water/environmental agency will be shared with engaged national experts.

As in many such global projects, it is to be expected that additional information sources and experts will arrive after the results of the project are presented and widely disseminated. Therefore, the project will remain active and open to any new set of information and updates which will be posted on the web page <https://mikasproject.org/>. In the meantime, a MIKAS

monograph, edited by AB members, will be prepared and published as an open access document.



Figure 1. Four approved MIKAS from four Continents: Tambomachay (Cusco, Peru) (upper, left); Bekhal (Soran, Iraq) (lower, left); La Loue (Besançon, France) (upper, right); Alley spring (Eminence, MO, USA) (lower, right) (photos by Z. Stevanović)

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Deep learning karst network generator

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Karst networks are structured around preferential pathways that strongly influence flow, making karstic environments highly vulnerable to extreme events such as severe droughts and torrential rainfall. Understanding the behaviour of karstic systems and quantifying forecast uncertainty are challenging. Modeling realistic karst networks is inherently complex due to strong structural variability and limited data availability, which motivates a probabilistic approach combined with a data augmentation scheme.

We propose a deep learning (DL) method to generate stochastic realizations of karst networks through graph representation, in which nodes and edges represent intersections and conduits, respectively, and encode both network topology and geometry through spatial coordinates and edge connections. A generative model comprising two DL models is proposed. First, a graph recurrent neural network (GraphRNN), proposed by You et al. (2018), is applied to learn and generate graphs (topology), with nodes represented as abstract points without spatial coordinates. The second step uses denoising diffusion probabilistic models on graphs (G-DDPM) to learn node features (spatial coordinates and, optionally, other properties), thereby reconstructing new karst networks from GraphRNN outputs, sharing the same statistical properties as the training dataset.

GraphRNN. A karst network can be represented as a graph using its adjacency matrix, binary and symmetric, with an entry equal to 1 at row i and column j if an edge links nodes i and j . Using a breadth-first search (BFS) ordering of the nodes yields an adjacency matrix with bandwidth m , which can be encoded as a reduced $n \times m$ matrix corresponding to the upper diagonals. To learn this structure, the reduced matrix is decomposed into a sequence of rows, where each row represents a node. Each row is further decomposed into a sequence of binary values indicating the presence or absence of connections with the previous nodes. The GraphRNN consists of two imbricated recurrent neural networks : one learning the node sequence (rows), and the other one the edge sequence (columns within a row).

G-DDPM. Denoising diffusion probabilistic models (Ho et al., 2020) were originally developed for image generation. The method consists in progressively adding noise to the pixel features of an image until it becomes Gaussian white noise (forward process). A second model learns to reverse this process by denoising the corrupted images (reverse process). Once trained, the reverse process can generate new samples by transforming Gaussian white noise into realistic images. In this work, DDPM is applied to graphs by considering the spatial coordinates as node features. In this case, the forward process progressively randomizes the node positions of the graphs of the dataset, whereas the reverse process is trained to denoise the node coordinates to recover the graph geometry (Fig. 1).

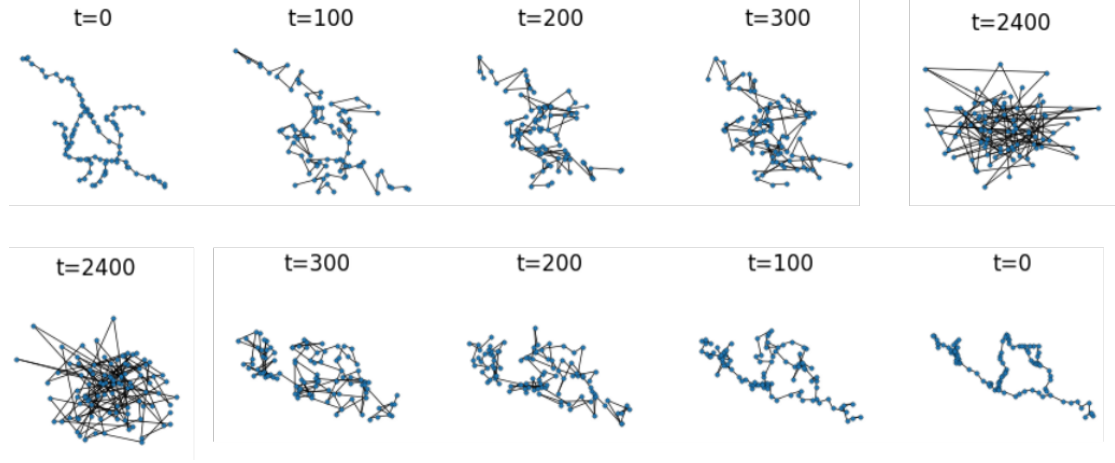


Figure 1. Illustration of the G-DDPM processes at selected time steps: top) forward process applied to a graph of the dataset ; bottom) reverse process applied to an output graph of the GraphRNN with initial noisy node coordinates.

Results

The proposed method has been applied using a training dataset of 1'000 connected subgraphs extracted from a real mapped karst network of Ox Bel Ha in Mexico (Coke, 2019), an almost horizontal underwater coastal system, such that node coordinates are treated as two-dimensional. Figure 2 shows graphs from the dataset (top left) and generated graphs (top right), and a comparison of statistics from selected topology and geometric metrics (Collon, 2017) for the dataset and an ensemble of 1'000 generated graphs.

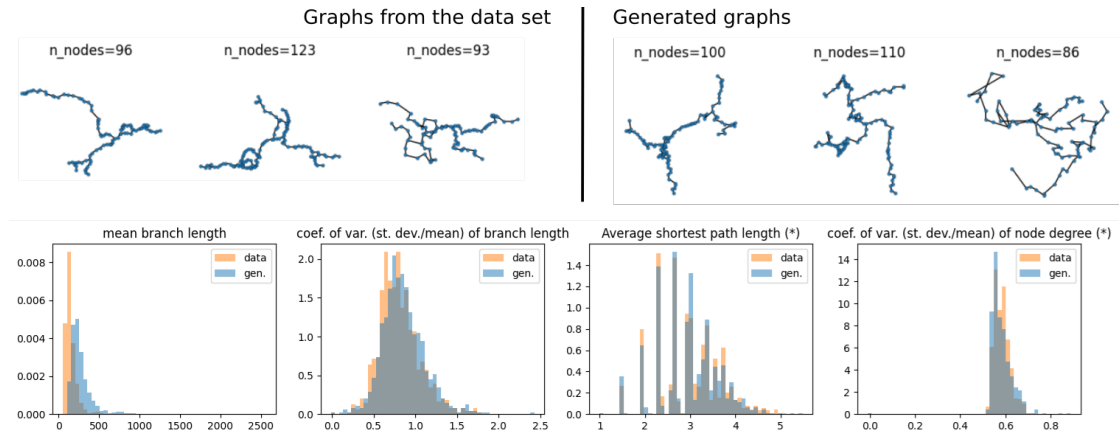


Figure 2. Results: top) graphs from the dataset and generated graphs ; bottom) selected statistics for the dataset (orange) and the ensemble of generated graphs (blue) : mean and coefficient of variation of length of branch (path connecting two nodes of degree not equal to 2) (geometry metrics) and average shortest path length (in number of edges) and coefficient of variation of node degree (topology metric, computed on the simplified graph where each branch is replaced by one edge).

The presented deep generative model (Lauzon, 2025 ; Straubhaar, 2025) enables the simulation of new graphs that share the topology and geometric statistics of karst networks used for training. The model has to be further tested on more complex and larger networks, by considering other datasets constituted, for instance, from KNdata, a database of real-world karst networks represented as spatial graphs (Trunz et al., 2026) ; furthermore, if available, additional features can also be considered for the G-DDPM part.

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Geometry and morphology of karst conduits

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The aim of the work presented in this poster is to characterize quantitatively the geometry of an ensemble of karst conduits that have been scanned with a LiDAR device. This work is carried out to better understand the relation between the geometry and the hydraulic properties of cave conduits and in particular the role of rugosity. In this poster, we only present the geometrical analysis. The hydraulic property analysis is conducted through laboratory experiments presented in Noffz et al. (2026).

We consider a set of karst conduits that have been mapped from point clouds acquired by LiDAR (Light Detection And Ranging). Each conduit consists of a two-dimensional triangulated mesh of its wall and a centreline (Racine et al., 2025). For any position along the centerline, a cross-section can be extracted by intersecting the wall model with a plane orthogonal to the centerline (Fig. 1). A cross-section is then a closed planar curve. We propose an ensemble of geometric descriptors or indicators for a closed planar curve. In a second step, we quantify how these descriptors vary along the conduit using variograms or spatial autocorrelation along the centerline. This allows us to identify typical length scales characterising the spatial variations of the conduit geometry parameters.

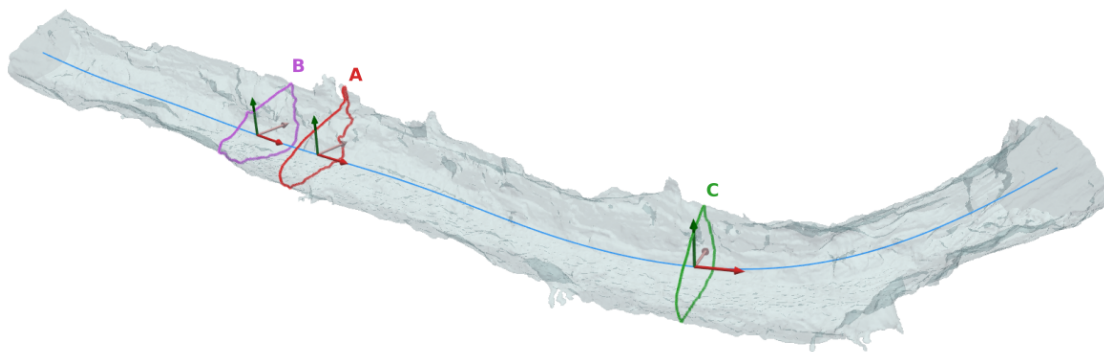


Figure 1. Example of a triangulated mesh of a karst conduit in Grotte de la Cascade (Môtiers, Canton of Neuchâtel, Switzerland), its centreline (~60 m long), and three cross-sections (see also Fig. 2).

Among the selected geometric descriptors for a closed planar curve, we consider the area A and the perimeter P , the hydraulic diameter $4A/P$ (for full immersion) and the isoperimetric quotient $4\pi A/P^2$, defined as the ratio of the section area and the maximal area that can be obtained with the same perimeter (disc). Other indicators can be computed, such as the convex hull, its area, and the solidity, defined as the ratio of the section area and the area of its convex hull. Figure 2 shows an example of typical results for the hydraulic diameter along the centerline.

