32nd INTERNATIONAL KARSTOLOGICAL SCHOOL
"CLASSICAL KARST"

32. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

EXTREME CONDITIONS AND EVENTS IN KARST

EKSTREMNI POGOJI IN DOGODKI V KRASU

ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

Postojna
2025

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10:00–10:15	**M. Lipar et al.**: Deciphering karst chronology through ferricrete (U-Th)/He dating: Insights from the pinnacle karst, Western Australia	
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	POSTER SESSION **POSTERJI**	
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11:00–11:15	**M. Vivier et al.**: Poljes, a pre-structuration of the hydrosystems in plateau karsts, the example of the Jura Mountain (France)	
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11:30–11:45	**A. Perșoiu et al.**: Recharge of karst aquifers by extreme rain events (and their long-term drying)	
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14:30–18:00	**Afternoon field trip (B) / Popoldansko terensko delo (B)** Periglacial processes and forest disturbances on karst *Bus drive and walk (several km).* Periglacialni procesi in motnje v gozdu na krasu *Vožnja z avtobusom ter hoja (nekaj km).*	
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18:00–19:30	*Break / Odmor*	
19:30	**Reception at the Karst Research Institute** **Sprejem na Inštitutu za raziskovanje krasa**	KRI IZRK

Friday, June 20th, 2025 **Petek, 20. junij 2025**		
08:30–16:00	**Whole-day field trip (D) / Celodnevno terensko delo (D)** Škocanjske Jame and Kraški Rob (Karst Edge) *Bus drive and walk (several km).* Škocjanske Jame in Kraški Rob *Vožnja z avtobusom ter hoja (nekaj km).*	

LIST OF POSTER PRESENTATIONS

The following list presents the order of the 2-min long flash presentations. Authors are kindly invited to prepare 1–2 slides to attract attention to the content of the poster. Flash presentation and poster showing will both take place at Karst Research Institute ZRC SAZU.

Na spodnjem seznamu je abecedni red dve-minutnih kratkih predstavitev. Avtorje vljudno vabimo, da pripravijo 1–2 prosojnici, da pritegnejo pozornost na vsebino plakata. Kratke predstavitve in predstavitev plakatov bodo potekali na Inštitutu za raziskovanje krasa ZRC SAZU.

	1st AUTHOR	TITLE
1	Bellec Morgane	Knowledge gaps and challenges towards an open-access European map of groundwater vulnerability in karst regions
2	Buzjak Nenad	Microclimatic controls on CO_2 dynamics in caves: insights from Samograd Cave (Croatia)
3	Çallı Süleyman Selim	Karst Mountains of Euro-Mediterranean and their groundwater potential in a changing climate
4	Cossu Quirico Antonio	Flash flood event recorded by atmospheric changes in the Bue Marino cave (Dorgali, Italy)
5	Dielmann Meline	Geomorphological mapping and terrestrial LiDAR scanning of speleogenetic features in the Cave under Babji Zob, Julian Alps, Slovenia
6	El Mellas Ismail	Direct numerical investigation of flow dynamics in karst conduits
7	Fabre Enola	Sustainability of drinking water supply in a Mediterranean city in the context of climate change. Study case: Montpellier (France) and Beni Mellal (Oum Er Rabia basin, Morocco)
8	Feroukas Konstantinos	Dispersion and deformation of a mixing front in heterogeneous media: reaction hotspots and the propagation of karst
9	Fleck Barbara	Modelling flow and transport to assess the influence of subsurface geometry on Alpine karst aquifer vulnerability
10	Frantar Peter	Preliminary assessment of groundwater recharge in karst areas using the mGROWA-SI model
11	Funk Barbara	Investigation of the phreatic karst zone using magnetotelluric measurements
12	Gąsiorowski Michał	Speleothem oxygen and carbon isotopes point to strong NAO teleconnection during the onset of MIS 6 in the Sudety Mountains (Central Europe)
13	Gebus-Czupyt Beata	Cave sulfate minerals and speleogenesis - an insight from the perspective of sulfur and oxygen stable isotopes
14	Grošanić Klara	Morphogenesis at the very edge of the Dinaric Karst - an example of the Ozalj region (Croatia)
15	Grundhöfer Tobias	Advancing contaminant transport modeling in karst systems: integrating Eulerian and Lagrangian approaches in openKARST
16	Housni Yousra	Scalable flow modeling in karstic media through graph simplification
17	Iepure Sanda	Sub-BioMon project - Addressing the challenges of monitoring subterranean biodiversity in karst
18	Iurilli Vincenzo Walter	Flood management needs as a challenge for geoconservation in a geopark. Case study of Gurgo di Andria in MurGEopark (Southern Italy)
19	Jaillet Stéphane	Dissolved carbonate exports in the Chevaline river (Choranche, Vercors). Period 2008 – 2018
20	Jelovčan Matej	Geomorphological characteristics of shallow karst depressions (dayas) on the Nullarbor Plain
21	Johnston Vanessa	Hydrogeochemical monitoring of the Postojna–Planina caves system to study carbon transfer between air, water and rock
22	Knez Martin	The Great Pyramid of Giza exposed to weathering
23	Koutník Jakub	Using tracer tests to characterize channel flow in different environments
24	Martin-Perez Andrea	Thrombolitic texture of subaqueous calcite moonmilk from Demänovská jaskyňa mieru, Slovakia
25	Mayaud Cyril	FloodWatch: a mobile application to monitor floods in karst areas
26	Mazej Tinkara	Semi-automatic detection of conical hills and uvalas based on the topographic openness index and shape delineation using the last closed contour method

27	Meus Philippe	A few considerations on improving dye tracer detection with activated carbon
28	Morelli Francesco	An up-to-date karst landforms and landscape map of Abruzzo region (Italy, Central Apennines)
29	Nagl Michael	Quantification of solid and dissolved load from the mass balance of a major karst spring
30	Nagy Judit Barbara	Investigation of the water balance of Lake Hévíz
31	Năpăruș-Aljančič Magdalena	Prototype for the Slovenian Karst Database – advancing to cataloguing multidisciplinary karst data
32	Noffz Torsten	Laboratory-scale investigations of flow in synthetic conduits with high roughness
33	Novak Uroš	Decoding a 60,000-year tectonic history: speleoseismicity from a fault in Postojna Cave
34	Oarga-Mulec Andreea	Climate change and extreme environmental events require more topics on protection and rescue
35	Pennos Christos	Microplastic contamination in karst waters: evidence from Greek cave systems
36	Perne Matija	Estimating parameters of calcite photoluminescence from video recordings
37	Racine Tanguy	Systematics of geometric and hydraulic properties of karst conduits revealed by LiDAR-derived 3D models of cave walls
38	Rzadkowski Kewin	Distribution and complexity of karst depressions in the Rovte area (Central Slovenia): a geomorphometric and lithological perspective
39	Skok Sara	Microbial diversity on cave walls in Slovenian karst caves
40	Stienss Jacek	Preliminary results of isotope studies in the Late Holocene speleothem from Gigant cave in the Prokletije mountains, Montenegro
41	Stokes Tim	Integration of karst spring hydrological data and land use disturbance information: towards development of a karst catchment management plan, Quadra Island, British Columbia
42	Szieberth Dénes	**Fluorescent calcites in the Molnár János Cave**
43	Šebela Stanka	The SLO KARST Near-Fault Observatory: monitoring tectonic dynamics in southwestern Slovenia
44	Tămaş Tudor	A study of silver-copper coin weathering in cave sediments
45	Temovski Marjan	U-Th dating of internal speleothem reference materials – laboratory comparison of LSCE and ATOMKI
46	Valea Codruța	Microfacies and mineralogical investigations of an Upper Eocene detrital sequence from Tăușoare Cave, Romania

GENERAL INFORMATION

Registration

- Registration is possible on Monday (8:00 – 13:00), Tuesday (8:30 – 11:00), and Wednesday (8:30 – 09:30) in the Cultural Centre Postojna (Gregorčičev drevored 2a, Postojna) in a separate space in front of the main entrance to the Cultural Centre on the right. **Registration is obligatory for all participants.**

Oral presentations

- Lectures will take place in the Cultural Centre Postojna (Gregorčičev drevored 2a, Postojna).
- PowerPoint presentations **should be given to the organizers** during the break before the Session with the presentation.
- Maximum duration of the lecture is 15 min (12 min for talk and 3 min for discussion). Invited lecturers (keynote speakers) have 30 min for the lecture. Due to a tight schedule, we ask you to please be punctual!

Posters

- Poster size: mandatory max. format is A0 – 841 x 1189 mm (portrait layout).
- Poster presentation and display will be held at the Karst Research Institute in the hall and the stairway.
- Flash presentation session will be organized at the beginning of the poster session. For this, each author(s) is asked to prepare a 2-minute-long flash presentation with 1–2 slides to attract attention to the content of the poster. After the flash session, the posters will be displayed and the authors will be able to answer the questions and discuss their research in detail.
- Leave the posters and short poster presentations (.ppt, .pdf) at the registration desk on Monday, June 16th, before the lunch break.
- Stand by your poster during the poster display.

Meals

- Lunches are not organized during the session days and afternoon field trips (Tuesday and Wednesday).
- During whole-day field trips (Thursday and Friday) simple lunches will be provided. Due to the length of the Thursday`s and Friday's excursions (Excursion C and D) we suggest you take with you some additional snacks.
- Lunch breaks are timetabled into the schedule during the session days (Monday, Tuesday and Wednesday). You can go for lunch to e.g. Štorja pod stopnicami, Bar Bor, Pri kaminu, Čuk, Bistro Perspektiva, etc.
- On Thursday a reception dinner will be provided.

Field trips

- All fieldtrips will be combined with a bus drive and walk (several km per day).
- Registration for each field trip will be possible only on Monday, 16th June 2025 at the registration desk.
- Bus departure for the field trips is from the parking place at the Postojna bus station (marked as No. 3 on the Map of Postojna).
- Because of visits of caves, walking shoes, field clothes and headlamps are obligatory. At most excursions, a lot of walk is expected. Please, be ready for possible hot weather or/and rain.
- Insect repellents are recommended as we will be walking in areas populated with ticks (Ixodes ricinus) that transfer mainly lyme desease and tick-borne meningitis. Check yourself in the evening after each field trip.
- Participation on the excursions is voluntary and at your own risk. The organizers do not accept any liability for any loss, damage, injury or death arising from or connected with the excursions. Participants are advised to arrange an appropriate insurance policy. The participants are obliged to comply with the instructions of the organizers.

OSNOVNE INFORMACIJE

Prijava

- Registracija je mogoča v ponedeljek (08:00 – 13:00), torek (08:30 – 11:00) in sredo (8:30 – 09:30) v Kulturnem domu v Postojni (Gregorčičev drevored 2a, Postojna), v ločenem prostoru pred glavnim vhodom v Kulturni dom, desno. **Registracija je obvezna za vse udeležence.**

Predavanja

- Večina predavanj poteka v Kulturnem domu v Postojni (Gregorčičev drevored 2a, Postojna).
- Prosimo, da PowerPoint predstavitve **oddate organizatorjem** v odmoru pred začetkom tematskega sklopa, v katerem imate predstavitev.
- Dolžina predavanja je omejena na 15 minut (12 minut za govor in 3 minute za razpravo). Vabljena predavanja so omejena na 30 minut. Prosimo vas, da se strogo držite predpisanega časa!

Posterji

- Velikost posterjev: obvezen največji format je A0 – 841 x 1189 mm (pokončna lega).
- V začetku predstavitve posterjev bo potekala hitra predstavitev s pomočjo prosojnic. Pri tem vse avtorje vabimo k pripravi dve minuti dolge predstavitve - napovednika (ena do dve prosojnici), v kateri pritegnete pozornost na vsebino posterja. Hitri predstavitvi bo sledil klasičen ogled posterjev, kjer bodo avtorji lahko odgovarjali na morebitna vprašanja udeležencev.
- Posterje in kratke prestavitve (.ppt, .pdf) pustite pri mizi za prijavo udeležencev, in sicer v ponedeljek, 16. junija, do odmora za kosilo.
- Med ogledom posterjev stojte poleg svojega posterja.

Obroki

- Kosilo med predavanji in popoldanskim terenskim delom (torek in sreda) ni organizirano.
- Med celodnevnim terenskim delom (četrtek in petek) organiziramo enostavne obroke. Zaradi dolžine četrtkove in petkove ekskurzije (Ekskurzija C in D) priporočamo, da si s sabo vzamete še kakšen dodaten prigrizek.
- Odmori za kosilo so v času predavanj (ponedeljek, torek in sreda) vključeni v program. Jeste lahko v Štorji pod stopnicami, Bar Boru, Pri kaminu, v Čuku, Bistro Perspektiva, itd.
- V četrtek je v večernem delu programa planirana pogostitev.

Strokovne ekskurzije

- Vse ekskurzije bodo kombinirane z avtobusno vožnjo ter hojo (nekaj km/dan).
- Prijave za strokovne ekskurzije bodo mogoče le še v ponedeljek, 16. 6. 2025 pri mizi za prijavo udeležencev.
- Odhod avtobusov je z glavne avtobusne postaje Postojna (označeno s št. 3 na karti Postojne).
- Zaradi predvidenih obiskov jam je obvezna primerna oprema (pohodni čevlji, terenska oblačila, svetilke). Na vseh ekskurzijah pričakujemo precej hoje. Pripravite se tudi na možno vročino ali/in dež. Na ekskurzijah bomo veliko hodili – bodite pripravljeni.
- Priporočamo uporabo repelentov proti insektom. Hodili bomo po območjih, kjer se nahajajo populacije klopov (*Ixodes ricinus*), ki so lahko prenašalci povzročiteljev lymske borelioze ali meningitisa.
- Udeležba na terenskem delu je prostovoljna in na lastno odgovornost. Organizator ne prevzema odgovornosti za morebitne izgube, škodo, poškodbe ali smrtne primere, ki bi nastali v povezavi s terenskim delom. Udeležencem svetujemo, da si pred odhodom na terensko delo uredijo ustrezno zavarovanje. Udeleženci so tekom terenskega dela dolžni upoštevati navodila organizatorja.