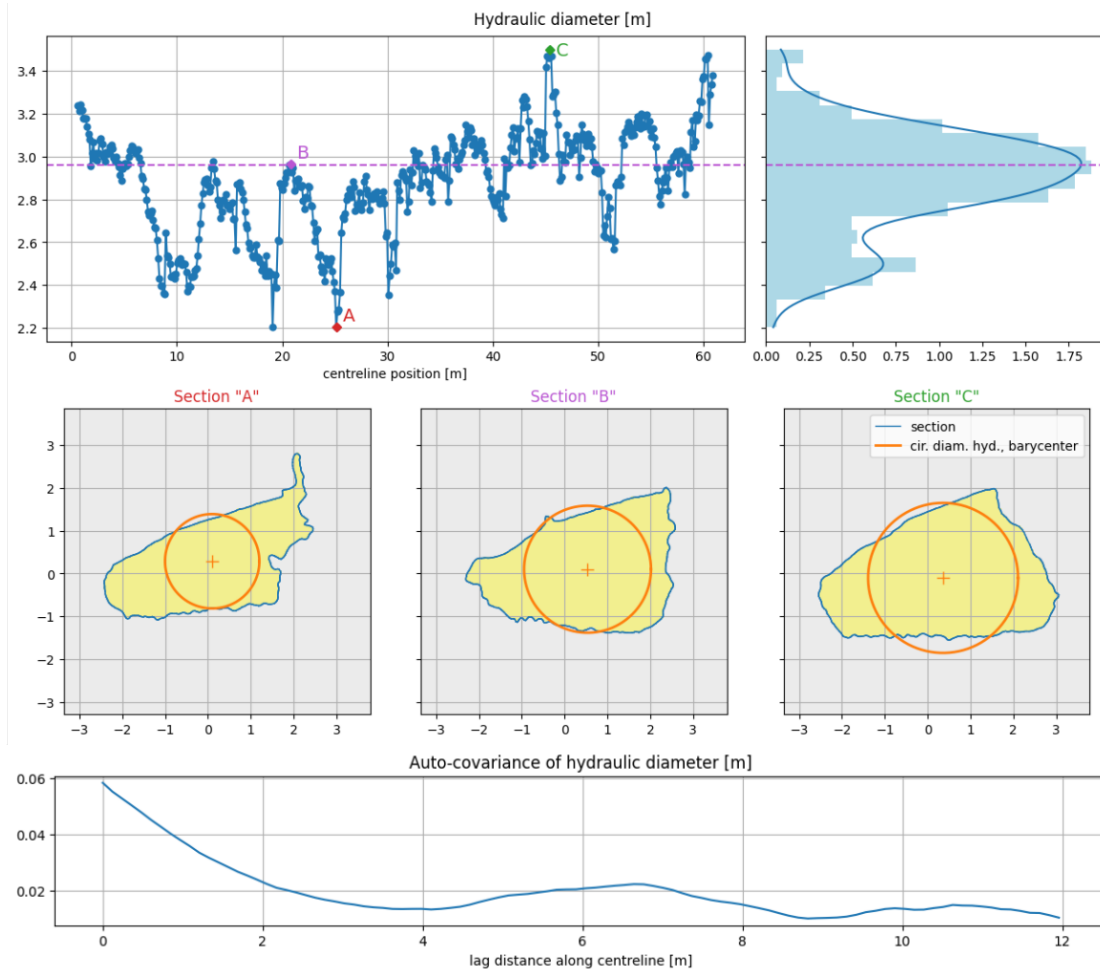


Figure 2. Top) hydraulic diameter computed on cross-sections along the centerline for the karst conduit of Fig. 1 and its density histogram ; middle) cross-sections corresponding to min, mode and max hydraulic diameter (these sections are also shown in Fig. 1), the orange circle is centred on the centre of mass of the section (barycentre) and has a diameter equal to the hydraulic diameter ; bottom) auto-covariance of the hydraulic diameter along the centreline.

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Recharge typologies of karst drip water in the vadose zone across southeastern Australia

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Groundwater resources already play a vital role in sustaining drinking water supplies, agricultural and industrial production, and ecosystem integrity (Murphy et al., 2017). With the increasing frequency of extreme weather events and water demands driven by population growth, groundwater is becoming an increasingly important resource worldwide. It is estimated that approximately 20% of global groundwater recharge occurs in karst regions, despite these areas covering only about 11% of the Earth's land surface, highlighting the high recharge efficiency of karst systems and the need for focused investigation of these environments (Wang et al., 2024). However, the structural heterogeneity and nonlinearity of karst aquifers make the identification of recharge dynamics using traditional methods, such as water table fluctuations, particularly challenging.

Karst caves provide a laboratory for observing recharge processes, with dripwater counts providing direct, high-frequency records of flow-path activation and storage release across different spatial settings. In this study, we develop and apply a multi-method time-series framework to classify dripwater recharge behaviour across six contrasting karst settings in southeastern Australia using Stalagmate© drip loggers (Baker et al., 2024). These cave sites are part of Australian National Groundwater Recharge Observation System (NGROS) and span a wide range of lithologies, geological ages, and climate types, offering a representative cross-section of karst vadose zone recharge behaviour in southeastern Australia (Baker et al., 2024; Priestley et al., 2025). Drip water time series were analysed using an integrated suite of time series techniques, including fast Fourier transform (FFT) to characterise dominant periodicities, cross wavelet transform (XWT) to quantify time-varying coherence with rainfall, and change point analyses (CPA) to detect regime shifts and transient recharge events. This multi-metric framework identified long-term, short-term, periodic, aperiodic, normal baseline and abnormal fluctuations, with particular emphasis on identifying transient recharge events that are critical for groundwater resource assessment and management.

This research successfully classified drip water behaviours into five recharge types with distinct rainfall sensitivity, lag structure (proxy for vadose zone transit time), and activation thresholds: dual flows systems (37.0% dominant by epikarst and 8.7% by soil storage), fast-responding fracture dominant recharge (17.4%), storage-controlled delayed recharge (13.0%), and threshold-dominated flow (23.9%). Our results highlight the significant spatial heterogeneity and temporal variability in karst responses both within individual sites and across southeastern Australia. The identified recharge types demonstrate that differences in karst architecture fundamentally control drip time series patterns, with precipitation-driven recharge switching between mechanisms and flow path also playing a role in drip water recharge rates.

Specifically, CPA variance proved particularly sensitive to critical transitions across karst environments. Overall, 8.70% of sites exhibited abrupt shifts largely consistent with major rainfall events, 67.4% displayed detectable but irregular changepoints, and 23.9% remained relatively stable over the monitoring period. Moreover, the combined interpretation of CPA with FFT and XWT further revealed the potential influence of external forces on recharge sensitivity. Younger karst generally exhibited buffered and storage-release responses reflecting matrix flow, whereas mature karst systems were primarily characterised by well-developed fractures and conduits dominated fast flow. Lithology governs recharge dynamics across and

within regions by controlling the distribution of storage and flow pathways in karst systems. Climatic regime plays a secondary yet consistent role in shaping recharge and flow dynamics.

Two fundamental mechanisms support the diversity of observed recharge behaviours: threshold activation and storage buffering (Sun et al., 2025). Threshold effects dominate event-driven recharge through fast preferential flow networks, whereas storage buffering sustains delayed, continuous slow flow. Individual sites exhibited either single or combined modes with possible switching of the dominant mechanism over time, reflecting shifts in the relative contributions of flow paths and storages. These determine drip water behaviour and influence water residence times, with implications for cave hydrochemistry (kinetics vs equilibrium chemistry) and cave formation processes (dissolution and secondary speleothem formation). While these processes and recharge types have been widely recognised at aquifer discharge scales, our results show that these are equally observable at drip scale and relevant for studying recharge processes. These findings therefore challenge static recharge conceptualisations and emphasise the necessity of distributed temporal monitoring and analysis in karst hydrological studies. By integrating multiple complementary time series methods, this study presents a comprehensive and transferable framework for characterising karst recharge behaviour using cave drip water records. Compared with the analysis of single indicators, the multi-dimensional classification more effectively captures both structural heterogeneity and temporal shifts within karst systems, provides a process-based interpretation for recharge variability and supports the development of physically informed numerical models.

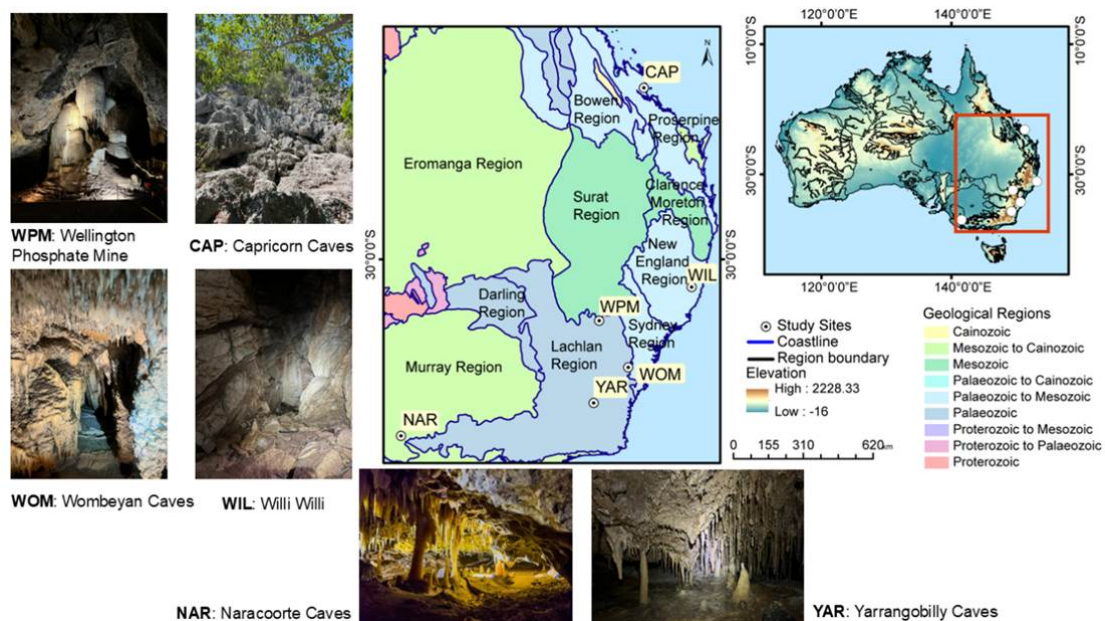


Figure 1. The location of all study areas. Colours on the left map show the broader geological region and geological age, while the colours on the right map show elevation (Raymond et al., 2012). A field photo from each cave is included.

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Climatology and microbial dynamics at Points Cave (France)

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In the context of subsurface warming and increasing CO₂ concentration resulting from climate warming, understanding what causes microorganisms' outbreaks in caves becomes crucial. Caves with openings to the outside that allow direct exchange with the outside atmosphere can disseminate microorganisms in the galleries. Confined caves also show subtle internal airflow patterns triggered by small thermal gradients at the karst massif scale, that can transport bioparticles. Dripping water is another source of aerosols that can affect the spread and growth of microorganisms. In this study, we combine thorough continuous environmental monitoring of cave climate (temperature (Seabird SBE56), pressure (Barologger Solinst), evaporation (Piche Evaporimeter), dripping rate (Stalagmate Driptych), radon (Barasol, Algade, France), and CO₂ content (Vaisala)), with seasonal collection of fungi and bacteria suspended in cave air. This allows us to investigate the dynamics of these microbial systems in response to changes in cave aerology.

The cave under study is Points Cave, a small prehistoric cave situated in the middle of the Ardèche River Gorge. It consists of a single 108-m-long gallery, that slopes slightly downward and exhibits a pronounced bend halfway through. A solid iron gate closes the gallery and enables air exchanges between the inside and the outside. The cave is not open to the public and is only periodically visited by archaeological teams and environmental surveyors. A vertical profile of both air temperature (5 SBE 56 sensors spaced every 70 cm) and evaporation (5 Piche evaporimeters) was set up at the bend in the gallery. Radon, CO₂ measurements, and a temperature probe/Piche evaporimeter couple were installed at the far end of the gallery. Ambient pressure and temperature were also measured in the decorated part of the cave, which is located halfway between the bend and the end of the gallery. Airborne particles were collected every three months using a Coriolis μ air sampler in two 10 minute-cycles in phosphate buffer saline. Upon return to the lab, the bacterial and fungal particles were grown in Petri dishes on trypticase soy agar with 50 mg/L of cycloheximide, and malt extract agar medium with 50 mg/L of chloramphenicol, respectively. The colony forming units (CFU) were counted after incubation and expressed as CFU per cubic meter. We further assessed the diversity of microbial communities through next-generation sequencing (NGS) by targeting the 16S rDNA gene for bacterial communities and the internal transcribed spacer (ITS) and 28S rDNA gene for fungal communities.

Temperature, radon and CO₂ measurements reveal the classic ventilation pattern of Points Cave, which involves the intake of cold outside air from mid-November to the end of April. During this period, a strong evaporation is also observed from the Piche evaporimeters. From May to November, the cave remains confined as demonstrated by higher, stable radon concentration and increasing CO₂ concentration. Interestingly, the vertical temperature/evaporation profile then reveals the presence of two superimposed air masses in the gallery: the lower air mass is undersaturated and slightly cooler (by about -0.1°C) than the upper saturated air mass. A significant rise in the water level is then observed in the two highest Piche evaporimeters while the water level continues to decrease in the three evaporimeters at the bottom of the profile. In parallel, the dripping rate increases indicating enhanced condensation at the ceiling and a drainage system not governed by a simple transfer through the fissure network. These observations suggest that natural convection occurs in the gallery during the confined period. Results of microbial growth indicate that the bioaerosol distribution is related to these airflow patterns as a shift in the spatial distribution of microorganisms occurs simultaneously. Maximal

bioaerosol concentrations at the cave entrance occur during periods of cold outside air intake, and the highest fungal concentrations are observed at the end of the gallery during confined periods (as confirmed by 11 years of biological monitoring by the LRMH). At the study site where the vertical profile was set, the bioaerosol concentration was higher during periods of homogenization of the air mass temperature across the cave height. On-going diversity analyses of NGS results will confirm these observations and determine the origin of the bioaerosols and the effect of changes in airflow patterns on microbial diversity within the cave.

Automated modeling of karst spring discharge across the entire Alpine Region using KarstMod

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Alpine karst aquifers cover approximately 40 % of the Alpine region and supply drinking water to major cities such as Vienna and Innsbruck [1]. Responding rapidly to hydrological events and being strongly influenced by temperature-driven snowmelt, karst groundwater systems are especially vulnerable to climate change. To sustainably manage karst water resources in the Alpine region under climate-change influences, robust, generalizable models that are applicable to a large number of springs are required. Reservoir or storage models, which represent karst systems as a sequence of connected storages with distinct capacities and drainage behaviors, are well-established approaches for describing spring discharge. Traditionally, these models require manual selection of the best model configuration and are consequently applied mainly to individual springs.

This study introduces an efficient, automated routine for configuration selection within the reservoir model KarstMod [2] and applies it to a novel, Alpine-wide dataset comprising 245 karst spring discharge time series [3]. The routine replaces manual reservoir-configuration selection with a pre-selection of feasible model structures and an optimization algorithm that determines the optimal arrangement automatically. Because many springs lack known catchment boundaries—information essential for the semi-distributed snow routine of the model and groundwater recharge estimation—a simple approximation method was developed. It infers the catchment area by combining estimated recharge rates, mean discharge, and topography. Based on calibrated model configurations and parameter sets, springs were clustered according to similar system behavior and compared with hydrograph-based classifications reported in the literature.

The resulting models constitute a valuable tool for assessing the potential impacts of climate-change scenarios on future available water volumes and their seasonal distribution in the Alpine karst region.

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Study of nitrogen transfer and origin in a large karst system using hydrochemical and isotopic methodology

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At the edge of a sedimentary basin, both autogenic and allogenic recharge can feed karst systems. In these cases, outlet springs water origins can be difficult to assess which leads to issues in water resource management. To better understand these origins and the variations in potential contaminants flow to the outlets of a large and complex karst aquifer, this study brings a geochemical and isotopic analysis to assess nitrogen mobility. It combines origin identification and groundwater flow path identification by geochemistry analysis, and assessment of respective contributions of the different origins (autogenic and allogenic) in outlet springs by a mixing model based on the geochemistry results. The Ouyse karst system is studied with this methodology. It is a large watershed (650km²) located in Western France and is exploited for its drinking water resource. The upstream part of the karst aquifer is fed by three main water origins: (i) diffuse infiltration on the karstic limestone bedrock; (ii) sinking stream coming from igneous-metamorphic rocks runoff; (iii) sinking stream fed by highly mineralized evaporite spring. This study shows how this watershed feeds the different outlets with the various origins in different hydrodynamics conditions. Geochemical model, hydrodynamical and nitrates isotopes study are applied and compared.

Hydrogéologie et fonctionnement du système aquifère carbonaté de la Hamada de Guir (Sud-Ouest Algérien).

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La Hamada de Guir, située dans le Sud-Ouest aride algérien, est une région où la rareté de l'eau impose une gestion critique des ressources souterraines. Le substratum de cette hamada est constitué d'une importante série de roches carbonatées, représentant un système aquifère karstique et fissuré essentiel pour l'approvisionnement local. Cette étude vise à caractériser de manière approfondie l'hydrogéologie et le fonctionnement hydrodynamique de ce réservoir carbonaté afin d'en évaluer le potentiel exploitable et la vulnérabilité.

Notre approche repose sur une méthodologie intégrée combinant l'analyse structurale (télédétection et terrain) pour identifier les réseaux de fractures et les zones de karstification, une campagne d'échantillonnage hydrochimique et isotopique ($\delta^{18}\text{O}$, $\delta^2\text{H}$) pour déterminer l'origine de la recharge et les temps de résidence, et une étude hydrodynamique des fourrages. Cette combinaison permet de délimiter les unités hydrogéologiques fonctionnelles et de proposer un modèle conceptuel d'écoulement.

Les résultats mettent en évidence un système aquifère complexe où les processus de karstification sont fortement contrôlés par les structures tectoniques (failles et diaclases). Nous avons identifié deux principaux modes de recharge : une recharge diffuse limitée, typique du milieu hamadien, et une recharge concentrée significative le long des oueds et des zones de failles majeures. L'analyse des gradients hydrauliques et la géochimie indiquant les débits régionaux de l'Est vers l'Ouest, avec des vitesses variables reflétant l'hétérogénéité de la perméabilité. La qualité des eaux révèle un risque de salinisation et de minéralisation croissant le long des axes d'écoulement, soulignant la vulnérabilité du système face à une surexploitation.

Ce travail apporte une contribution majeure à la compréhension des systèmes carbonés en milieu hyperaride. Le modèle de fonctionnement établi est essentiel pour la mise en place de stratégies de gestion durable de cette ressource vitale dans un contexte de stress hydrique croissant. Les conclusions éclairent la nécessité d'une surveillance renforcée des zones de recharge concentrée et des niveaux d'exploitation compatibles avec les faibles taux de renouvellement de l'aquifère de la Hamada de Guir.

Mots-clés : Hamada de Guir, Hydrogéologie, Aquifère Carbonaté, Karstification, Recharge, Hydrodynamique, Sud-Ouest Algérien.

Assessing groundwater contamination risk in post-quarry karst: Scenario analysis for the Edwards Aquifer, Texas

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Karst aquifers supply much of the freshwater in the Texas Hill Country, but remain highly vulnerable to contamination due to rapid development in the region. The common practice of quarrying for limestone in such areas greatly worsens this vulnerability. Yet despite extensive research on karst vulnerability mapping and urbanization impacts separately, systematic assessment of post-mining quarry redevelopment scenarios remains absent. The Lime Creek Quarry in Cedar Park, Texas, situated on the Edwards Aquifer Recharge Zone, exemplifies this challenge. Although mining operations ended in 2023, 173 years of extensive excavation removed portions of protective karstic layers below the water table, exposing the recharge zone. The city's proposed urban redevelopment of the 216-acre site raises concerns by channeling contaminated runoff into the Edwards Aquifer. This study aimed to predict how groundwater contamination risk varied under three redevelopment scenarios: (A) urbanization with minimal reclamation, (B) urbanization with stormwater management practices, and (C) conservation/nature park. The GIS workflow established a baseline vulnerability assessment using EPIK methodology adapted for post-quarry karst conditions, followed by scenario-specific pollutant load mapping derived by georeferencing conceptual plans from city documents. Contamination risk maps were generated by overlaying vulnerability and hazard models for each scenario. Scenarios A, B, and C contained 42.2%, 25.72%, and 17.82% high-risk zones for groundwater contamination, respectively. Stormwater controls reduced high-risk area by 39% compared to minimal reclamation, while conservation reduced it by 58%. The risk models were validated by single-parameter sensitivity analysis and water quality testing of groundwater at the site, yielding a strong correlation ($r=0.82$) between predicted vulnerability and NO_3 . This study provides a transferable approach for predicting groundwater contamination risk to inform development decisions in quarried karst areas worldwide.

Application of the 3D stochastic karst simulation tool pyKasso: The case study of the alpine karst system of Tsanfleuron, Switzerland

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Located in the Swiss Alps, the Tsanfleuron karst system is a well characterized example of high-altitude alpine glacio-karst. The study area, capped by the Tsanfleuron Glacier, consists of a large plateau of Urgonian limestone, moraine terrain and Eocene limestone. Ranging from 1500 m a.s.l. to 2900 m a.s.l., each of these zones offer specific karst development and recharge processes (Gremaud et al., 2009).

In its upper part, above an elevation of approximately 2400 m a.s.l., the recent retreat of the glacier since 1850 has led to a polished limestone bedrock surface covered by thin, patchy melt-out till and scattered rock debris. With the absence of soil, numerous karst landforms are clearly visible. These include dolines, meandering karren, solutionally enlarged faults, vertical shafts, and large depressions that are often several hundreds of meters wide and several tens of meters deep (Gremaud et al., 2009). A particularly detailed characterization of fractures and faults is therefore possible, and Tanaka et al. (2025) performed a statistical analysis of the fracture orientations. In the lower part of the plateau, the landscape forms a typical alpine karrenfield that has developed since the end of the Pleistocene glaciations. Across the whole area, speleological investigations have identified and explored more than 158 caves, yielding a total mapped length of over 10 km, distributed over 28 sites. In addition, extensive tracer tests have been conducted over the past decades, allowing a clear delineation of the catchment boundaries and the characterization of groundwater transit times (Savoy et al. 2008, Gremaud et al. 2011).

As demonstrated by tracer tests, the main outlet of the system is the Glarey spring, which is captured and used by the municipality of Conthey. In the context of the ongoing glacier retreat, the impact of climate change on the water resource constitutes a key research question that can be addressed using groundwater flow modeling. Different simulation approaches have been developed to model groundwater flow in karst. Each presents specific advantages and limitations depending on the objectives of the study, the spatial and temporal scales considered, data availability, and the number of calibration parameters required (Jeannin et al., 2021).

Salamin (2023) applied a reservoir-based approach to simulate total discharge at the Glarey spring under a wide range of climate scenarios. The model was calibrated using discharge measurements from the spring and its estavelle. If the results of this lumped-model provided satisfactory results, uncertainty remains regarding the most severe climate scenarios (Salamin 2023).

Given the relatively well-constrained geometry of the system and the availability of speleological, fractures and tracer test data, this site offers an excellent opportunity to test the applicability of a physically based model to simulate groundwater flow and provide more reliable projections under future climate scenarios. Such an approach would also allow a direct comparison between physical-model simulations and the discharge projections already obtained. OpenKARST (Kordilla et al. 2025) is an open-source framework designed to simulate flow and transport process in karst conduit network. It handles mixed free-surface and pressurized flow under both transient and steady-state conditions within complex conduit geometries. Its application requires a realistic representation of the karst conduit network, including both known and inferred portions of the system.

Since some disjunct parts of the karst conduit network are known, pyKasso (Miville et al., 2025) is used to fill in the unknown portions of the system. PyKasso is a stochastic karst simulator that generates plausible three-dimensional conduit networks based on geological, hydrogeological, and structural data, such as fracture orientation and density. As demonstrated by Fandel (et al. 2022), pyKasso produces realistic networks when inlet-outlet connections are

correctly assigned. As already presented, in the case of Tsanfleuron, such data is available at the catchment scale. With the aim of applying OpenKARST to the Tsanfleuron system, the results of the three-dimensional pyKasso simulations and the complete conduits network at the catchment scale are presented here. These results are expressed as three-dimensional probabilistic maps of conduit occurrence.