MAP OF POSTOJNA

ZEMLJEVID POSTOJNE

1 - Karst Research Institute ZRC SAZU / Inštitut za raziskovanje krasa ZRC SAZU
2 - Cultural Center of Postojna / Kulturni dom Postojna
3 - Postojna bus station / Avtobusna postaja postojna
4 - Entrance to cave Postojnska jama / Vhod v Postojnsko jamo

A - Pizzeria and restaurant Minutka / picerija in restavracija Minutka
B - Bistro Štorija / Bistro Štorija
C - Restaurant Proteus / Restavracija proteus
D - Bistro Bar Bor / Bistro Bar Bor
E - Pizzeria and restaurant Čuk / Picerija in restavracija Čuk

Post office / pošta
ATM / bankomat
Market / trgovina
Bakery / pekarna
Fast food / hitra prehrana

INVITATION TO A SPECIAL SESSION: KARST JAM

(Monday, 16th June 2025)

This year's school will be as always a great meeting point between experienced and new researchers from different parts of the globe.
This year, for the third time in a row, we will hold a "Karst Jam" session, where a debate will be challenged by the moderator and attendees, where different karst topics will be addressed. The idea is to talk about some open/unresolved/ambiguous/problematic topics in a friendly environment with a lot of fun. Young researchers and students will get the possibility to hear both (or several) answers to the unresolved questions within karst science, where recognized scientists will get the possibility to mingle.
No contribution is needed, just your presence, goodwill and constructive ideas.
See you on Monday, 16th of June in the evening at the Karst Research Institute ZRC SAZU!

POVABILO NA POSEBNO SEKCIJO: KRAŠKE DEBATKE

(ponedeljek, 16. junija 2025)

Letošnja šola bo kot vedno odlično stičišče izkušenih in novih raziskovalcev iz različnih koncev sveta.
Letos bomo tretjič vpeljali sekcijo "Kraške debatke", kjer bo debata potekala s pomočjo moderatorja in udeležencev ter kjer bodo obravnavane različne kraške teme. Ideja je, da se o nekaterih odprtih/nerešenih/dvoumnih/problematičnih temah pogovarjamo v prijaznem okolju z veliko zabave. Mladi raziskovalci in študentje bodo imeli možnost slišati oba (ali več) odgovorov na odprta krasoslovna vprašanja, kjer bodo dobili možnost druženja s priznanimi krasoslovci.

Prispevek ni potreben, le vaša prisotnost, dobra volja in konstruktivne ideje.
Se vidimo v ponedeljek, 16. junija zvečer na Inštitutu za raziskovanje krasa ZRC SAZU!

FIELD TRIPS

TERENSKO DELO

Afternoon field trip (A):

KARST SPRING LINTVERN: AN EXTREME CASE OF INTERMITTENCY

Tuesday, June 17th 2025, 15:00–19:30

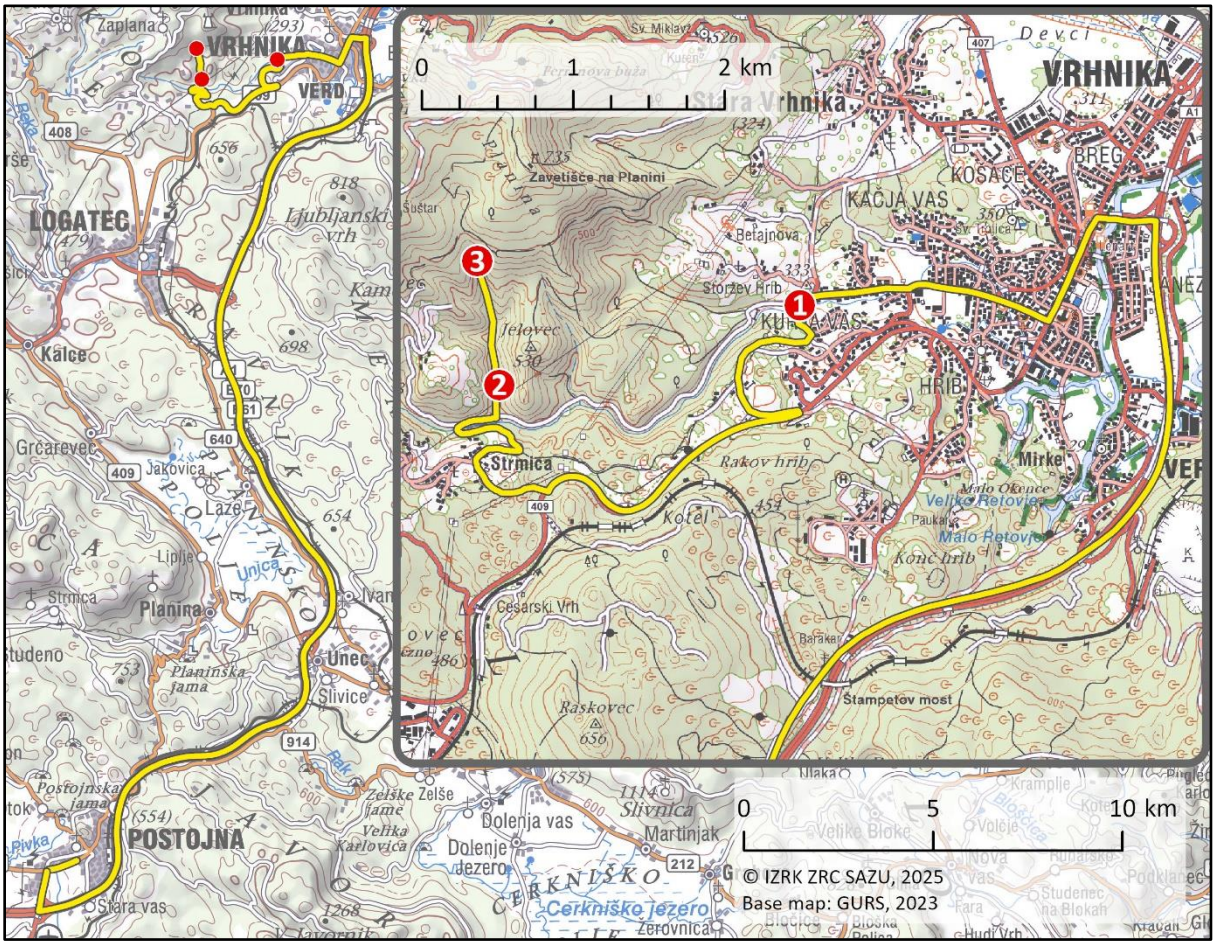
Franci Gabrovšek

Stops:

1 – Alluvial fan of the Bela Stream

2 – Stari Maln

3 – Lintvern intermittent spring



Izvir Lintvern pri Vrhniki kot primer izjemne intermitentnosti

Popoldanska ekskurzija (A); torek, 17. junij 2025;

Fluviokraško območje potoka Bele, zahodno od Vrhnike, z intermitentnim izvirom Lintvern je morda manj znan del prispevnega območja Ljubljanice, vendar zato nič manj zanimiv. Potok Bela že v zgornjem toku del vode izgubi v kraško podzemlje, a se mu ta »z obrestmi!« vrne prek kraških izvirov na vršaju potoka ob robu Ljubljanskega barja. Več izvirov je aktivnih le ob visokih vodah, ko so poplavljene tudi vrtače (in kleti hiš) ob robu vršaja. Območje predstavlja tudi skrajni del areala proteusa. Eden od izvirov Bele je tudi izjemen intermitentni izvir Lintvern, ki s svojo silovitostjo že stoletja buri duhove domačinov in raziskovalcev.

THE BELA STREAM SYSTEM

The Bela Stream is a tributary of the Ljubljanica River, located west of the town of Vrhnika. It forms a complex fluviokarstic drainage system on Main Dolomite and Jurassic limestones in the transition zone between the Dinaric and Alpine systems. The Bela stream is fed by small tributaries and distinct karst springs in dolomite, and by karst springs in Jurassic limestone at the edge of an alluvial fan (Fig. 1.1).

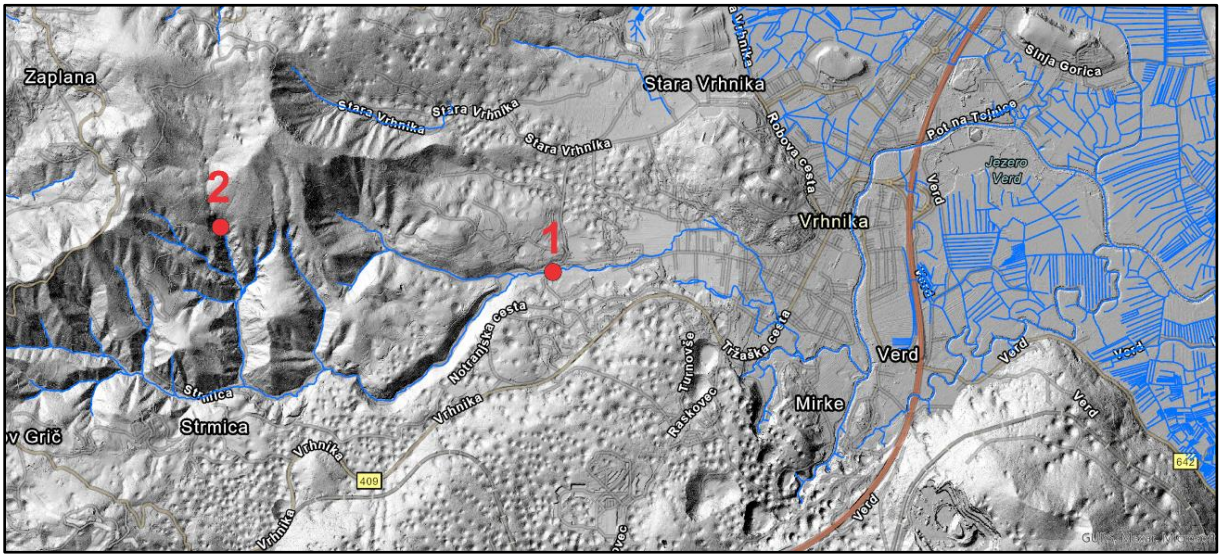


Fig. 1.1: The Bela fluviokarstic system west of Vrhnika with position of stops. 1: Bela alluvial fan at the rim of Ljubljana Basin. 2: Lintvern Spring.

Several tracing tests have been conducted in the area, confirming that the Bela Stream loses water in the narrowest section of its flow, and that this water reappears at the Kožuhov Izvir (Kužuh Spring), the westernmost spring of the Ljubljanica. A connection between the cave Ferranova Buža (length = 2.340 m, depth = 358 m) and the springs around the Bela alluvial fan (Fig. 1.2) has also been confirmed by water tracing (Staut & Auersperger 2006).

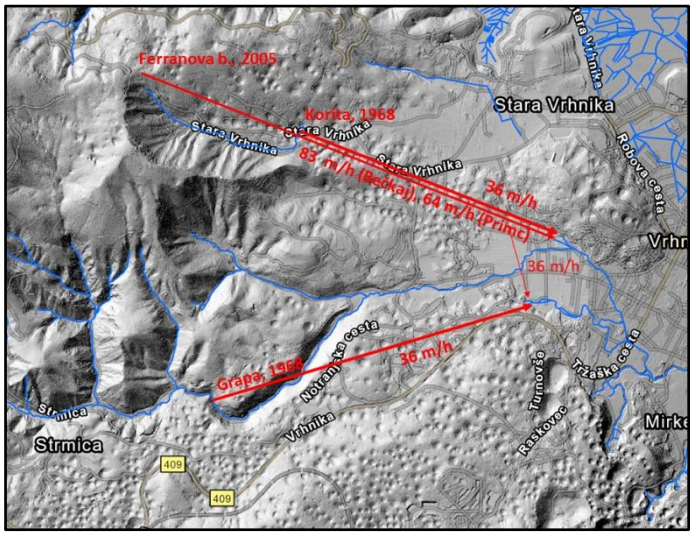


Fig. 1.2: The tracing tests that were conducted in the Bela Stream and adjacent karst system.

The western rim of the alluvial fan is dotted with numerous dolines (Fig. 1.3), which become flooded after intense rainfall, occasionally causing flooding of nearby houses. The alluvial fan lies above a well-developed karstic system, as demonstrated by tracing tests and direct observations at the springs.