Presentation of KNdata, the new opendata Karst Network database for large scale graph analysis

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To improve water flow and storage prediction in karst systems, it is important to know their shape and connectivity at the scale of an entire network. Since not all karst networks are accessible, we need to be able to predict the general shape of the network at a specific location. Karst systems are very complex because they are determined by the direction, density, shape, and connectivity of their constituent conduits, which in turn are controlled by geology and climate. However, the structure and properties of karst networks can be studied through the lens of graph theory, by simplifying them to a series of links and nodes where the branches connect (Collon et al., 2017, Jouves et al., 2017). Traditional cave survey measurements made by cavers represent caves as a centerline, composed of splay shots and stations. For this reason, cave survey data are a perfect source of information, since they already represent the cave as a mathematical graph!

To characterize and predict karst networks topology from different geological or climatic contexts, we followed the approach initiated by Collon et al. (2017) and Jouves et al. (2017) by collecting and cleaning a large data base of open source or proprietary cave survey centerlines and splays data. In this presentation, we summarize the current state of the data collection and describe the data processing workflow (Figure 1).



Figure 1. Data processing workflow from the original cave survey files to the clean files, together with the export of conduit geometry measurements (Left-Right-Up-Down = LRUD, and splay shots).

Cave survey data come from all over the world in a wide variety of data formats (Therion, Toporobot, Visual Topo, GHTopo, Compass, Survex, Onstation, AGHgis, ...). As of now, we received 175 usable datasets containing a total of 370 individual caves and about 5000 km of cave passages, spanning across 20 countries. Some of the datasets have been shared with us under CC-BY-NC-SA open-data agreements, and the clean datasets are stored and shared on the KNdata repository (to be published on Zenodo). The rest of the datasets are proprietary or

sensitive datasets shared with us under a confidentiality agreement, only the results of the statistical analysis will be published.

All those raw datasets have been transformed into a standardized Therion file format containing information relevant for the graph analysis on the nodes and links. We use Therion because it is one of the most flexible and open-source caving survey programs and because it can export data into multiple formats. We developed opensource python scripts to translate the original survey formats into human-readable text compiled by the Therion interpreter.

Finally, we cleaned each cave survey datasets. A key contribution of this work is the development of a hybrid cleaning workflow shown in Figure 1 that explicitly addresses the gap between raw survey practices and graph-based analysis. Cave surveys are primarily designed for exploration and mapping and often include artifacts such as splays, duplicate segments, surface paths, or topological inconsistencies that can strongly bias network statistical metrics. Cleaning operations aim to preserve the structural backbone of the cave network while removing non-structural elements, ensuring that resulting graphs reflect true conduit morphology rather than survey artifacts. The cleaning process combines automated detection rules with systematic 3D visual validation. This open-source semi-automated procedure can help other cavers or researchers to process or analyze their own cave survey data.

The result of this work is the largest clean datasets of cave network graphs known so far. It can be used to analyze the statistical properties of the geometry and organization of those networks and compare or classify caves properties with speleogenetic controls. In a related study (Brissemoret et al. 2026), we present preliminary results of the statistical analysis performed on the database.

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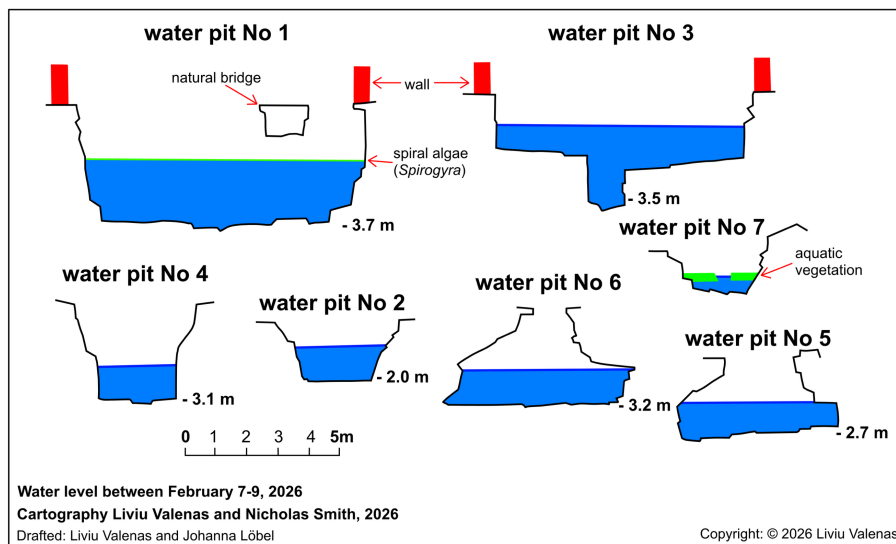
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Morphology, hydrochemistry and genesis of water pits in quartz sandstones of Phu Pha Dak, Northeastern Thailand

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The water pits of northeastern Thailand are typical karst phenomena on quartz sandstones in this part of the country. In Nong Khai province, not far from the Mekong River (the border between Thailand and Laos), there is a relatively isolated mountain, Phu Pha Dak, a kind of "mini-tepui", as in Venezuela. The mountain dominates the Houay Hir valley with 200 m, and at the top has a small almost horizontal plateau. On this plateau our research, which began in 2025 and continued in 2026, identified 7 water pits, with depths of almost 4 m. In contrast to other water pits in Thailand, two water pits in Pha Pha Dak have an impressive volume, between 145 m³ and 120 m³. Even in the dry season, between 40% and 50% of the total volume is still occupied by water. As a step towards explaining their genesis, some precise measurements of their depth and shape have been carried out; additionally, stagnant waters from these natural tubes have been subjected to chemical analysis. The water in this water pit certainly has no connection with the groundwater table, which is anyway at a depth of 250 meters from the plateau on the top of Phu Pha Dak mountain but are formed and fed exclusively by rainwater during the wet monsoon season. Their formation is the result of four factors. The primary factor is the process of quartz sandstone arenization, whereas secondary factors are calcium carbonate dissolution within the sandstones, mechanical erosion processes, and biocorrosion related to vegetation and animal activities. A graphic model of the main factors that formed these natural water-filled tubes is presented for the first time.



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Pre-structuring and evolution of plateau karsts. The example of the Loue catchment (Fr. Jura Mountains).

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In the case of plateau karsts, current hydrographic network and underground water flows are inherited from karstogenetic history. Therefore, the aim of this work is to propose a chronological model of the different stages of karstification of plateau karsts.

The study area is the Montrond plateau, the northernmost plateau of the Loue basin (1000 km²), located in the French Jura Mountains. It is a typical plateau karst, with a high karstification degree (numerous dolines and around twenty karst networks over 100 m). Underground study site is a horizontal gallery in the Cavottes karstic networks. These 550 m long gallery is located 50 m under the plateaus surface.

First, a detailed surface morphological mapping revealed 3 major chronological stages of karstification and drainage organisation. Second, underground morphological observations highlight 3 major chronological stages of speleogenesis. Third, U/Th dating help us to replace the last chronological stages on the geological timescale.

The combined results aided us to reconstruct the surface and underground karstogenic model of the plateau area of the Jura massif. The oldest and still observable stage of karstification is the alteration in flooded conditions of the geological reservoirs leading to the development of corridors oriented N60. Then, after the formation of the Jura Mountains fold-and-thrust belt (JFTB) paleo-poljes are developed enclosed between the raised hydrological barriers of anticlines (fold systems). At this point, surface and underground drainage seems to be oriented towards the N-NO. Underground, this translates into a paragenetic NS conduit whose functioning predates the dating limit using the U/Th method (450 ky). Slowly, surface drainage is organised into a network that intersects the bottom of the paleo-poljes, and the base level gradually sinks. The Loue eventually cut through the plateaus, lowering the base level by 150 metres and catching up with the surface drainage network through regressive erosion. The horizontal underground gallery is now perched in the vadose zone and is intersected by vertical flows (32 ± 0.5 ky). Finally, glacial periods are the source of pebbly debris flows and laminated clays that fill the galleries (20 ± 0.3 ky).

This study proposes a new karstogenic model that can be extended to karstic plateaus of the Jura Mountains and gives new highlight on the current groundwater flows.

Art Meets Science. The conception of Inception Horizon

Norah Constance Walsh

Dublin, Ireland

In a presentation of Art Meets Science, composer Norah Constance Walsh outlines the background to her composition *Inception Horizon*, a four-part choral work inspired by the eponymous geological phenomenon. Experience ephemeral turloughs and anastomotic caves like never before in this musical celebration of the Irish underground karst network. The presentation includes a video performance of the work by Irish choir Mellow Tonics.

Estimation of groundwater recharge in Australia's Karst Regions

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Groundwater is an important source of freshwater in Australia, supplying approximately 30 % of total water use for drinking water, irrigation, livestock production, mining, industrial activities, and bottled water production (Famiglietti, 2014). It provides water security for urban centres, regional communities, and groundwater-dependent ecosystems, particularly in arid and semi-arid regions where surface water availability is limited. Despite its importance, groundwater resources are increasingly stressed by over-extraction, climate change-related variability in rainfall and increasing drought frequency, resulting in widespread declines in groundwater levels across large parts of the continent, especially in southern Australia (Green & Moggridge, 2021). Reliable estimates of groundwater recharge are therefore essential to support sustainable allocation and climate-resilient water resource management.

Australia contains significant carbonate landscapes underlain by karst aquifers that are hydrologically distinct in their high heterogeneity and dual flow properties. Karst aquifers are characterized by dual porosity domains—the conduit network enabling rapid flow and matrix domains controlling diffuse storage and transmission—making recharge processes inherently complex, scale-dependent, and highly sensitive to spatial variability. This complexity challenges large-scale groundwater modelling, which often inadequately underestimates groundwater recharge in karst regions (Hartmann et al. 2017).

Karst terrains occur across the continent, with estimates suggesting that up to ~15 % of Australia is underlain by carbonate bedrock related to karst processes, though only a fraction (~4 %) is expressed at the surface as classic karst morphology such as sinkholes, caves, and conduits (Jennings, 1975). Notable karst systems are found in New South Wales (e.g., Wombeyan, Yarrangobilly), Queensland (e.g., Chillagoe), Tasmania (Mole Creek), and South/Western Australia (e.g. Naracoorte, the extensive Nullarbor Plain, Tamala Limestone), where solution-enhanced networks determine subsurface flow and storage.

In this study, we apply the VarKarst-R groundwater recharge model (Hartmann et al., 2015, Sarrazin et al., 2018), a semi-distributed modelling framework tailored to karst landscapes that separates soil and epikarst storage and allows calibration against dynamic hydrological responses. Unlike typical calibration approaches that use indirect indicators such as spring discharge hydrographs, our application leverages daily cave drip rate datasets from Australia's National Groundwater Recharge Observing System (NGROS). NGROS (Baker et al., 2024), a collaborative initiative involving the University of New South Wales and the Australian Government, provides the first sensor network for observing groundwater recharge in vadose zone caves, tunnels, and mine shafts to record drip rates reflective of potential recharge events in Australia (Figure 1). This unique dataset enables the identification of rainfall recharge thresholds and the timing of recharge responses (Priestley et al., 2025), providing a basis for robust calibration of VarKarst-R soil and epikarst storage parameters. Cave drip rate observations are incorporated within a Monte Carlo calibration framework, in which model parameters describing storage and percolation are systematically sampled and evaluated using drip rates as a likelihood function. This behaviour-based calibration constrains the model to reproduce observed recharge dynamics, ensuring that VarKarst-R captures the contrasting storage and flow properties of different cave systems. The datasets are derived from caves spanning multiple climate zones, enabling recharge responses to be clustered and subsequently upscaled to regional, national, and global scales.

Using calibrated model outputs, we generate an Australian karst groundwater recharge map that quantifies spatial variability in recharge rates. This product supports water resource assessments and informs regional management strategies by improving estimates of recharge volumes and variability in karst aquifers. Our results underscore the value of integrating high-resolution drip monitoring with semi-distributed modelling to enhance understanding of karst recharge mechanisms and address critical hydrological knowledge gaps in sustainable groundwater governance.

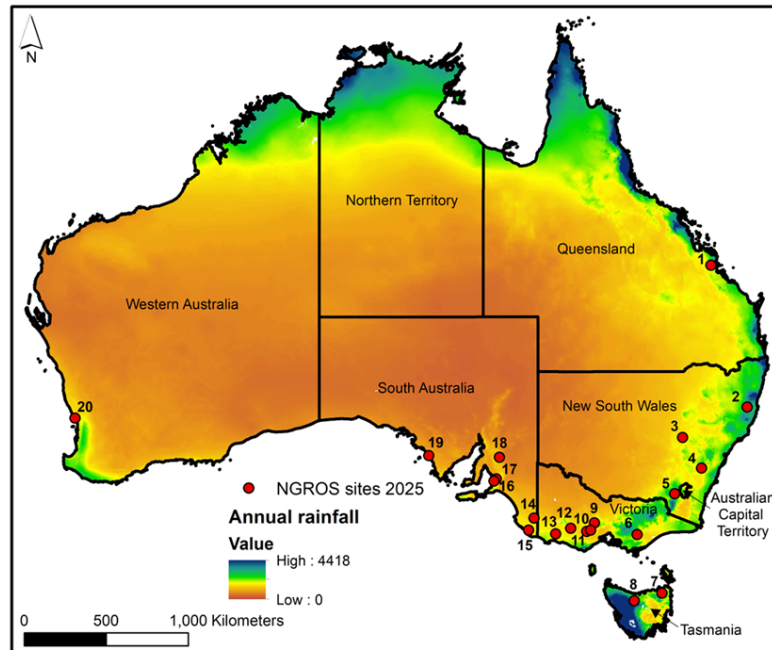


Figure 1. Map of Australia showing annual average rainfall and the locations of NGROS sites (source NGROS). The following sites are used in the calibration process of the VarKarst-R model: Site 1, Capricorn Caves; site 2, Daylight Cave; site 3, Wellington Phosphate Mine; site 4, Wombeyan Caves; site 5, Yarrangobilly; site 8, Marakoopa Cave; site 14, Naracoorte Caves; site 20, Yanchep.

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Controls on the distribution of cenote blue holes on Andros Island, North-west Great Bahama Bank

Fiona Whitaker¹, Mills Harriet², David Leslie³

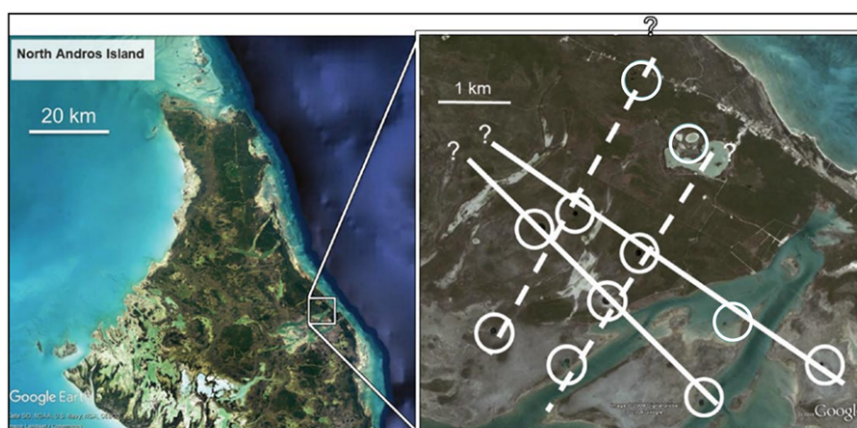
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The Bahamas platform is widely recognised as the most stable continental block in the Caribbean. It is underlain by a series of normal and wrench faults, which are inherited from a late Jurassic rifting phase but presumed inactive since. These deep faults appear to control the geometry of the steep platform margins and deep-water re-entrants. At the surface and extending up to 40 km, major fracture systems occur parallel to the platform margins and show diagenetic alteration by circulating groundwater. Similar systems with evidence of syn-depositional cave development are described in ancient platform margins including the Canning Basin of Australia and Guadalupe Mountains in the US.

Distinct from these clearly fracture-guided linear cave systems developed along the eastern margin of the North-west Great Bahama Bank, numerous water-filled circular karst collapses (“cenotes”) are distributed across Andros Island. Here we present a statistical analysis of the spatial distribution of these large-scale features, which provides the first evidence for extensive fracturing up to 35km from the platform margin. Some 177 cenotes were identified from satellite imagery. At the surface these features have a diameter of 105 ± 60 m, with the largest spanning 370 m. Field survey shows they have a maximum depth of c.110m, with floors of collapse boulders and soft sediment suggesting active autochthonous infill. Underwater exploration of a subset of cenotes suggests they tend to increase in diameter with depth, possibly because of mixing-zone dissolution and associated collapse. Only a few of the smaller cenotes are known to connect with lateral cave passage, but this apparent absence may simply reflect dissolution, collapse, and infill of the larger features.

Perpendicular regression reveals the distribution of cenotes is significantly non-random, and identifies many lineations, defined by rows of up to 6 cenotes. The distribution suggests that cenote formation may be focussed at the intersections of lineations. Most lineations within 10km of the eastern bank margin are oriented parallel to this margin, with a subset perpendicular. However, further inland, the orientation of many lineations echoes that of the N60°W trending Sunniland (Bahamas) Fracture Zone. This is a long-lived transform feature related to Jurassic rifting that extends across the Floridian Peninsula and crosses the Great Bahama Bank to the north of Andros Island. The vast majority (98%) of identified cenotes occur within 35km of the western bank margin. The absence of cenotes at greater distances from the margin may reflect increased infill by sediment generated on the shallow modern bank, or alternatively may be controlled by the location of the margin of the underlying Cretaceous Andros Bank.



Scale-dependent transmission of tidal pressure signals in a karstified carbonate aquifer, North Andros Island, Bahamas

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With the ever-expanding number of people living on continental margins and islands, coastal water resources around the world are under increasing pressure. To evaluate, manage and protect these resources, it is critical to develop more sophisticated hydrogeological representations of the structure and function of coastal aquifers. Mapping the discontinuities in hydraulic properties that govern flow in real-world aquifers is challenging, especially in karstic aquifers. A simple, but under-used, approach to characterising coastal aquifers is interpretation of the aquifer response to the ocean tide that is termed the “groundwater tide”. The distribution of aquifer hydraulic properties determine the degree to which the amplitude of the tidal signal is dampened and the timing of tidal peaks and troughs is delayed relative to the ocean. Additionally, groundwater tides have a significant influence on groundwater flow and solute dispersion, affecting the salinity of the freshwater lens and the thickness of the underlying fresh-salt mixing zone. Understanding interactions between ocean and groundwater tides is also important as they influence the discharge of freshwater and solutes from the aquifer to the sea and the extent of salt-water intrusion.

This study focuses on how amplitude and lags of groundwater tides relative to those around the coastal margins groundwater tides can be used to better understand the distribution of hydraulic properties and aquifer connectivity in the karstified carbonate aquifer of northern North Andros Island, Bahamas. Using a network of boreholes distributed across the northern part of North Andros in the Bahamas we characterise groundwater tides in a young eogenetic limestone multi-layer, aquifer in which cavernous porosity is developed within a rock retaining large primary porosity. Transmission of the tidal signal was measured in shallow (2-5m) and deep (24-34m) boreholes at 25 locations across the island, in a subset of intermediate depth legacy wells, and in natural karst features (“blue holes”). Tidal efficiency and lag were derived by comparison with coastal tides from stations distributed around the island from the east coast where the island borders the 2 km deep Tongue of the Ocean to the shallow carbonate bank on west side where seawater circulation is restricted. Harmonic analysis of the tidal signal was undertaken using Fast Fourier Transform decomposition to provide more accurate estimate of the origin of the tidal signal and the mixing of multiple tidal signals.

Groundwater tides measured in boreholes show rapid lateral transmission of the tidal pressure pulse through the deeper part of the aquifer at a rate similar to that across the shallow seawaters on the platform top. The signal from the east coast extends some 11 km inland, although within 1-2 km of the coast there appears to be locally reduced permeability, perhaps reflecting marine cementation of the platform margin. Further west, groundwater tides are more complex, influenced by the signal from both north and west coasts. Karst features (blue holes), some of which are known to connect to cave systems, have an efficiency and lag similar to that of the deep boreholes, suggesting a very high degree of lateral connectivity of dissolutional features throughout the aquifer at depths of 24-34 m.

For any location, the tidal signal in the shallow part of the aquifer is more delayed and dampened relative to that in the deeper borehole, reflecting the greater karstification in older limestones during repeated diagenetic overprinting driven by oscillations in Pleistocene sea-level and subsidence. The vertical transmission of tidal pressure pulse from the depth of the aquifer to the surface is further demonstrated by harmonic analysis of the groundwater tides. The transition from a mixed semi-diurnal tidal cycle on the east coast to a semi-diurnal tidal cycle on the west coast allows more accurate estimation of the origin of the tidal cycle measured in the boreholes and the mixing of such signal. The utility of this approach is demonstrated even for short datasets which do not include all tidal constituents.

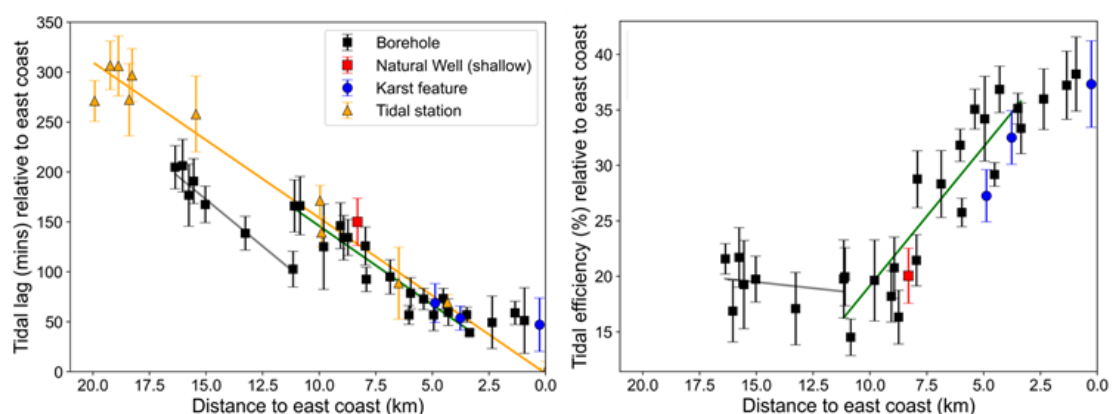


Figure 1. Shows increase in tidal lag (A) and decrease in tidal efficiency (B) relative to the ocean tide on the east coast with increasing distance from the fracture-controlled east coast. Groundwater tide is measured in deep (24-34 m) boreholes (black squares) and karst features (inland blue holes - blue circles) and compared with suppression of deep water tidal signal measured at tidal stations distributed around the coast on the shallow bank. A subset of boreholes located on the western side of the island show a shorter tidal lag and higher tidal efficiency than expected, reflecting 3D complexities in the distribution of tidal forcing around the coast of the island, and hint at large-scale structural controls on hydraulic properties.

Topographic control on the hydrogeology of a karstified eogenetic limestone island aquifer – a key to understanding vulnerability to sea-level rise and climate change

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The Intergovernmental Panel on Climate Change (IPCC) identifies Small Island Developing States (SIDS) as some of the most vulnerable regions to climate change. Island aquifers often comprise a thin freshwater lens that overlies denser saline groundwater and constitute critical water resources. Those island aquifers hosted by young eogenetic limestones contrast markedly in structure and function with those in texturally mature limestones that have undergone burial and uplift. Exposure of diagenetically immature carbonates to meteoric waters results in a strongly scale-dependent permeability, with dissolutional voids that range from touching-vugs to laterally extensive mixing-zone cave networks, developed within a matrix that retains significant interparticle porosity. Many such islands are also low-lying, with subdued topography. Their proximity to sea-level increases the impact on the freshwater resource of rising sea-level and the increased frequency of intense and more slow-moving tropical storms.