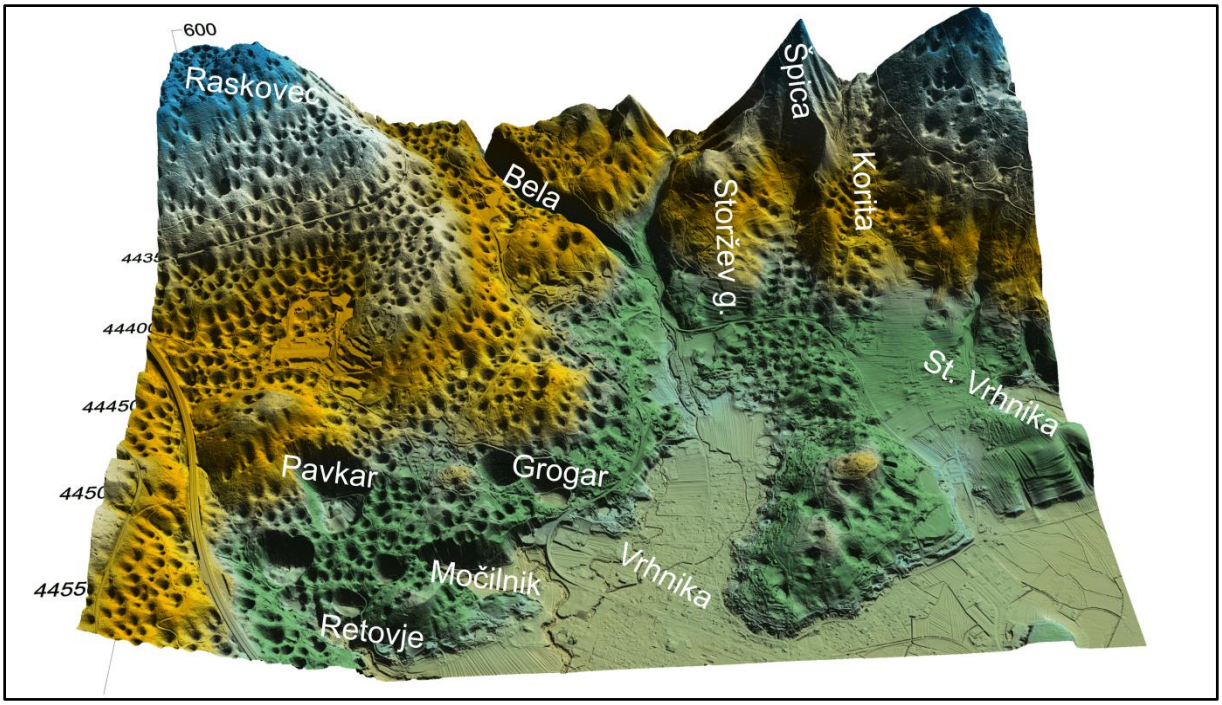
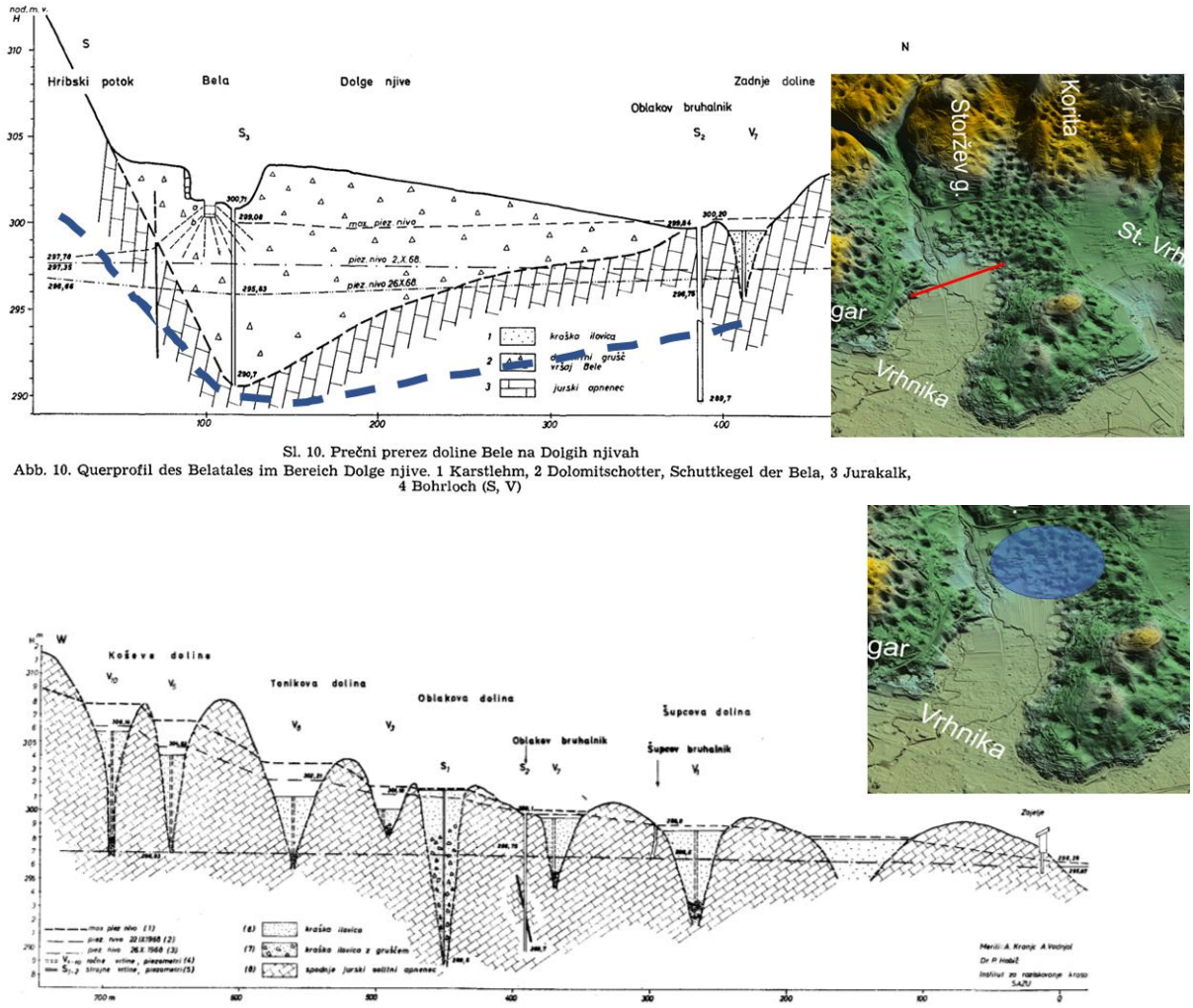


Fig. 1.3: DEM of the area west of Vrhnika with Bela alluvial fan and its immediate karstic vicinity.

Fig. 1.4 shows a cross-section through the alluvial fan, underlain by well-karstified Jurassic limestone. The dashed line schematically indicates the conduits through which a pressure pulse, caused by a rise in spring level on one side (using sluice gate) triggered an immediate response in water level at the springs on the opposite side. The dolines in the immediate hinterland of the fan have deep infillings (Fig. 1.4, bottom), reaching well below the groundwater level.



Sl. 10. Prečni prerez doline Bele na Dolgih njivah
Abb. 10. Querprofil des Belatales im Bereich Dolge njive. 1 Karstlehm, 2 Dolomitschotter, Schuttkegel der Bela, 3 Jurakalk, 4 Bohrloch (S, V)

Fig. 1.4: Upper figure: Cross-section through the alluvial fan along the red line shown in the DEM. Lower figure: Cross-section through dolines in immediate hinterland of Bela alluvial fan (Modified after Habič, 1976).

THE INTERMITENT SPRING LINTVERN

Lintvern is a remarkable intermittent karst spring and one of the principal sources of the Bela Stream. Its unusual hydrological behavior has been recognized since antiquity, when local folklore attributed its periodic activity to the agitation of a mythical dragon. The name Lintvern is etymologically linked to the *Lindwurm*, a mythical serpent-like dragon from Northern, Western, and Central European folklore.

The renowned Slovene polymath J. V. Valvasor documented Lintvern in the 17th century; it is also speculated that the site marks his earliest recorded mention of Proteus anguinus. However, there is no confirmed evidence of human fish inhabiting the Lintvern spring itself. Nonetheless, regular occurrences of Proteus individuals during flood conditions have been reported at other high-water springs situated along the alluvial fan of the Bela stream.

Situated in a gorge, the spring lies at an elevation of 504 meters above sea level, and about 210 m from the base level of other prominent karst springs in the area. It emerges from Upper Triassic Main Dolomite, which underlies the spring and its immediate surroundings. The catchment area assessed by Habič (1970) is about 3 km^2 large.

Lintvern has been the subject of investigation by numerous researchers. A general consensus attributes its intermittency to the operation of a siphon mechanism, though the specifics of this process remain a matter of debate. Habič (1970) conducted early quantitative assessments of discharge and basic functioning, but significantly more detailed data have become available through recent studies. These include long-term, high-resolution time series capturing water level (as a proxy for discharge), electrical conductivity, and temperature.

Today, the spring is incorporated into the local water supply system, though it serves primarily as a backup source. Under baseflow conditions, water from Lintvern is directly channeled into the pipeline network. During high-flow events, however, excess discharge overtops the weir and flows past a flap-gate door into the gorge below (Fig. 1.5). What outlines Lintvern's behaviour is the extreme ratio between the peak flow rate (approx. 750 l/s) vs. the flow rate (order of 3-10 l/s) which triggers (primes) the system.

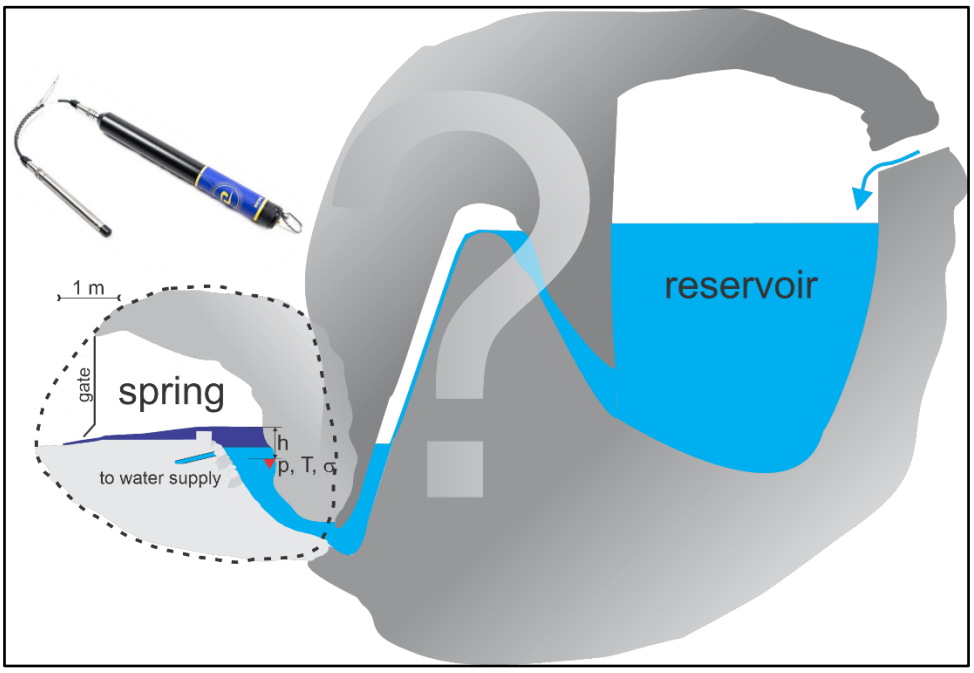


Fig. 1.5: Schematic representation of Lintvern. The area enclosed by the dashed line depicts known features; elements beyond this boundary are inferred.

SUMMARY OF OBSERVATIONS AND INTERPRETATION OF THE LINTVERN SPRING MECHANISM

The observations obtained from long-term monitoring of the Lintvern spring may be summarised into the following key conclusions:

Frequency and Precipitation: The frequency of spring outbursts is evidently correlated with precipitation events. Fig. 1.6 shows level hydrograph between March 15th and December 31st, 2024. All together 400 outburst events were recorded (spikes marked by the red dots), the peak-to-peak interval is ranging from less than 30 min to over 400 hours.

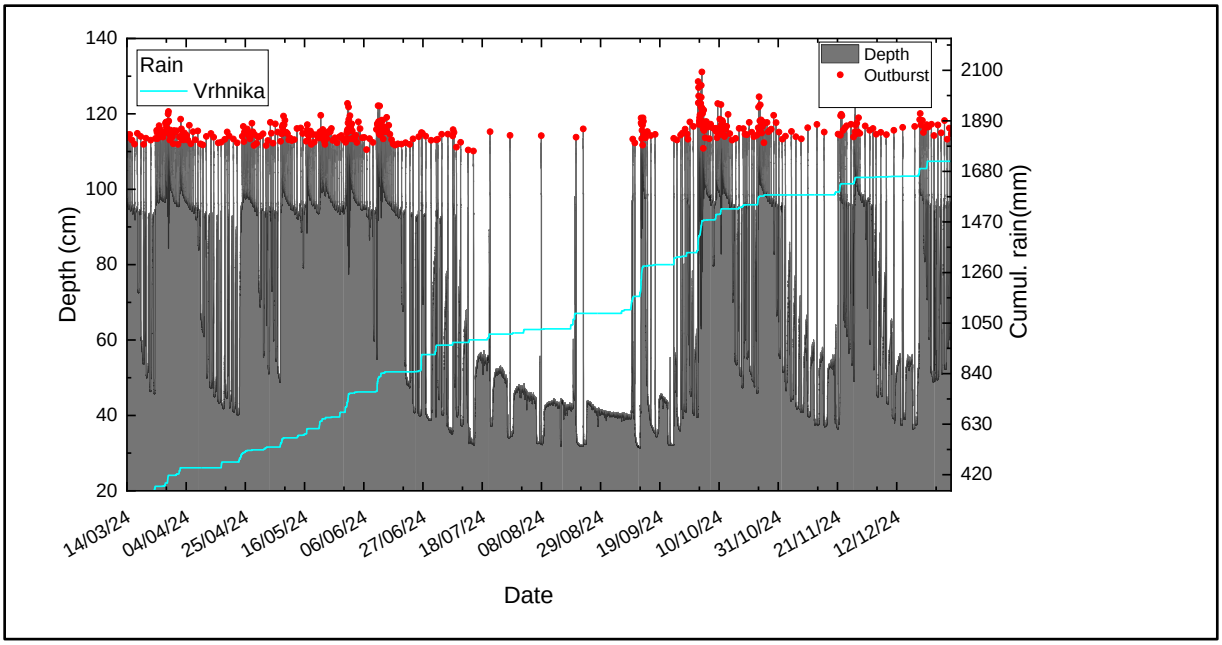


Fig. 1.6: Level hydrograph and cumulative rainfall in Vrhnika from March 2024 to December 2024.

Fig. 1.7 illustrates the correlation between peak-to-peak intervals and cumulative precipitation in the preceding 1 to 2.000 hours. Negative correlation values indicate that greater rainfall is associated with shorter delays between outbursts. The correlation reaches its minimum at approximately 70 hours, suggesting that cumulative precipitation over the preceding ~3 days exerts the strongest influence on the frequency of outburst events.

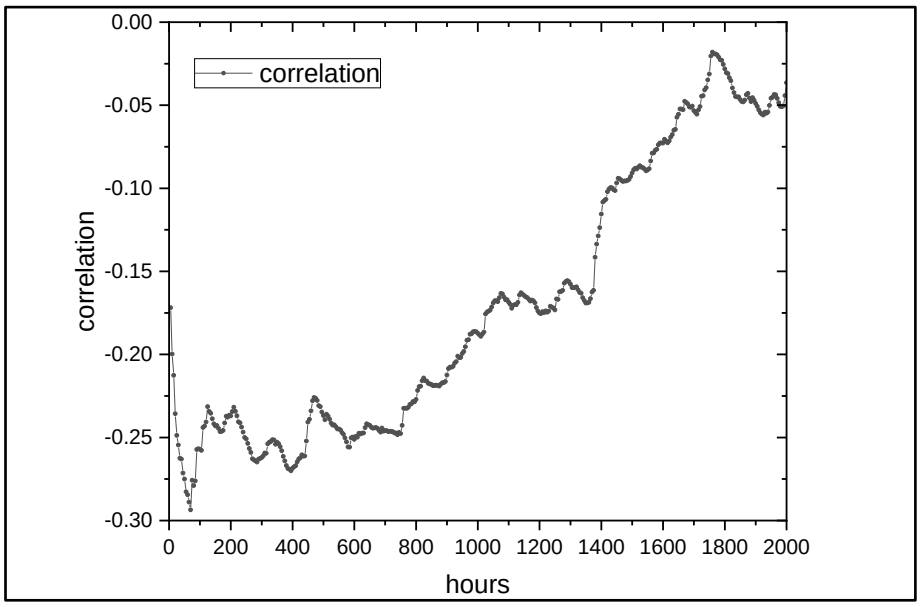


Fig. 1.7: Correlation between peak-to-peak interval and cumulative precipitation across time windows from 0 to 2.500 hours.

CHARACTERISTIC OUTBURST PATTERN

Fig. 1.8 shows a typical recession pattern during a dry period following a strong precipitation event. Initially, the outbursts are frequent (almost continuous, but keeping the outburst character) with continuous flow over the weir. During recession, the peak-to-peak interval increases and characteristic pattern of low/high level states and outbursts is observed.

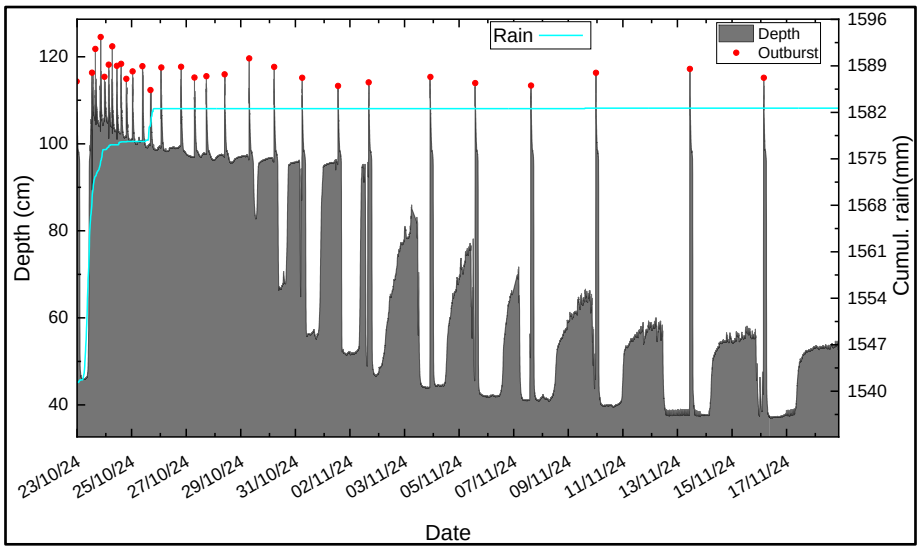


Fig. 1.8: Rain period with frequent outbursts followed by dry period with increasing peak-peak delay.

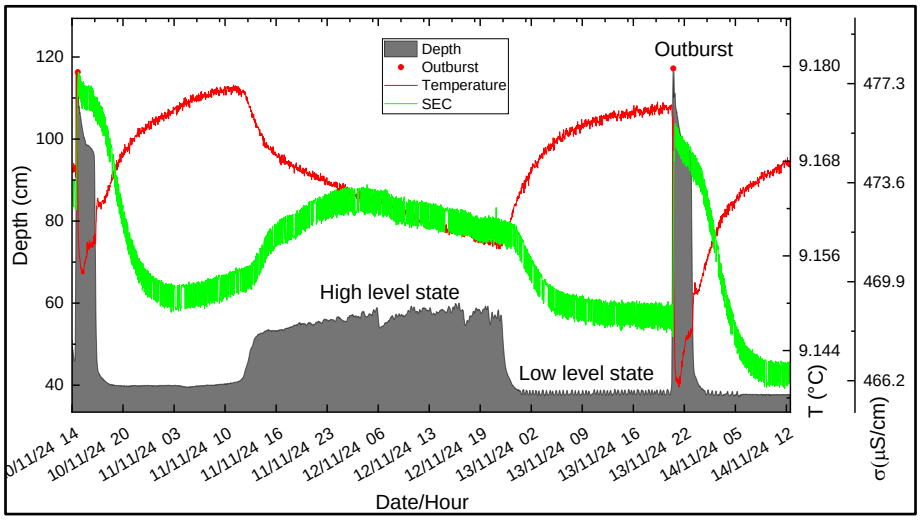


Fig. 1.9: A characteristic level/temperature/SEC hydrograph during successive outbursts.

Level/depth in figures show the depth of the water above the pressure transducer. It corresponds to flow rate, which is a bit tricky: below the weir the spring is discharged through a tube into a water shaft. Above 95-97 cm, the flow over the weir is channelized into a stream bed.

Between the outbursts, the spring exhibits two distinct states, observed in water level data (Fig. 1.9):

- Following an outburst, the water level typically declines to a low-level state, which may persist from several hours to multiple days.
- Subsequently, the level rises to a high-level state, which can persist from hours to days or even weeks. For instance, in summer 2022, the elevated state endured for 67 consecutive days,

terminated only by an extreme hydrological event. This indicates (but does not prove) that the system can run into situation, when outburst would not occur.

- In most cases, an outburst is initiated from the lower state. During sustained high-level phase, the water level shows frequent drops partially toward the lower state following a curve with same characteristics to the pre-outburst recession. However, it returns to the higher state before the outburst would occur (Fig. 1.10).

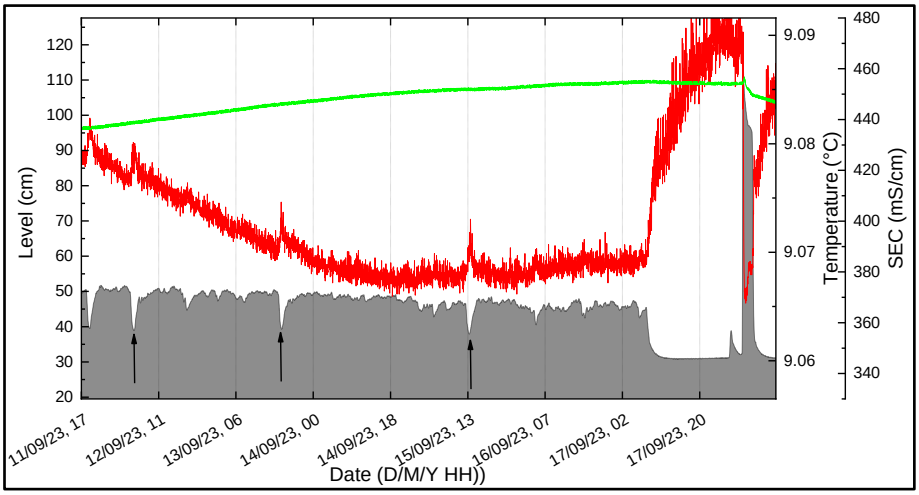


Fig. 1.10: High stage with frequent partial drop of spring water level.

The temperature and SEC hydrographs exhibit distinct behaviour during outbursts:

- Temperature: The water temperature at the lower state is lower than at the higher state and during outburst peaks, suggesting different subsurface flow paths. A slight decrease in temperature also accompanies the water level decline prior to outbursts (Fig. 1.10), followed by a rewarming trend as the level rises during the outbursts. Note, that all these dynamics happen within less than a fraction of a degree, in presented case within 0.03°C.
- Specific Electrical Conductivity (SEC): SEC also varies within 10 µS/cm, but supports the inference of differentiated flow paths contributing to the observed hydrochemical variability.

Water from the siphon appears to mix with bypassing water that exhibits slightly different physicochemical characteristics. Thus, variations observed at the spring under otherwise stable conditions can be attributed to flow dynamics within the siphon pathway.

DISCHARGE CHARACTERITICS

Fig. 1.11 illustrates a typical outburst, from a low state to peak discharge and recession back to low state:

- From the weir equation, peak discharge has been estimated at approximately 0.75 m^3/s.
- The total volume discharged during a single outburst event is above 2.000 m^3.
- During low water state, discharge rates are significantly lower, on the order of a few liters per second. During high water state the discharge is probably in the order of 10 l/s.

The total duration of the outburst (low state-peak-low state) is about 3 hours. It takes about 15 min from the low state to peak flow. The duration of flow over the weir is about 2 hours and 30 minutes, while the recession back to low state level takes another 30 min. This is to a good approximation valid

for all outburst hydrographs starting from low state. Note the initiation and termination of the outburst are rather smooth, indicating continuous (non-abrupt) processes. These values remain preliminary, pending further analysis and calibration/acquisition of the hydrometric data.

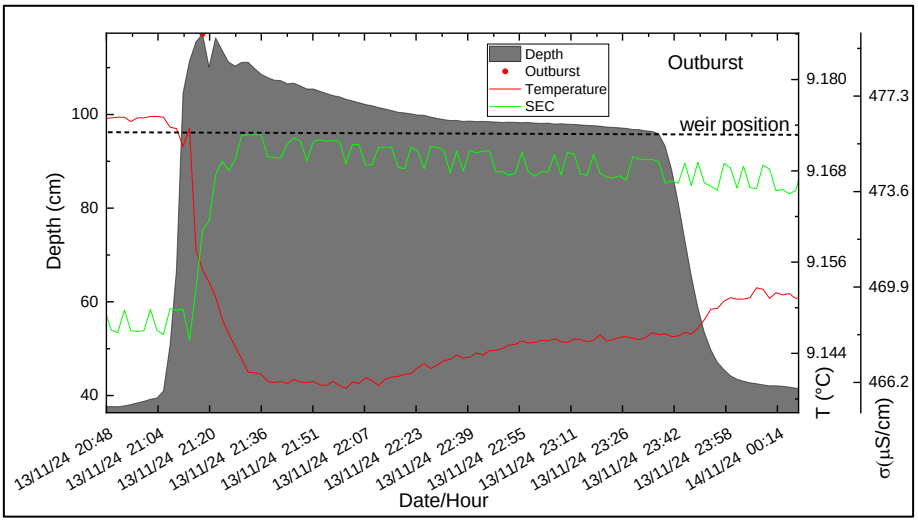


Fig. 1.11: Example of a typical outburst.

THE MECHANISM: A SELF-PRIMING SIPHON SYSTEM

The understanding of Lintvern's intermittent dynamics is evolving towards a comprehensive conceptual model, with the following working hypothesis:

- The spring operates as a self-priming siphon system.
- The outflow limb of the siphon is sealed such that external air entry from the spring end is inhibited. This allows siphon with large peak discharge to be primed with small inflow flow rate.

The observed behaviour arises from the complex interplay between air entrapment, air entrainment, and water velocity. These are broad statements that, while helpful as a general framework, fall short of explaining the finer details. Nonetheless, they represent the extent of our current understanding—as captured in this guidebook at the time of writing. During the field trip, however, we will introduce one or two working hypotheses. These are informed by educated guesses and supported or refined through numerical modelling.