Andros is the largest island in the Bahamian archipelago with the most extensive freshwater lens in the country, yet the average vadose zone thickness is less than one meter. The aquifer comprises a sequence of flat-lying shallow-water limestones overlapped on the windward side by Pleistocene aeolian dune ridges up to ~4 m a.s.l, and on the leeward side by low permeability Holocene tidal flat deposits. The island interior is a complex mosaic of sparse forest of Caribbean Pine dissected by freshwater ponds and marshes. Previous workers have invoked hydraulic control by a series of low permeability paleosol horizons to explain the fact that the freshwater lens is significantly thinner than expected based on island geometry and assumed recharge and hydraulic conductivity. However, a series of wells developed through the lens and underlying fresh-salt water mixing zone wells record transmission of the ocean tidal signal up to * km inland, evidencing the pervasive karstification at relatively shallow depth.

In this study we use MODFLOW-6 simulations of coupled groundwater flow and solute transport, constrained by field observations, to i) understand the impact of laterally extensive horizons of high effective permeability on the salinity stratified aquifer of Northern North Andros, and ii) assess the effect of sea-level rise on the freshwater lens given the low-lying topography. In our study area, a broad swathe of mangrove marsh was previously thought to bisect the freshwater lens. Salinity profiling across the island has identified that there is a single continuous lens, although beneath the marsh slightly brackish waters extend to the base of the lens. Monitoring of water levels and salinity across the interior marshes demonstrates that they function as a zone of net groundwater discharge, via increased evapotranspiration. However, this effect must be differentiated from the impact of seawater inundation during surges associated with hurricanes, recovery from which can takes decades.

Although sediment aggradation may mitigate against coastline retreat in some areas of Andros, the increase in elevation of the water table is already resulting in expansion of marshes across large areas of the low-lying interior of the island. Overall, the fate of the water resource is uncertain. Detailed studies of the hydrogeology of karstified eogenetic limestones are key to an improved conceptual understanding of lens dynamics under future sea-level and climate scenarios and to inform groundwater management strategies in low-lying carbonate island systems worldwide.

Using hydrochemistry and inverse modelling to investigate salinization processes in karst aquifers: The case studies of karst systems in Zakynthos and Kaiafas (W. Greece)

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Introduction

Karst aquifers are a valuable source of groundwater, especially in the Mediterranean region. However, they are very sensitive to both natural and artificial pressures because they are very permeable and flow quickly [1]. Salinization of groundwater is a major problem in karst systems particularly in coastal, tectonically active, or geothermal areas. In coastal karst aquifers, salinization is usually caused by seawater intrusion due to overexploitation and hydrogeological conditions. However, in regions influenced by deep flow, groundwater chemistry could suggest mixing with ion-enriched fluids produced by extended water–rock interaction at elevated temperatures [2]. To investigate the dominant geochemical processes controlling groundwater composition, inverse geochemical modelling using PHREEQC was combined with hydrochemistry, allowing a comprehensive analysis of salinization mechanisms in karst aquifers.

Study area

The Kaiafas area (Figure 1a) is located in western Greece and is part of the external Hellenides. The Gavrovo-Tripoli and Pindos Geotectonic Zones constitute most of the area's geological structure. The Gavrovo-Tripoli Zone's thick-bedded to platy limestones make up most of the area's basement. To enable a comparative assessment of karst aquifers influenced by contrasting tectonic and hydrogeological conditions, a second study area was selected on Zakynthos Island (Figure 1b). The karst aquifer developed within the Paxos geotectonic Zone constitutes the main deep groundwater system of Zakynthos Island. The geological framework of the Paxos Zone is strongly controlled by tectonic deformation related to the convergence of the African and Eurasian plates, resulting in intense faulting and fracturing that enhance karstification, secondary porosity, and hydraulic conductivity [3,4]. However, intercalated marly limestone horizons locally reduce permeability, introducing hydrogeological heterogeneity and influencing groundwater flow paths and residence times [5].

Figure 1. Geological framework and groundwater sampling locations of the (a) Kaiafas (GKF) spring system and (b) Zakynthos Island.

Materials and methods

Groundwater samples from two regions were collected from different hydrogeological settings. Samples from Zakynthos were obtained from groundwater boreholes, whereas samples from the Kaiafas area were collected from karst springs. All samples were analyzed for major cations and anions using standard hydrochemical methods at the Hydrogeology Laboratory of the University of Patras. Selected trace elements were also measured to provide additional constraints on salinization sources and geochemical processes.

Results and discussions

The geochemical diagrams show distinct differences between the two karst systems, reflecting contrasting salinization mechanisms. Groundwater samples from the Kaiafas (GKF) area

exhibit higher $\text{SO}_4^{2-}/\text{Cl}^-$ and $\text{Sr}^{2+}/\text{Ca}^{2+}$ ratios (Figure 2), together with elevated Li and B concentrations, indicating dominant water-rock interaction and contributions from deep-circulating fluids. In contrast, Zakynthos samples plot closer to the seawater end-member, with lower ionic ratios and systematic increases of Li and B with Cl^- , pointing to salinization mainly controlled by seawater intrusion [6,7]. Positive CAI-I and CAI-II values in both systems indicate reverse ion exchange associated with progressive salinization, a process widely reported in coastal karst aquifers [8,9].

Inverse geochemical modelling was conducted using PHREEQC, including seawater as a potential end-member to investigate seawater influence. Acceptable inverse models were obtained for both Zakynthos aquifer and the Kaiafas spring. The results indicate contrasting roles of marine mixing in the two karst systems.

Figure 2. Groundwater samples from GKF and Zakynthos (a) $\text{Sr}^{2+}/\text{Ca}^{2+}$ versus $\text{SO}_4^{2-}/\text{Cl}^-$ (b) Chloro-Alkaline Indices (CAI-II vs CAI-I) (c) Li versus Cl^- (d) B versus Cl^- .

Conclusions

The results show that elevated concentrations of chloride, sodium, and related ions in karst groundwater do not necessarily indicate seawater intrusion. Although both studied systems exhibit increased salinity, the combined analysis of ionic ratios, trace elements, and inverse geochemical modelling reveals distinct controlling processes. Seawater mixing is confirmed as the dominant salinization mechanism in Zakynthos, whereas groundwater chemistry in the Kaiafas system is explained by water-rock interaction and deep fluid circulation without marine contribution. These findings highlight the need for integrated hydrogeochemical approaches to reliably identify salinization sources in complex karst aquifers.

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Understanding complex karst aquifer functioning through hydrochemical and isotopic monitoring of Driza Spring, N. Peloponnese

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Introduction

Karst aquifers are vital global freshwater resources but highly vulnerable to contamination, over-extraction, and climate change. This study is a part of a dissertation that investigates the hydrogeological functioning of the Ziria karst groundwater system in northern Peloponnese, Greece, through an integrated framework combining isotopic, hydrochemical, and hydrological analyses with numerical modeling to evaluate groundwater dynamics, recharge processes, vulnerability, and the influence of tectonics on karstification.

We conducted extensive monitoring of major ions, stable isotopes, and saturation indices at springs and boreholes. Here, we present hydrochemical and isotopic time-series data (2016-2023) from Driza Spring (S2).

Study area

The Ziria karst system (EL0200220), delineated in River Basin Management Plans (Special Secretariat for Water, 2013), lies in northern Peloponnese, ~45 km west of Corinth, covering ~200 km². The aquifers form within Mount Killini/Ziria (2368 m.a.s.l.), a rugged nearly circular massif with steep slopes dominating much of the hydrological system. A large E-W karstic polje occupies the southern part, hosting Stymphalia Lake amid Quaternary clay deposits.

Geologically, it comprises Upper Triassic–Cretaceous limestones/dolomites (Tripolis Zone) thrust over Cretaceous limestones (Olonos-Pindos Nappe), with metamorphic bedrock (quartzites, phyllites, schists) mainly in SW/NW areas. Prominent karstification features dolines, swallow holes, and caves, fed by diffuse and concentrated recharge (Morfis, & Zojer, 1986).

The Stymphalia spring front (618–620 m elevation), located in the polje's northern part, emerges where alluvial deposits disrupt underground flow. It discharges a major aquifer supplying drinking water to Corinth and Kiato cities, plus irrigation for the polje. Driza Spring (S2), the largest outlet (Fig. 2), experienced complete drying in 2020 and several months of 2021, revealing significant discharge variability.

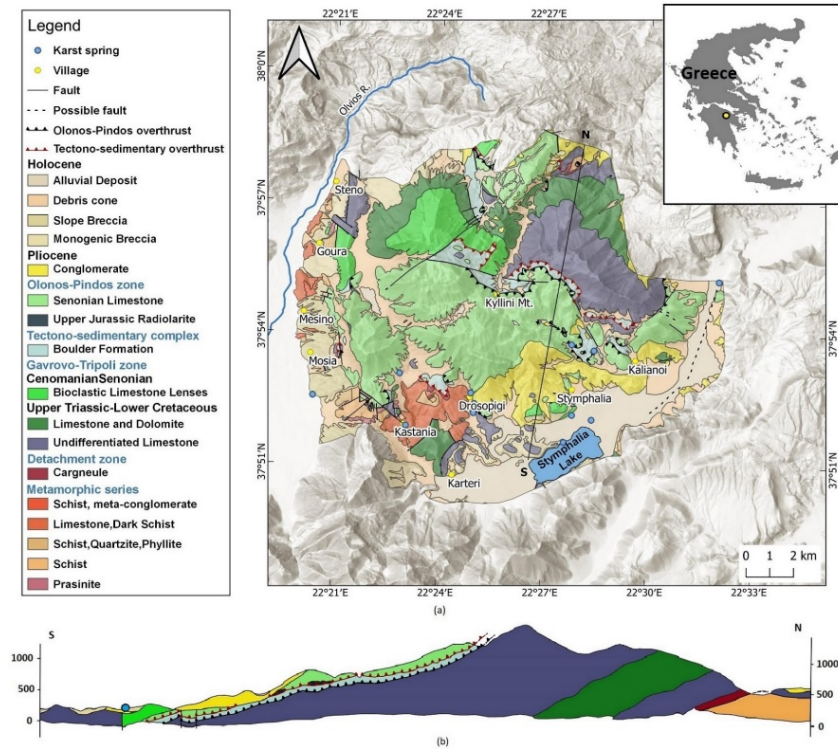


Figure 1. Geological setting of the study area, and b) schematic cross-section (Nanou, 2025)



Figure 2. Driza Spring under contrasting conditions: (a) normal flow in 2017; (b) prolonged dry period in 2021 (Nanou, 2025).

Results and discussions

Groundwater from Driza spring predominantly exhibits a Ca-Mg-HCO_3 hydrochemical facies, influenced by the Tripolis dolomites, though it occasionally shifts to a Ca-HCO_3 .

The temporal distribution of major ionic concentrations at the sampling site offers valuable insights into the functioning of the Stymphalian spring front (Fig.3). Temperature fluctuations are minimal, ranging from 10°C to 13.2°C , with rare occurrences exceeding 11°C . This temperature stability indicates that the groundwater flows deep underground, remaining largely unaffected by seasonal variations. Electrical conductivity (EC) presents average values of $321 \mu\text{S/cm}$.

The temporal distribution of calcium (Ca) and magnesium (Mg) concentrations provides key insights into the functioning of the Stymphalian spring front. Calcium concentrations range from 45.2 mg/L to 61.6 mg/L , with magnesium levels fluctuating between 4.14 mg/L and 14.9 mg/L . The response of Ca and Mg concentrations to rainfall events reveals notable patterns.

Following cumulative rainfall both typically increase, accompanied by heavier $\delta^{18}\text{O}$ isotopic values (above the average of -9.38‰), indicating a strong storage capacity within the aquifer. However, in some cases, an increase in calcium levels coincides with a decrease in magnesium concentrations, while $\delta^{18}\text{O}$ values become lighter. This pattern suggests the activation of recharge areas within the Cretaceous limestone of Pindos during specific rainfall events or snowmelt periods, where calcium concentrations remain elevated while magnesium levels decrease significantly. These findings align with the hydrogeological setting of the system, reinforcing previously established hydraulic connections between the mountain aquifers.