References:

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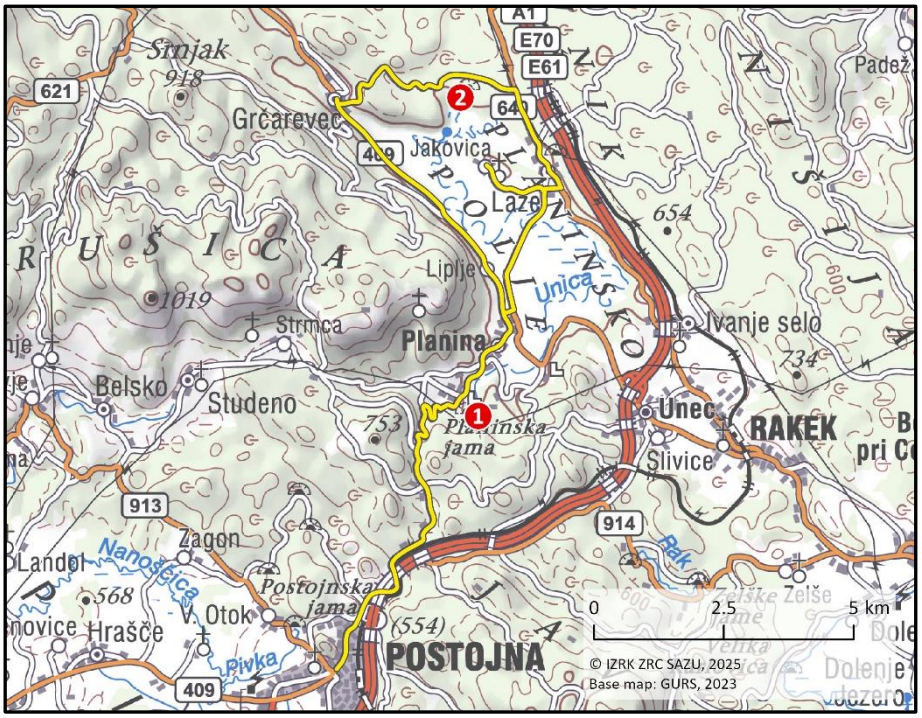
Afternoon field trip (B):

PERIGLACIAL PROCESSES AND FOREST DISTURBANCES ON KARST

Wednesday, 18th June 2025, 14:30–18:00

Matej Blatnik, Jaroslav Obu, Nataša Ravbar, Urša Vilhar, Cyril Mayaud

Stops:
1 – Planinsko polje – Viewpoint and forest study site above Planinska Jama
2 – Planinsko polje – Skednena Jama



Periglacialni procesi in motnje v gozdu na krasu

Popoldansko terensko delo (B); sreda, 18. junij 2025;

V prvem delu ekskurzije bomo obiskali merilno mesto v gozdu nad Planinsko jamo, ki predstavlja eno izmed lokacij za spremljanje napajanja podzemne vode. Merilna mreža sicer zajema celoten navpični profil kraškega vodonosnika, znan kot kritično območje krasa. To vključuje atmosfero, vegetacijo, prst ter nezasičeno in zasičeno cono vodonosnika. S posebej razvito opremo neprekinjeno spremljamo različne parametre, kot so: padavine na prostem, prepuščene padavine, temperatura zraka in prsti, vlažnost prsti, pa tudi vrsto in pretok prenikle vode v jamah, ponikalnic, podzemnih rek in izvirov ter druge lastnosti vode, kot sta temperatura in električna prevodnost. V drugem delu ekskurzije bomo obiskali Skedneno jamo, v kateri so prisotni periglacialni pojavi, in sicer sortirani kolobarji. Sortirana strukturna tla se sicer najpogosteje pojavljajo na Arktiki in v visokogorju, najdemo pa jih tudi v kraških jamah. Zaradi ponavljajočega zmrzovanja in odtajanja v zimskih mesecih pride na vhodnih delih jam do sortiranja grobih in finih delcev ter tako do nastanka sortiranih kolobarjev.

ADVANCING GROUNDWATER RECHARGE MONITORING IN KARST AQUIFERS: AN EXAMPLE OF DISTURBED FOREST ABOVE PLANINSKA JAMA

Worldwide carbonate rocks cover about 15 % of the land surface, of which up to a third is forested (Fig. 2.1; Vilhar *et al.* 2022). Events that result in the loss of forest biomass, such as wildfires, have in recent years devastated numerous European and American forests. Other types of forest disturbances, such as droughts and diseases infestations can also be destructive. One example is a massive ice storm (glaze or sleet) that hit Slovenia in 2014. More than half of the country's forests were damaged, and in the following years they were further affected by windthrows and spruce bark beetle infestations (Kutnar *et al.* 2021).

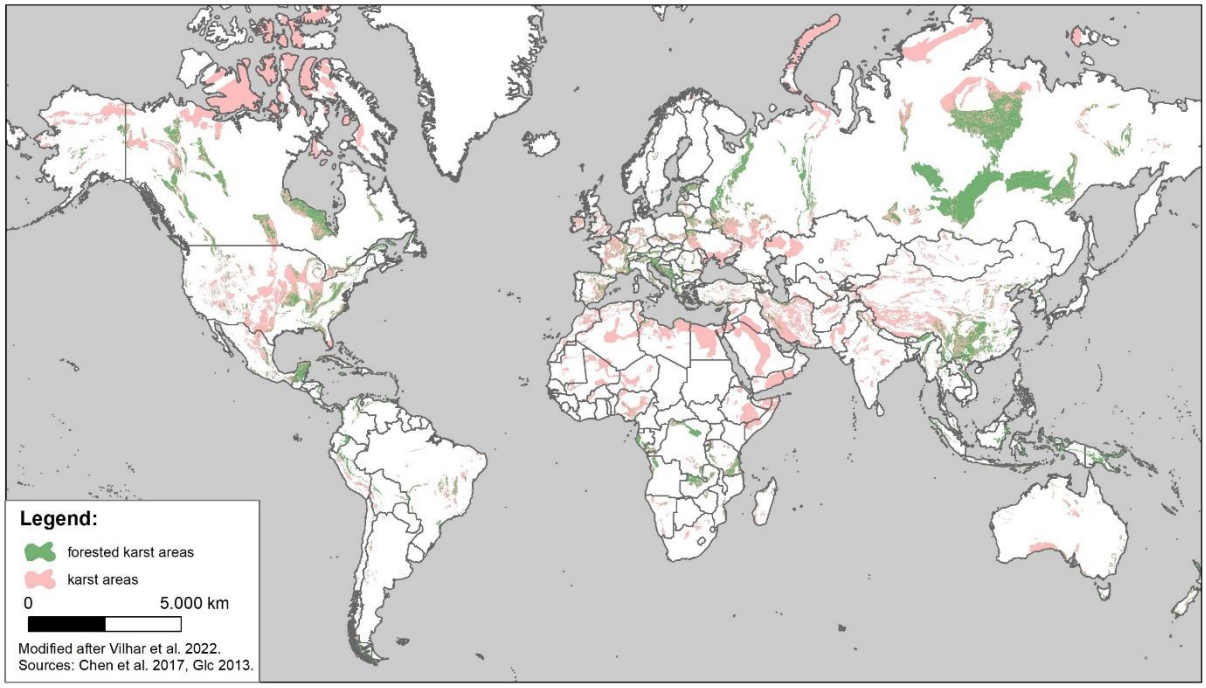


Fig. 2.1: Geographical distribution of carbonate rocks and forests on karst worldwide (Vilhar et al., 2022).

Since almost half of Slovenia's territory is characterized by karst, over 70 % of the forests are found in karst terrains, which provides numerous ecosystem services and resources. The most important is certainly water, which plays a key role in freshwater supply and the preservation of underground biodiversity. As a result of the extreme weather events or other natural disasters, the impacts on vegetation cover, the water cycle and other natural processes are expected to become more frequent and severe (IPCC 2022).

Understanding the effects of environmental change on karst aquifers — particularly in relation to precipitation, evapotranspiration and infiltration — is crucial for assessing groundwater recharge dynamics. These processes are influenced by changes in soil and vegetation cover and are crucial for the conservation of karst water resources (Vilhar *et al.* 2022). However, the complex nature of water flow in karst complicates the assessment of groundwater recharge, particularly due to the challenges presented by measurement and sampling systems in these areas.

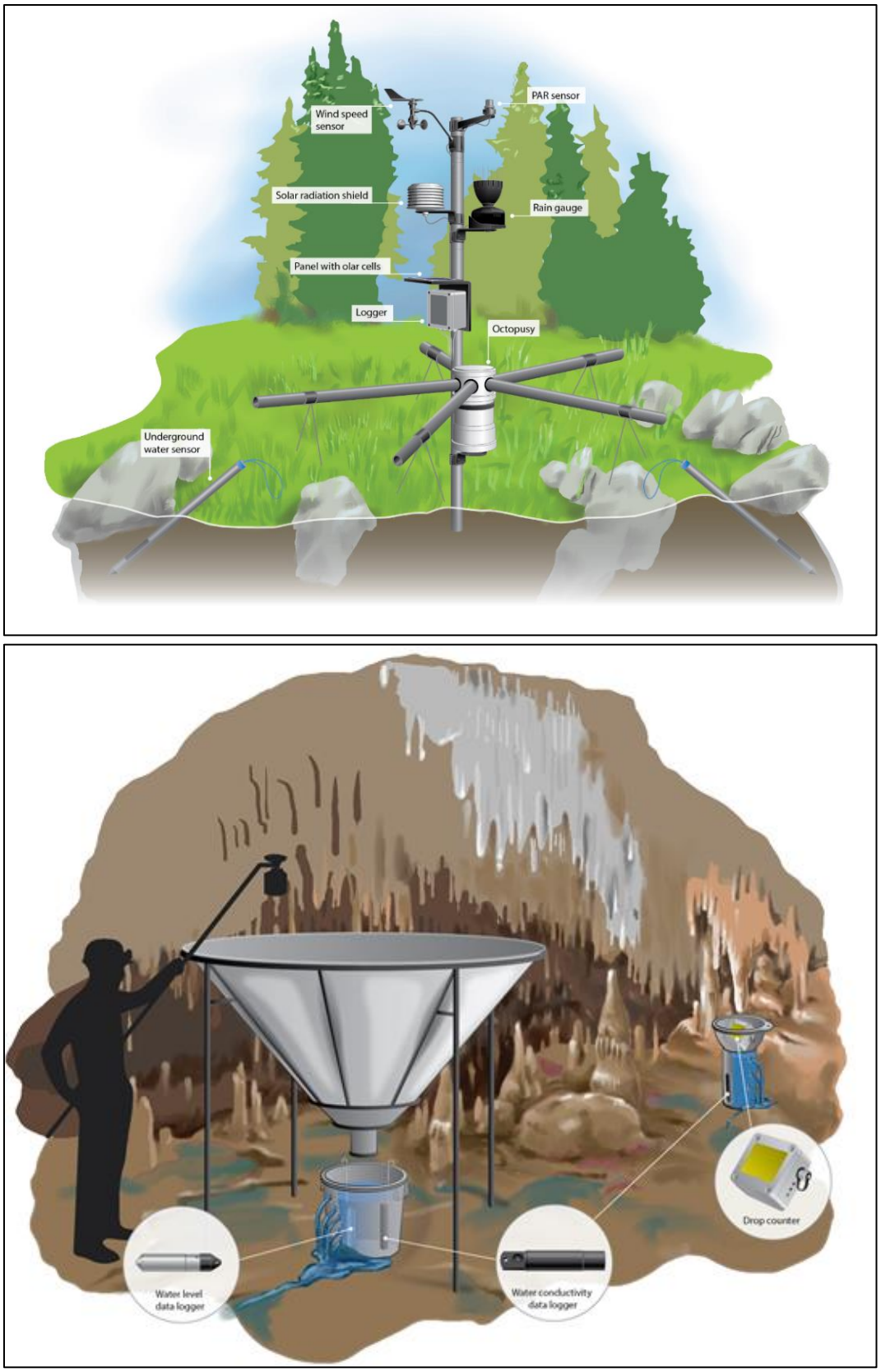


Fig. 2.2: Schematic representation of the monitoring devices at the surface monitoring sites (top). For the underground monitoring sites, the sketch shows the monitoring devices under the cave drips (bottom). The sketches are not to scale.

In a recent study, a robust monitoring network was introduced that focuses on groundwater recharge across the vertical profile of the karst aquifer, known as the karst critical zone, which includes the atmosphere, vegetation, soil, and both the unsaturated and saturated zones of the aquifer. In the Postojna-Planina karst region in SW Slovenia, we have established 21 monitoring sites both on the surface and underground. The work includes detailed inventories of geology, geomorphology, vegetation and soil properties. Using specially developed equipment, we continuously monitor various parameters such as open-field precipitation, throughfall, air and soil temperature, soil moisture as well as the flow and levels of cave seepage, sinking streams, underground rivers, springs, and water properties such as temperature and electrical conductivity (Fig. 2.2).

However, the challenges remain in achieving spatial and temporal representativeness and ensuring operational reliability. Opportunities of this study lie in improving equipment protection, refining monitoring and sampling methods, integrating sensor networks with remote sensing and up-scaling from plot to aquifer scales. Threats include environmental pressures, equipment tampering and funding stability. Nevertheless, this comprehensive approach will lead to improved understanding of ecohydrogeological processes, support geophysical modeling, and foster interdisciplinary collaboration (Ravbar *et al.* in review).

PERIGLACIAL PROCESSESS IN CAVES – CASE OF SKEDNENA JAMA

Sorted patterned ground is one of the most characteristic landforms in periglacial environments. It consists of sorted fine and coarse material that form patterns, usually circles on flat surfaces and stripes on slopes (Ballantyne 1998). The main mechanism of formation is repeated frost heave that is caused by freeze-thaw cycles. Ice formation in fine particles causes vertical movements, which move larger particles horizontally towards the coarser particles (Hallet 2013). This results in a formation of self-organised patterns. Smaller patterns in size of up to 30 cm can form due to diurnal freeze-thaw cycles by needle ice. Larger patterns exceeding 30 cm usually form by growing ice-lenses that require several days of negative temperatures to grow.

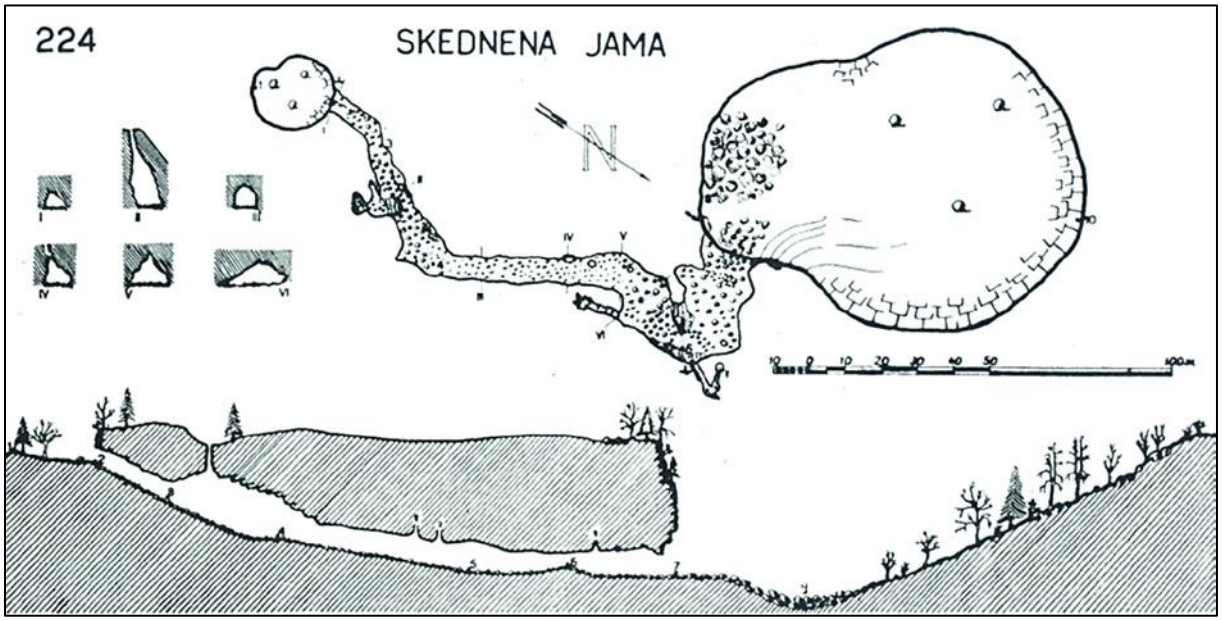


Fig. 2.3: Cross section through Skednena Jama (After Gams, 1963). Through three entrances strong air currents occur, causing long lasting seasonal ice and periglacial processes.