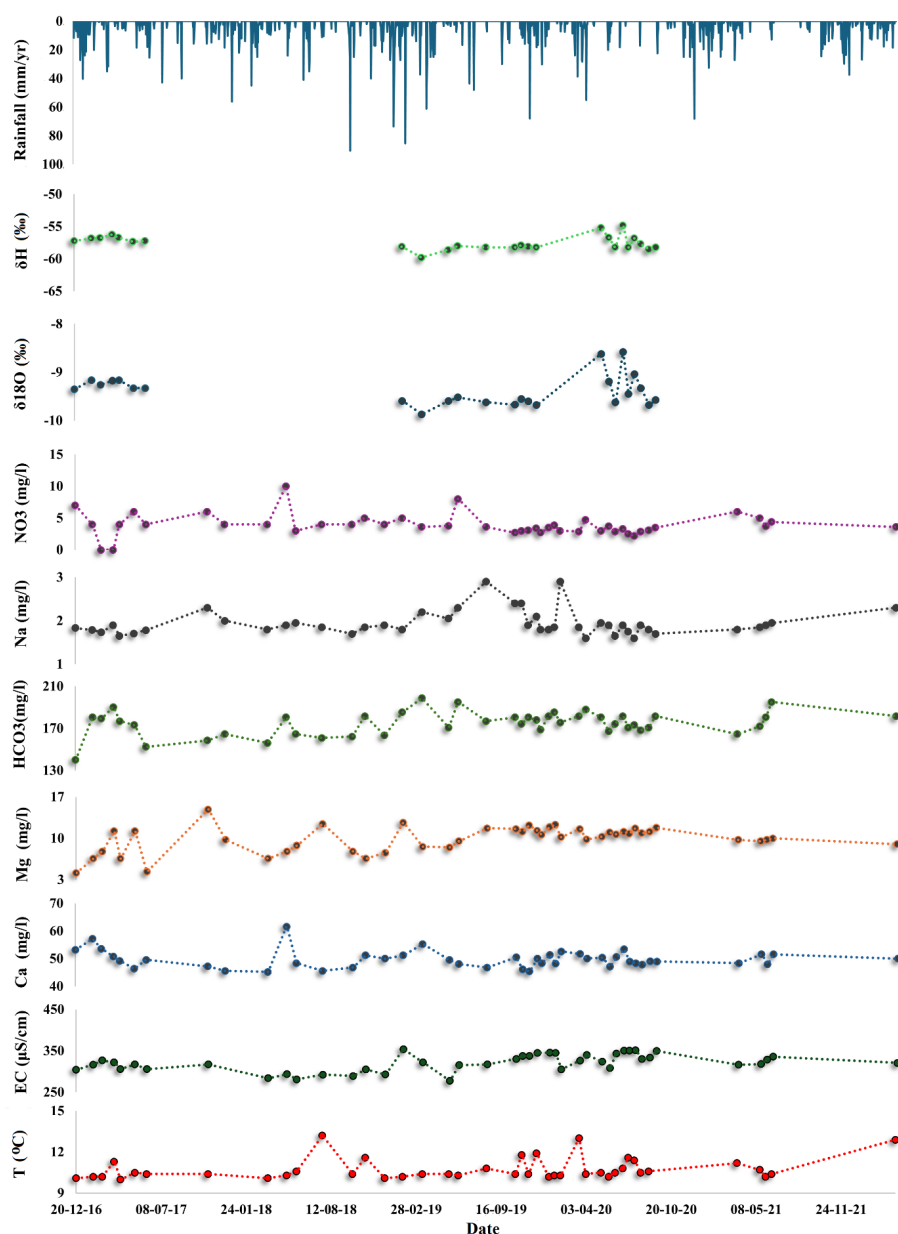


Figure 3. Chemograph illustrating the temporal variability of major ions and physicochemical parameters at Driza Spring, and their responses to rainfall events and seasonal changes.

Driza Spring represents water directly emanating from the aquifer system, with hydrochemical correlations reflecting strong interactions between groundwater constituents (Figure 4). Notably, there is a high positive correlation between magnesium and electrical conductivity (Mg-EC, 0.6) and between bicarbonate and electrical conductivity (HCO_3 -EC, 0.51),

highlighting the influence of mineral dissolution and ion exchange processes at the spring source. Additional relationships, such as bicarbonate and calcium ($\text{HCO}_3\text{-Ca}$, 0.46), reflect carbonate mineral equilibria, which is typical of such environments.

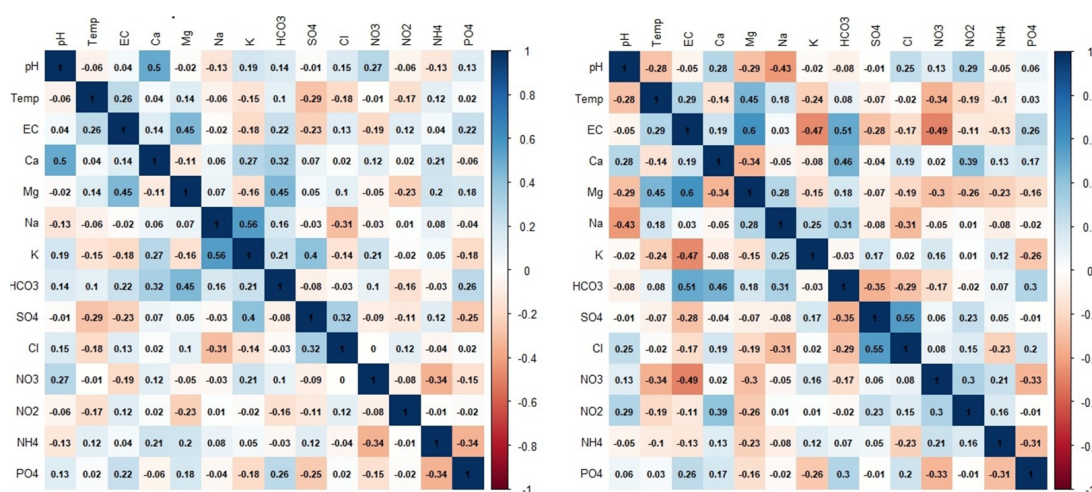


Figure 4. Spearman correlation matrices for hydrochemical parameters at Driza Spring (S2).

Conclusions

Overall, Driza spring represents the aquifer within the Tripolis carbonates, characterized by conduit flow, as evidenced by its rapid discharge response to rainfall events. The aquifer exhibits significant storage capacity, reflected in elevated calcium (Ca) and magnesium (Mg) concentrations following specific precipitation events.

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Hidden pollutants in karst sediments: Microplastics from show cave, relict passages, and spring beds

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Introduction

Karst systems are highly sensitive hydrogeological environments, where rapid contaminant transport and limited natural filtration increase the vulnerability of subsurface water and sediment systems. Despite growing global awareness of microplastic (MP) pollution, defined as synthetic plastic particles smaller than 5 mm, the occurrence, movement, and long-term accumulation of these particles within karst terrain remain poorly understood. Cave sediments and cave stream beds act as critical sinks, offering valuable insight into both long-term accumulation and immediate transport of MPs from diverse anthropogenic sources, ranging from surface runoff via sinking streams to direct contamination from human presence within caves.

This study compares sediment-bound microplastic pollution in three distinct karst environments in England and Wales: (1) chalk karst springs fed by smaller scale conduits and fissures, with no known caves developed (2) a river bed in a hydrologically active Carboniferous limestone cave system (Poole's Cavern, Derbyshire) which is also a tourist cave (so MP inputs are both via the cave stream from the surface and via cave visitors) and (3) sediments from dry relict cave passages, Ogof Ffynnon Ddu (OFD, South Wales) where MP sources are recreational cavers (with little/no modern aqueous sources).

By examining the abundance, size distribution, and morphological characteristics (shape and polymer type) of recovered microplastics, this research aims to characterise and compare microplastic contamination in these environments and to infer what these patterns may suggest about deposition, transport, and accumulation within these vulnerable subsurface ecosystems.

Materials and methods

Sediment samples were collected from 5 Chalk spring chambers, 10 locations in Poole's Cavern (from the streambed, including underwater and nearby bank sediments), and 10 locations in the dry relict cave, OFD (compacted and non-compacted sediments). Samples were processed using Fenton's reagent for organic digestion and high-density ZnCl₂ (density 1.7 g/cm³) for density separation. MP analysis was performed using micro-Fourier Transform Infrared Spectroscopy (μFTIR), following carefully controlled sample preparation and clean-up procedures, capable of detecting particles as small as 25 μm. To support qualitative identification of possible sources, caving gear samples were also examined using ATR-FTIR, allowing assessment of polymer types potentially associated with recreational activities.

Results and discussion

Recreational Caving Drives Microplastic Hotspots in Cave Sediments

Microplastics were detected in all sediment samples (Figure 1), with concentrations ranging from 2,273 - 7,495 MPs/kg in chalk springs, 32- 6,978 MPs/kg in Poole's Cavern, and 438 - 45,196 MPs/kg in OFD. Notably, OFD exhibited $\sim 6\times$ higher MP levels than other sites, highlighting intense recreational input. Within the chalk springs, Site 3 was identified as a hotspot, with MP concentrations three times higher than Site 2 and above the mean (3,751 MPs/kg). In Poole's Cavern, streambank samples contained higher MP loads than submerged streambed samples, with Site 1 at the stream exit having the highest concentration (6,978 MPs/kg), indicating heterogeneous deposition. At OFD, Sites 9, 7, and 6 were the most contaminated, and non-compacted sediments often had equal or higher MP levels than compacted areas (site 1, 4 and 10). Overall, MP levels were highly variable, reflecting the combined effects of visitor traffic, sediment compaction, and localised inputs, and confirming that recreational caving drives MPs hotspots.

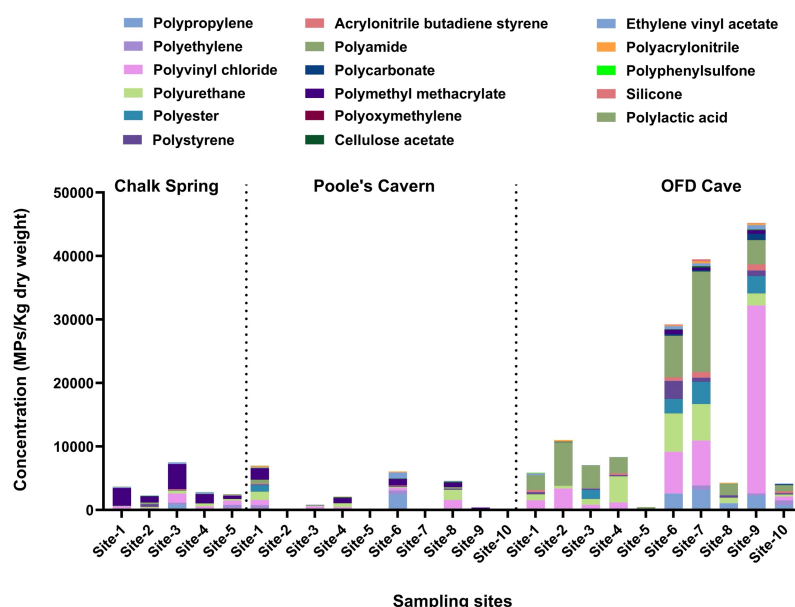


Figure 1. Concentration and distribution of microplastics in karst sediment systems

Insights into sources and pathways from the characteristics of microplastics

Among 21 targeted polymers, dense polymers, including polyvinyl chloride, polyurethane, polyamide, and polymethyl methacrylate, were frequently detected. Polymethyl methacrylate dominated sediments in Chalk springs (51%) and Poole's Cavern (22%), reflecting localised anthropogenic inputs such as tourism, cave infrastructure, or nearby urban/industrial sources, while polyamide (PA) was abundant in the OFD cave system (29%). This matches the chemical profile of typical caving equipment such as nylon ropes and oversuits, and ongoing analyses of specific gear polymers aims to further pinpoint these recreational activities as primary sources. Silicone was detected primarily in OFD. The dominance of dense polymers aligns with sedimentation processes. Most particles were $\leq 150 \mu\text{m}$ (Figure 2 a, b), with OFD particles mainly $25\text{--}50 \mu\text{m}$, and Chalk Springs and Poole's Cavern containing more $\leq 25 \mu\text{m}$ particles ($\leq 150 \mu\text{m}$: 92% Poole's, 89% Chalk, 83% OFD). Micro-FTIR could only detect particles $\geq 25 \mu\text{m}$, so smaller particles may have been missed. Morphologically, most particles were low-aspect-ratio fragments, with fibres (aspect ratio >5) observed only in OFD (23 particles) (Figure 2c). The detection of 18 PA fibres in OFD aligns with intense recreational use and, given the

dominance of PA in caving oversuits and ropes, suggests direct fibre shedding via rock abrasion as a primary contamination pathway.