Although patterned ground is usually found in polar regions or mountains, it has also been reported from close to entrances in several karst caves in Slovenian Dinaric Mountains (Zupan Hajna *et al.* 2007, Mihevc & Urbančič 2019). The main conditions required for patterned ground formation are presence of silt-rich sediments together with coarser debris, repeated freezing and thawing, and sufficient soil moisture (Obu *et al.* 2018). Karst caves can contain significant amounts of silty sediments that accumulated during flood events when the cave was situated in the floodwater zone or can originate from fine rock weathering. Frost shattering of parent bedrock is a potential source for coarse debris. Freeze-thaw cycles that can last from several days to weeks occur in karst caves due to cold air trapped as a consequence of cave morphology (Fig. 2.3). Sufficient soil moisture is usually provided by drip water, that can supply moisture also during the winter (Fig. 2.4). Furthermore, there is no snow that would dampen air temperature propagations to ground and no vegetation that would stabilise the ground.

Fig. 2.4: The entrance of Skednena Jama with abundant amounts of sediment, inflow of percolated water and presence of cold air, resulting in icicles development (Photo: M. Blatnik).

The sorted circles in Skednena Jama (Fig. 2.5) were studied with LIDAR scanner for comparison between unfrozen and frozen state. The fine sediments were uplifted on average around 5 cm with maximum reaching up to 15 cm (Mihevc & Urbančič 2019). Another sorted circles were monitored using time-lapse photogrammetry in Barka Cave on Javorniki-Snežnik Plateau (Obu *et al.* 2023). Three to four longer freeze-thaw cycles and several shorter occurred there during the last winters. Similar vertical movements of around 10 cm were recorded on the fine sediment between frozen and unfrozen state. Horizontal movements of up to 1.5 cm were recorded during one freeze-thaw cycle, likely spanning over few centimetres during one winter (Fig. 2.6).

Fig. 2.5: Sorted circles at the entrance of Skednena Jama (Photo: M. Blatnik).

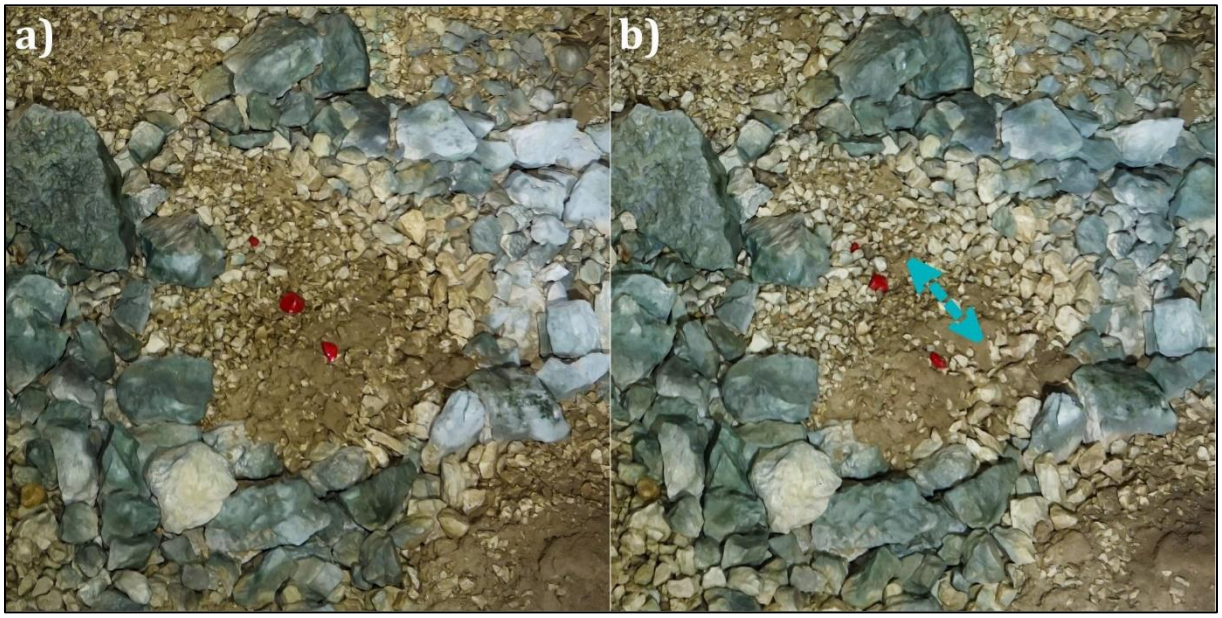


Fig. 2.6: Red stones show total horizontal movements that occurred during the winter 2021/2022 in the Barka Cave.

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Whole-day field trip (C):

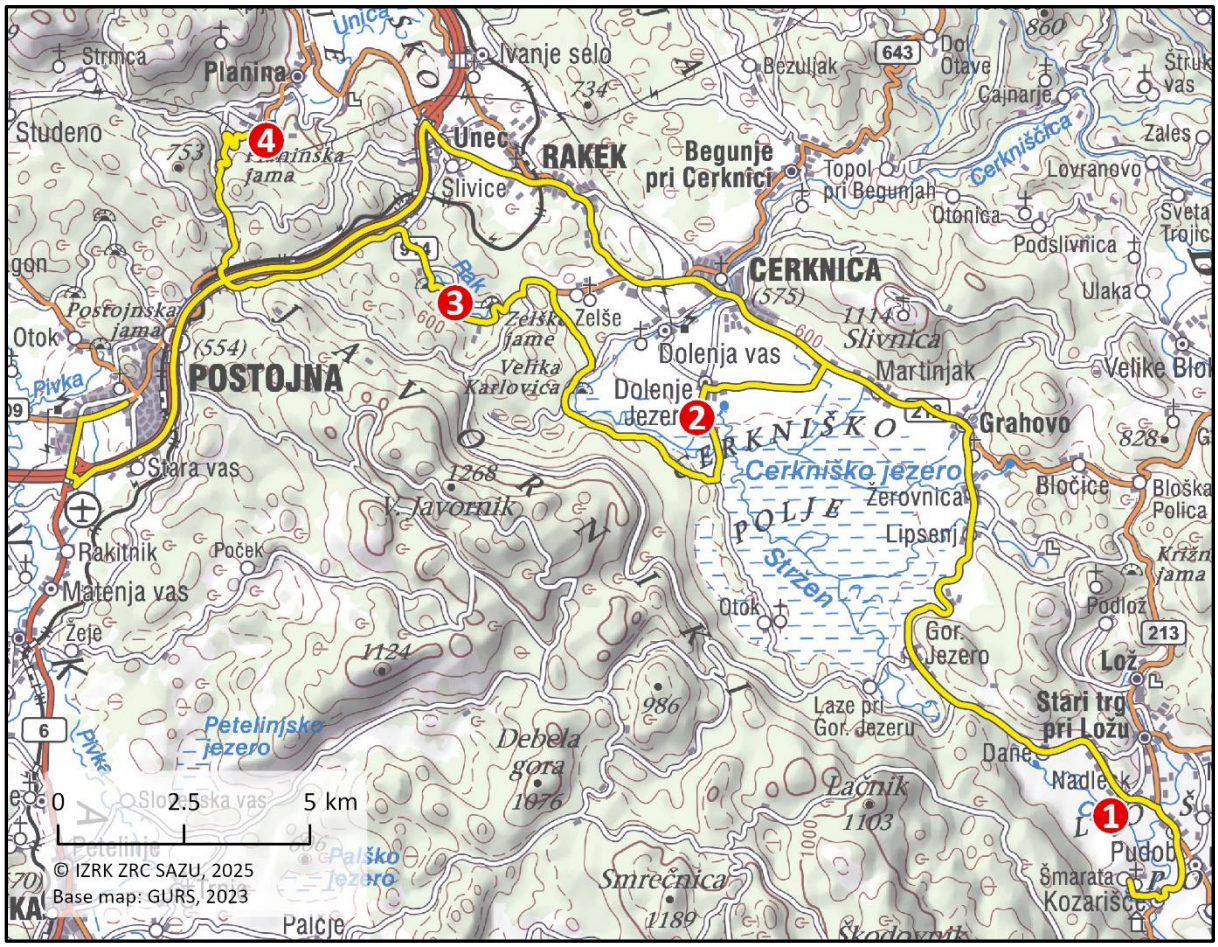
HYDROLOGY AND EXTREME FLOODS IN THE NOTRANJSKA POLJES

Thursday, 19th June 2025, 8:30–18:00

Cyril Mayaud, Matej Blatnik, Franci Gabrovšek, Blaž Kogovšek, Nataša Ravbar, Metka Petrič

Stops:

1 – Loško polje – The Snežnik castle and the ponor of the Golobina Cave
2 – Cerkniško polje – Outflow zone of Rešeta and view point of Cvinger
3 – Rakov Škocjan – Hydrology of the Rakov Škocjan karst valley
4 – Planinsko polje – Overview of the polje hydrology. Planinska jama



Hidrologija in ekstremne poplave na kraških poljih Notranjske

Celodnevno terensko delo (C); četrtek, 19. junij 2025;

Za kraško zaledje izvirov Ljubljanice je značilno menjavanje kraških polj in kraških planot. Niz kraških polj s ponikalnicami ima dinarsko smer (SZ–JV), del vode pa prispeva Pivška kotlina na JZ delu porečju Ljubljanice. V prvem delu ekskurzije predstavljamo Loško polje, Cerkniško polje ter Rakov Škocjan z najbolj značilnimi kraškimi pojavi (kraški izviri, požiralniki, jame, vodotoki). Drugi del ekskurzije je posvečen izvirom Unice in Planinskemu polju.

GENERAL INTRODUCTION: HYDROGEOLOGY OF THE LJUBLJANICA RIVER RECHARGE AREA

The central part of the Slovenian Dinaric Karst drains to the springs of the Ljubljanica River, located on the southern edge of the Ljubljana Basin (Fig. 3.1). Although the area is about 26 km of straight-line distance close to the Adriatic Sea, intense tectonic activity has triggered drainage into the Sava-Danube river basin, which flows to the Black Sea. The estimated total size of the Ljubljanica recharge area is almost 1800 km^2, of which about 1100 km^2 are karstified. The karst catchment area was delineated during an extensive tracing campaign in the 1970s (Gospodarič & Habič 1976).

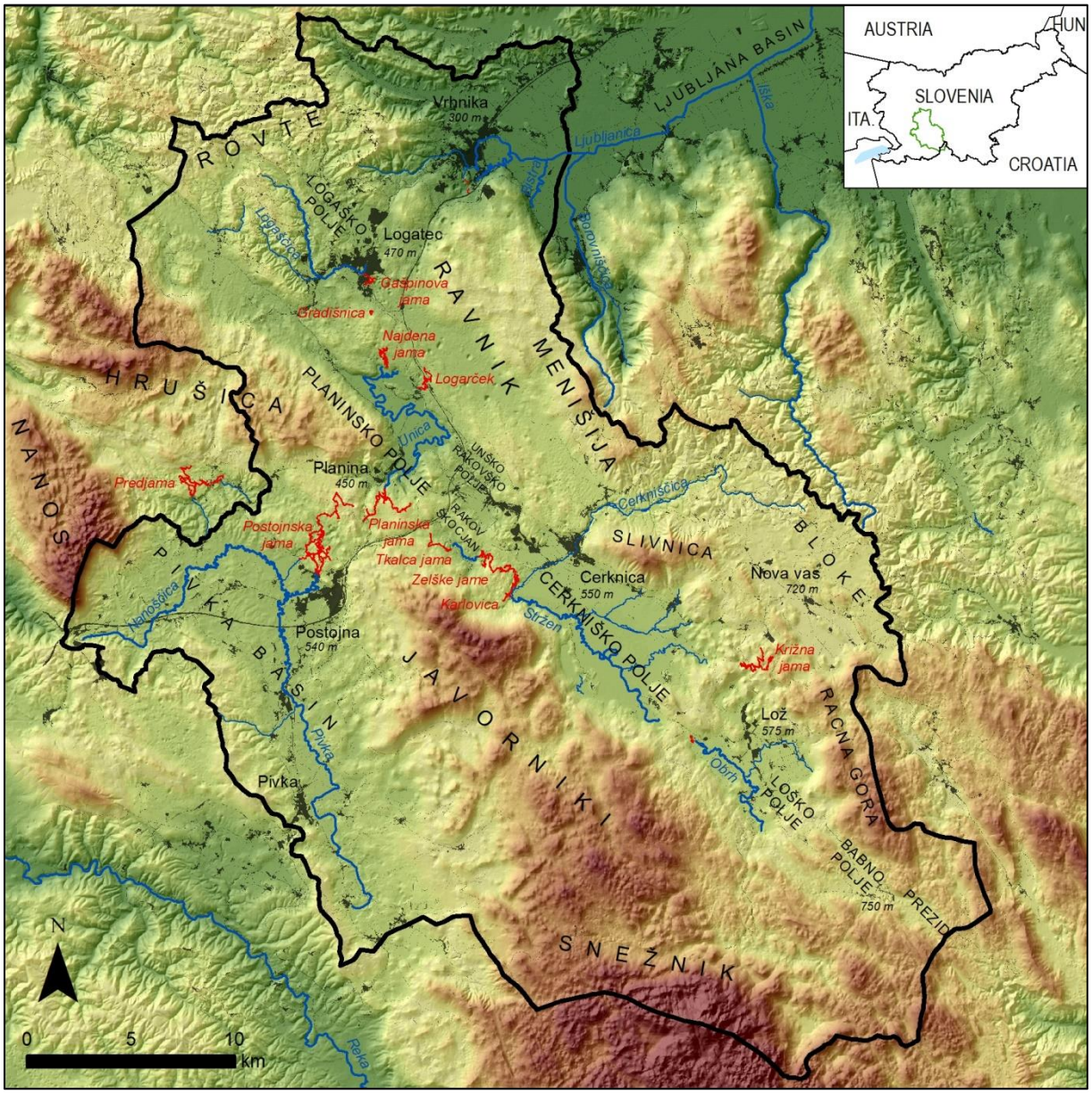


Fig. 3.1: Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.

The karst rocks are mostly of Mesozoic age. They are generally micritic, locally oolitic limestones and predominantly late-diagenetic dolomites. They formed on the Dinaric platform under conditions of continuous sedimentation that allowed high rock purity, generally with less than 5%,

locally even only 0.1%, insoluble residues. The total thickness of the carbonate sequence is almost 7 km.

Structurally, the entire Ljubljanica catchment belongs to the Adriatic Plate. The area consists of several nappes that were overthrust during the peak of the Alpine orogeny in the Oligocene in a NE to SW direction (Placer 2008; Placer *et al.* 2010). A later change in the direction of plate movement led to the formation of the Idrija Fault Zone, a dextral strike-slip fault that crosses the area in the direction of NW-SE (Fig. 3.2) (Vrabec 1994). The Idrija Fault Zone largely determines the direction of regional flow (Fig. 3.2). In general, the steepest hydraulic gradient is oriented northwards, from the Notranjska region towards the Ljubljana Basin, which represents a regional base level. However, the fault zone acts as a barrier to groundwater flow and forces the water to surface in the poljes. At the same time, it diverts the flow in the Dinaric direction (SE-NW) (Šušteršič 2006).

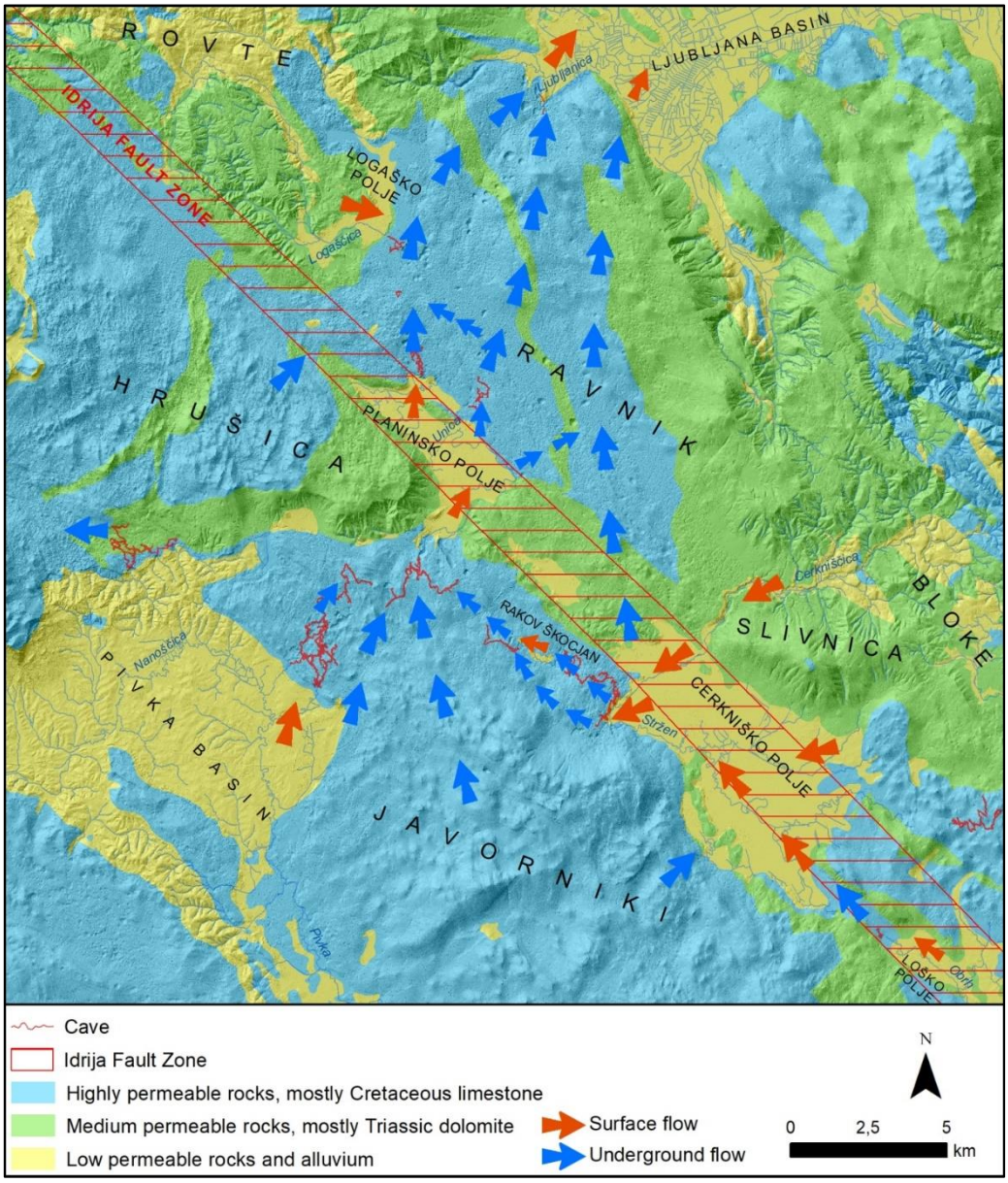


Fig. 3.2: Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).

Several poljes have developed along the Idrija Fault Zone (Gams 1965a, 1978; Šušteršič 1996). These large flat-bottomed depressions are regularly flooded and are often the only areas where water appears at the surface. The formation of poljes is preconditioned by tectonics, in this case by the structures within the Idrija strike slip fault (e.g. pull-apart zones), but the forming mechanism is the corrosional planation at the groundwater level.

In general, the water follows the SE-NW direction with surface flow on the poljes and groundwater flow in-between (Fig. 3.3). Additional water enters the flow system at numerous springs draining the areas of the Snežnik and Javorniki mountains in the south of the Idrija Fault Zone. Several sinking rivers draining dolomite or flysch areas also contribute to this system (Gams 2004). Along the way toward the Ljubljanica springs, the altitude of the poljes drops from about 750 m to 450 m (Fig. 3.3). The streams that flow through them have different names: Trbuhovica, Loški Obrh, Stržen, Rak, Pivka and Unica. Apart from a relatively small amount of water flowing directly from Cerkniško Polje to the springs of the Ljubljanica River, most of the water comes to the surface along the southern edge of Planinsko Polje. Along its eastern and northern edges, the water sinks back underground and flows northwards to several large and many small springs aligned along the southern edge of the Ljubljana Basin, which is connected to the gradual tectonic subsidence of the area (Krivic *et al.* 1976; Gams 2004). The average annual discharge of the Ljubljanica springs is 38.6 m^3/s. An additional amount of water drains from the low- to medium-permeable Rovte plateau and contributes to the Ljubjanica springs by sinking into the ponors of Logaško Polje (Mihevc *et al.* 2010).

There are almost 1600 known caves located in the recharge area of the Ljubljanica River (Cave register 2019). Most of them are accessible fragments of a fossil underground drainage system (Habič 1973; Gospodarič 1981; Šušteršič 1999, 2002). The average cave length is 48 m and the depth 18 m. However, the largest cave systems are water-active and sum a total of about 80 km of epiphreatic channels that have been explored and documented (Fig. 3.3).

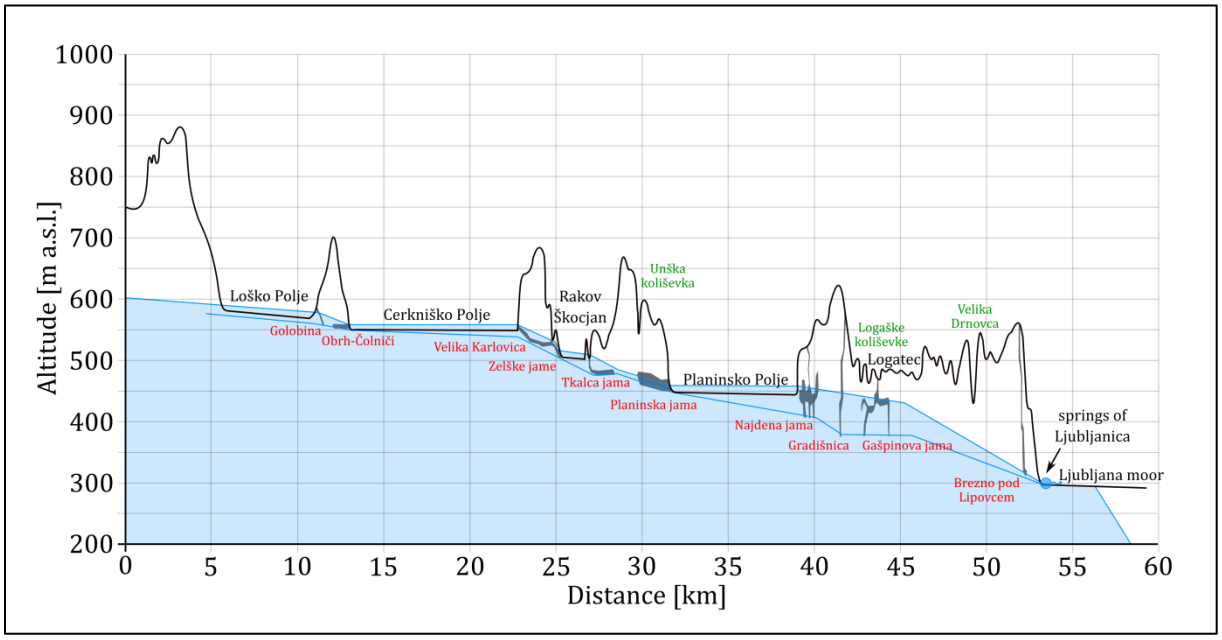


Fig. 3.3: Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in green.

LOŠKO POLJE

Loško Polje is located on the southeast of the Notranjska region (Fig. 3.4) and is a typical example of overflow polje. The polje is bordered by the Javorniki massif on the west, the Snežnik massif and Babno Polje on the south, Cerkniško Polje on the northwest, the Loški Potok and Račna Gora massifs on the east, and by the Bloke plateau on the north (Fig. 3.4). The polje surface is about 6 km long and about 4 km large. Its floor is rather flat with altitudes comprised between 570 and 580 m , while the surrounding plateaus culminates between 800 and 1.000 m Its flanks are surrounded by dense forests that have been used for logging since centuries. Loško Polje is a densely populated polje with more than 2,900 inhabitants living in 16 small settlements widespread on its whole surface. The villages of Stari Trg pri Ložu, Lož, Pudob, Kozarišče and Markovec are the most populated. In a geological point of view (Fig. 3.4), the polje floor is constituted of quaternary sediments while its surrounding hills are alternating between limestone and dolomitic rocks respectively of Cretaceous and Triassic ages (Krivic *et al.* 1976). The polje is aligned along the major Idrija fault zone that crosses Slovenia in a typical Dinaric southeast-northeast orientation (Vrabec 1994).

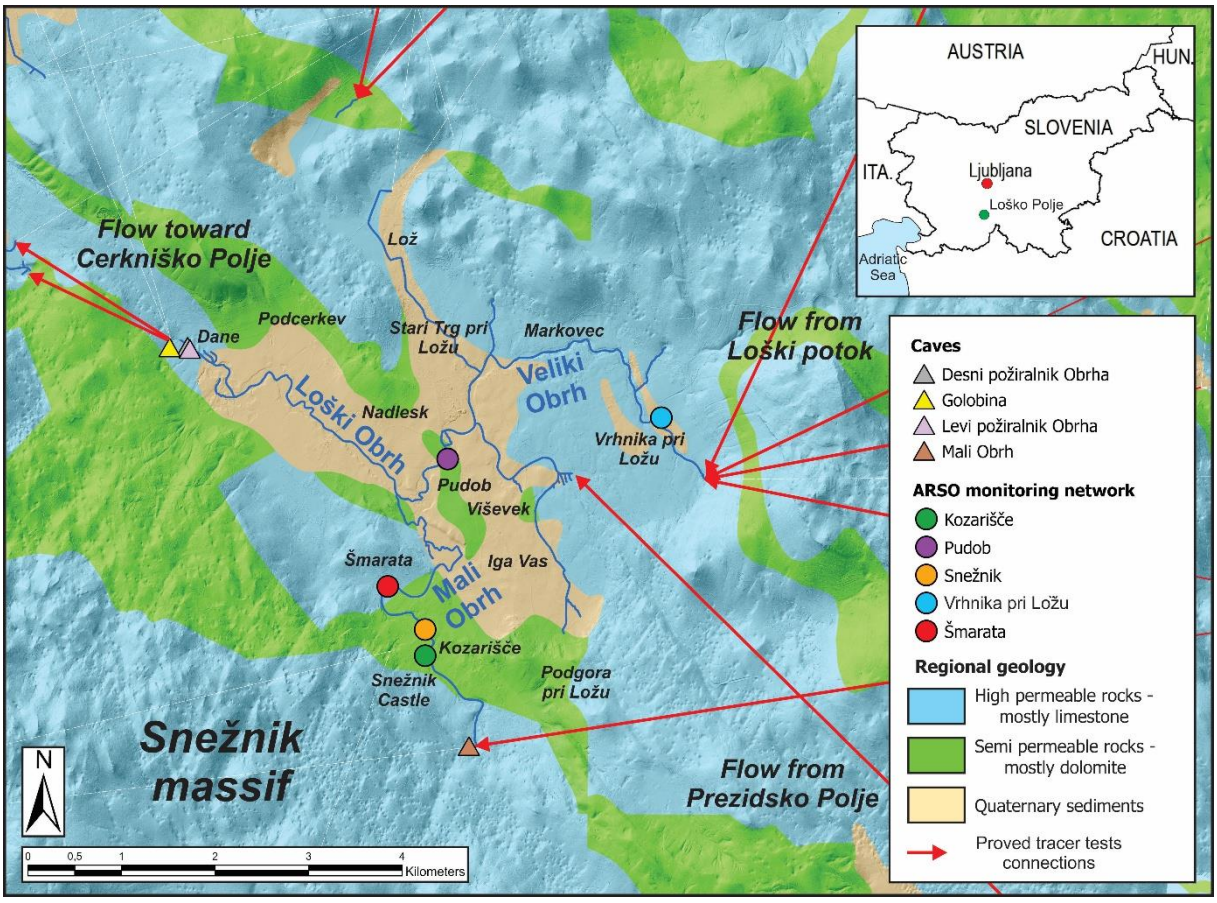


Fig. 3.4: Simplified hydrogeological map of Loško Polje. Current and past monitoring stations managed by the Slovenian Environment Agency ARSO (ARSO 2025) are indicated.