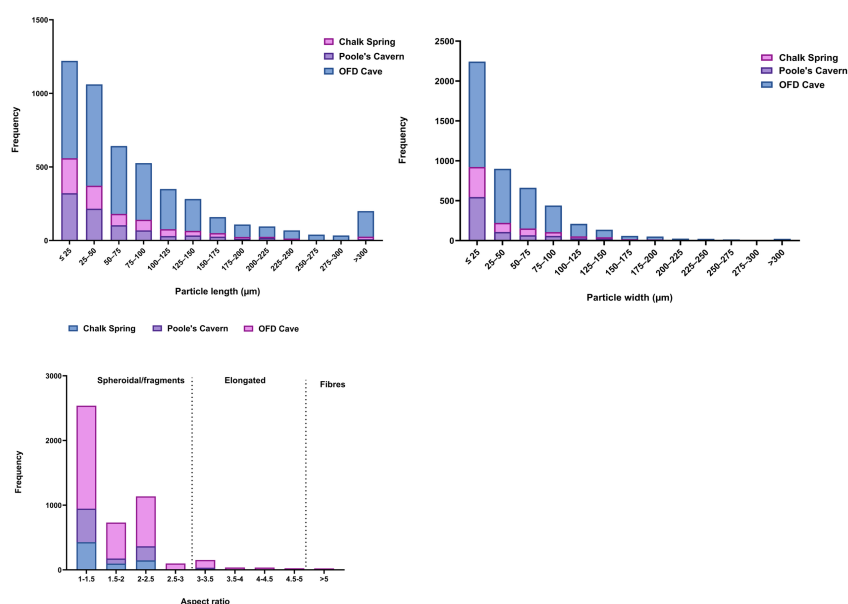


Figure 2. Size and shape of microplastic particles in the karst sediment system: (a) Length, (b) width, and (c) aspect ratio (shortest-to-longest dimension)

Conclusions

This study provides the first comparative analysis of microplastics in sediments from diverse UK karst settings, showing that they are present in all environments, that deposition is influenced by hydrology and recreational activity, and that sediments act as long-term sinks for microplastic accumulation.

Evaluating karst groundwater model structures with $\delta^{18}\text{O}$ signatures of spring discharge

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Karst groundwater models calibrated against spring discharge alone often suffer from equifinality, which limits confidence in simulated storage and transport processes and is particularly problematic when models are used to quantify contamination risk through fast flow in karstic conduits. Stable water isotopes ($\delta^{18}\text{O}$) provide independent information on groundwater age structure and mixing, yet their added value for improving the robustness and predictive reliability of karst spring simulations has not been quantified across contrasting karst systems. In this study, we assess how isotope information constrains model structure, parameter uncertainty, and prediction skill in karst groundwater modeling.

We apply the VarKarst hydrological model coupled with a StorAge Selection (SAS) transport approach to a multi-site subset of karst springs across major European karst provinces and different hydro-climatic conditions. To isolate the information gain from isotopes, all sites follow an identical, stepwise modeling workflow. Large Monte Carlo ensembles are first evaluated using discharge-only calibration, after which isotope transport parameters are introduced and assessed through multi-criteria performance metrics. Two alternative representations of conservative transport are tested, differing in whether transport is treated as a single integrated system or separated into vadose-zone and groundwater domains.

This work aims to develop a transferable framework for isotope-informed karst groundwater modeling, providing a methodological basis to improve the interpretability, robustness, and reliability of spring discharge simulations across diverse karst systems.

Benthic foraminifera assemblages in the Grotta delle Corvine (Ionian coast of Apulia, southern Italy): response to environmental stress

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Marine caves are sensitive environments influenced by the interaction between marine and terrestrial processes. Due to their biological, geological, and geomorphological peculiarities, they represent a unique habitat with a significant ecological value as biodiversity hotspots, playing a role in supporting broader marine ecosystem health and biodiversity. They are also included in the list of natural habitats of community interest to be preserved and protected, regulating their conservation status (Council Directive 92/43/EEC, Habitat type 8330). Their ecosystems are highly fragile, showing extreme sensitivity to groundwater pollution, water warming (Parise and Pascali, 2003; Chevaldonné and Lejeusne, 2003), and anthropogenic impacts. During the last decade, several studies have focused on the chemical and physical analyses of their sediments, as well as on their microfaunal content, particularly benthic foraminiferal assemblages (Romano *et al.*, 2022). Benthic foraminifera are highly sensitive to short- and long-term physico-chemical variations due to their short life cycle and preservation potential, respectively; therefore, they represent a good proxy for monitoring the environmental quality of these settings, recognizing possible environmental stress due to both natural and anthropogenic factors. In this regard, benthic foraminiferal assemblages from Grotta delle Corvine (Ionian coast of Apulia, southern Italy) were analysed to define the seasonal variability of this habitat in terms of ecozones, considering the chemical and physical features of cave sediments and waters.

Grotta delle Corvine is a submarine cave located within the Porto Selvaggio Natural Reserve. The cave formed through karst processes affecting Mesozoic limestones and, later, was partly modified by marine processes. It is of significant scientific interest for a variety of disciplines, from geomorphology and speleogenesis (Parise and Pascali, 2003), to biology and hydrogeology, not to mention the need to investigate the presence of radon within the karst system (Parise *et al.*, 2022). The cave, about 50 m-long and characterised by a wide entrance of 12 meters below the sea level, is one of the most extensive karst caves in the area. In its final sector, it includes two aerated rooms, not connect to the external environment. The cave floor consists of discontinuous sandy-silty sediments, due to presence of breakdown deposits in its inner part.

Starting from the cave entrance, 5 sampling stations were positioned at 10 m intervals along the cave, with two additional stations located within a lateral niche. At each station, separate aliquots of surface sediment (0-2 cm) were collected for grain size, Total Organic Carbon (TOC), Total Nitrogen (TN), and benthic foraminifera analyses. Water parameters were measured using a multi-parametric probe (Hanna Instruments HI98494). Two seasonal sampling campaigns were conducted in May and October, 2025.

As concerns the quantitative analyses of living and dead benthic foraminifera, the preliminary results highlight the presence of abundant and well-diversified assemblages throughout the entire cave, mostly dominated by calcareous hyaline species with an epifaunal attached lifestyle, such as *Gavelinopsis praegeri* and *Rosalina bradyi*, similarly to other Mediterranean caves (Bergamin *et al.*, 2020; Romano *et al.*, 2023). However, the development of periodic environmental stress conditions cannot be excluded, given the occurrence of stress-tolerant taxa such as *Lagenammina difflugiformis*, an infaunal species with an agglutinated test that inhabits circalittoral to bathyal environments and is indifferent to organic enrichment (Jorissen *et al.*,

2018). Further investigations will focus on understanding the origin of the observed stress conditions.

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Hydrogeology of the Wester sector of the Classical Karst: a transboundary aquifer shared between NE Italy and SW Slovenia

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The Classical Karst, located astride the border between Italy and Slovenia, represents one of the most important carbonate karst aquifers in the Mediterranean basin and one of the first to be studied worldwide. It is well known among researchers and speleologists primarily for studies and explorations aimed at understanding the underground drainage network of the Timavo River (Reka in Slovene), a watercourse that sinks into the impressive Škocjan Caves, a UNESCO World Heritage Site, and remerge in Italy at the Timavo Springs at San Giovanni di Duino. With an average discharge of about 30 m³/s, these springs represent one of the most significant spring systems in the Mediterranean region.

In addition to being recharged by the waters of the Timavo River, the aquifer is also sustained by losses from the Vipava and Isonzo rivers, which delineate its western boundary. This area has long been poorly investigated, and the connections between recharge areas and spring systems were largely unclear. The region is characterized by an extensive wetland area, including four karst lakes (Mucille, Doberdò, Pietrarossa, and Sablici) and a spring system composed of more than 50 individual springs.

A multi-year research project was therefore initiated, involving several public institutions (the University of Trieste, Italian and Slovenian water utilities, the Italian Geological Service of Friuli Venezia Giulia and the Slovenian Geological Survey) as well as the precious Italian and Slovenian speleological groups, with the aim of conducting a systematic investigation of the area. A continuous monitoring network was established through the installation of eight instruments that record water level, electrical conductivity, and temperature at 30-minute intervals in springs, lakes, and caves. In addition, based on the results of continuous monitoring and the geochemical characterization of the waters, five groundwater tracing tests were carried out in the recent years. The results of these studies indicate that the spring system can be subdivided into two sectors: a western sector, recharged by losses from the Isonzo and Vipava rivers and by precipitation, and an eastern sector, recharged by the waters of the Reka–Timavo River sinking at Škocjan and by precipitation. The Timavo spring represents the junction between the two sectors, showing a predominance of the Reka–Timavo contribution during high-flow conditions and a predominance of the Isonzo–Vipava contribution during low-flow conditions. These results help clarifying the connections between the different recharge areas and demonstrate the intrinsic complexity of the karst system and the importance of a joint work between countries in order to protect a precious resource.

Earthquake hydrogeology in carbonate reservoirs: from steady-state to transient groundwater flow modelling

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Earthquakes generate co-seismic static and dynamic strain within the Earth's crust, inducing perturbations in aquifers by modifying their hydro-mechanical properties and groundwater flow dynamics. These perturbations commonly manifest as anomalous variations in spring discharge, river stage, and groundwater levels, as well as changes in hydrochemical and isotopic signatures. The temporal evolution of these responses varies considerably, ranging from short-lived phenomena lasting hours to persistent anomalies enduring months or even years post-event. Large-magnitude earthquakes accompanied by co-seismic surface faulting have produced the most dramatic and well-documented hydrogeological effects worldwide, creating natural laboratories for investigating coupled seismo-hydrological processes, with structurally complex, fractured, and karstified carbonate reservoirs representing the most compelling case studies.

This work advances the understanding of long-lasting, earthquake-induced, hydrogeological perturbations in carbonate reservoirs through a conceptual and numerical modelling approach. Extending previous steady-state modelling efforts [1], we implemented time-dependent groundwater flow simulations to capture the dynamic evolution of the hydrogeological system. Transient hindcasting simulations with distributed numerical models explore the critical role of seismogenic faults in controlling subsurface hydrodynamics. The duality of karst systems is considered with a suitable discrete-continuum model approach. The numerical models examine how the hydraulic properties of seismogenic faults, implemented as variable-permeability barriers, influence groundwater storage and flow partitioning before and after co-seismic rupture.

The proposed modelling approach provides a transferable and adaptable tool for the quantitative assessment and anticipation of critical scenarios in aquifer dynamics worldwide, with potential practical relevance for groundwater resource management.

Keywords: active fault, carbonate hydrostructures, distributed numerical modelling, discrete-continuum models, turbulent flow

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