Loško Polje is recharged by several karst springs. Among them, the Veliki Obrh and Mali Obrh springs are the two most important. The Veliki Obrh spring is located on the polje eastern border upstream from the village of Vrhnika pri Ložu, and drains mostly water from the region of Loški Potok (Šerko 1946; Gams 1965b; Fajfar 2006; Janez 2011). The Mali Obrh spring is located upstream from

the village of Kozarišče (Fig. 3.5a) and the Snežnik Castle on the polje southern border. This spring receives the vast majority of its water from the Snežnik plateau but also drains water from the Loški Potok region (Šerko 1946).

Fig. 3.5: Field impressions of Loško Polje. (a) The Kozarišče Bridge near the Snežnik Castle (Photo: C. Mayaud). (b) The Mali Obrh River near its spring (Photo: C. Mayaud). (c) The Loški Obrh River sinking a few meters before the cave Levi požiralnik Obrha (Photo: C. Mayaud). (d) The artificial entrance of the Golobina Cave (Photo: C. Mayaud). (e) Excavating work at the entrance of the Golobina Cave in the 1930s (Source: http://stareslike.cerknica.org; picture from the personal collection of Janez Škrbec; author unknown). (f) Flood of 1907 near the village of Pudob (Source: http://stareslike.cerknica.org; picture from the collection of Župnišče Stari Trg; author Dragutin Žagar).

Several other small springs are located on the polje eastern and southern sides, and drain respectively water from Prezidsko Polje located further east in Croatia and from the Snežnik massif (Gams 1965b). The Mali Obrh and Veliki Obrh springs form respectively the Mali Obrh and Veliki Obrh Rivers (Fig. 3.5b), that flow across the polje for about 5.5 km and 6.5 km before to merge as Loški Obrh River after the village of Pudob. Under normal water situation, the Loški Obrh flows for about 3.4 km toward the northwest and disappears in the caves Desni polžiralni Obrha and Levi polžiralnik Obrha that are located on its streambed (Fig. 3.4 & Fig. 3.5c). Under higher water situations and floods, these two ponors have not the capacity to swallow all the water. The Loški Obrh continues then to flow for about 190 m before to sink into the large entrance of the Golobina Cave (Fig. 3.5d). Then, the water flows in the underground cave network before to emerge at the Cemun and Obrh springs that are located at a respective airline distance of 1.6 km and 2 km on the southeastern side Cerkniško Polje (Šerko 1946; Gams 1965b).

In an attempt to improve the outflow capacity of the polje and reduce the impact of high floods, the last 350 m of the Loški Obrh River has been artificially widened and channelized in 1906 (Fig. 3.5e). At this occasion, the large artificial entrance of the Golobina Cave has been dug out at the end of the channel. As the new entrance of the Golobina Cave is about 8 meters below its natural entrance, this helped reducing the duration of the floods in the polje, improving considerably the life of its inhabitants (Fig. 3.5f).

Daily water level and discharge of the Veliki Obrh and Mali Obrh Rivers have been recorded at irregular intervals by the Slovenian Environment Agency ARSO (ARSO 2025). For discharge, the Mali Obrh River has been monitored at the stations Kozarišče (between 1961 and 1969), Šmarata (between 1973 and 1988) and Snežnik (between 1954 and 1975). The discharge of the Veliki Obrh River has been recorded for longer periods at the stations of Pudob (between 1952 and 1989) and Vrhnika pri Ložu (between 1961 and 2022). Conversely, the water level dataset is much longer but still recorded at an irregular interval for the stations of Pudob (between 1931 and 1989) and Snežnik (between 1936 and 1975). The station of Vrhnika pri Ložu registered both water level and discharge during the same time interval, while the stations of Kozarišče and Šmarata recorded the water level for a year longer (respectively between 1961-1969 and 1973-1989). Finally, the Karst Research Institute monitors the large water level fluctuations happening in the Cave Mali Obrh since Autumn 2019. The data collected gives a very valuable information about the hydrological behaviour of the Javorniki and Snežnik karst massifs under low water situation.

Because of its hydrogeological configuration with one single outflow zone, Loško Polje is subject to large floods events. The floods negatively impact the life of the polje inhabitants and the nearby villages may remain inundated for weeks. When looking at the hydrological dataset collected by the Slovenian Environment Agency ARSO (ARSO 2025), it can be seen that the Veliki Obrh River might reach a maximum discharge above 32.9 m^3/s at Vrhnika pri Ložu and 39.4 m^3/s at Pudob, while the maximum discharge of the Mali Obrh River is of 22.5 m^3/s at the Snežnik station, of 22.6 m^3/s at the Kozarišče station, and of 19.6 m^3/s at the Šmarata station. This led to a maximum total inflow of about 60 m^3/s entering the polje during the largest floods events. The same dataset shows that high floods occurred in the polje in 1965, 1966 and two times in 1979. For both 1979 floods, the water level surpassed the elevation of 572 m for about 12 days.

Other major flood events comprise the floods of 1851, 1907, 1933, 1934, 1939, 1949, 1954 and 2000 (Černivec *et al.* 2008). Among them, the flood of 1851 reached a record with a maximum elevation indicated by a flood water mark near the entrance door of the Snežnik Castle. More recently, the floods of January and November 2014 were also very large and inundated the lowest

parts of the villages of Pudob, Kozariče, Markovec and Šmarata for several days. Their respective maximum elevations are also shown on the outside wall of the Snežnik Castle.

For the last flood that occurred in Loško Polje in March 2025, a maximum water level of 574 m could be estimated by measuring the elevation of the flood-line marker near the artificial entrance of the Golobina Cave with the mobile application FloodWatch (Fig. 3.6a & Fig. 3.6b). The flood situation in the polje the 20.03.2025 could be seen via satellite image (Fig. 3.6c), while the maximum flood extension based on the water level measured with FloodWatch could be computed (Fig. 3.6d).

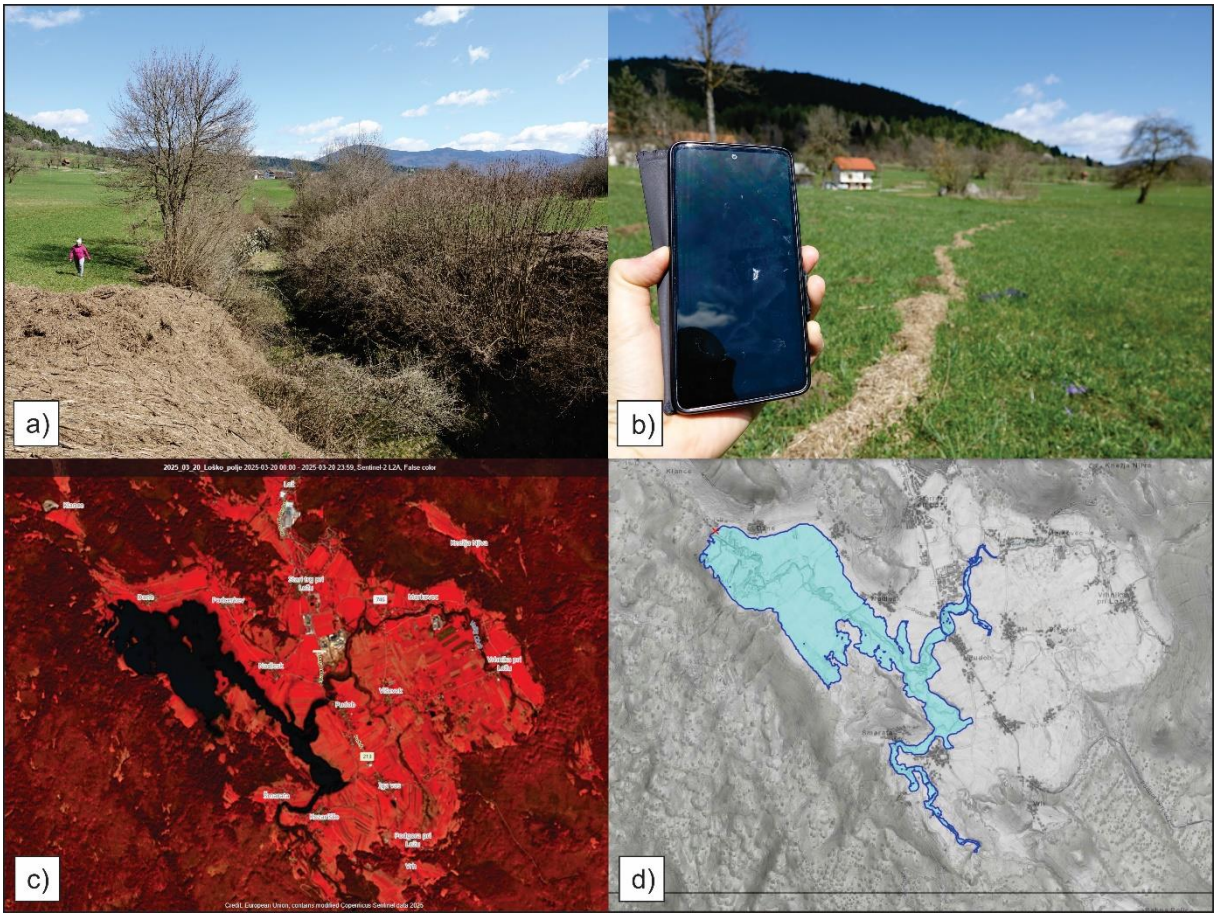


Fig. 3.6: The flood of March 2025. (a) Accumulation of flood material above the artificial entrance of the Golobina (Photo: C. Mayaud). (b) Flood line marker showing the flood maximum near the entrance of the Golobina and the hamlet of Škrilje (Photo: C. Mayaud). (c) Satellite image on false colours (bands B8, B4 and B3) taken the 20.03.2025 of the flooded situation in Loško polje (Source: Copernicus Sentinel data, 2025). (d) Flooded situation on Loško Polje for the flood of March 2025 drawn with the help of the mobile application FloodWatch (Photo: C. Mayaud).

CERKNIŠKO POLJE

Cerkniško Polje is the largest karst polje in Slovenia (Gams 1978, 2004). It is often called Cerkniško Jezero (Lake of Cerknica) because of its regular floods (Fig. 3.7a). When full, the intermittent lake covers up to 26 km^2 out of 38 km^2 of the polje's total area. The bottom of the lake is at an average altitude of 550 m. Its intermittency has attracted many scholars since 1600 including the polihistorian Valvasor, who published his famous study of the Cerkniško Jezero in 1689 (Shaw & Čuk 2015). The main part of the polje is underlained by Upper Triassic dolomite at its N, E and SE borders. The areas to the W and NW, on the other hand, are mainly underlain by Cretaceous limestone (Fig. 3.2).

Fig. 3.7: (a) Flooded Cerkniško Jezero (Spring 2013) (Photo: C. Mayaud). (b) Ponors of Rešeta during low flow conditions (Summer 2017) (Photo: M. Blatnik).

The polje is regularly flooded for several months (Fig. 3.8), mostly in autumn, winter and spring (Kovačič & Ravbar 2010). On average, the water is above the level of 550.3 m for about 10.2

days per year, which corresponds to a flooded area of 21.84 km^2 (Ravbar *et al.* 2021). The main inflows into the polje come from a series of karst springs called Žerovniščica, Šteberščica and Stržen, located on its eastern and southern borders. The springs on the SW side (e.g. Suhadolca, Vranja jama) are recharged by the Javorniki massif and add a lot of water during floods. In addition, an important allogenic component arrives from the Cerkniščica River, which drains a dolomitic area of about 44 km^2 in the east (Gams 2004). Finally, several estavelles (e.g., Vodonos) also contribute to the inflow into the polje.

In addition to the estavelles, several ponor zones located in the inner part of the polje drain a certain amount of water directly (Fig. 3.7b) to the springs of Ljubljanica (Krivic *et al.* 1976), while the main ponors are aligned along the W side of the polje, with the caves Velika and Mala Karlovica being the most prominent. These caves extend for over 8.5 km between Cerkniško Polje and the Rakov Škocjan karst valley. So far, only a small section between Velika Karlovica and Zelške Jame (located in Rakov Škocjan) is unexplored as an important collapse zone is located there. Recent studies have shown that at low to medium water levels (Gabrovšek *et al.* 2010; Ravbar *et al.* 2012, Kogovšek 2022), a large part of the water sinking into the ponor of Mala Karlovica reaches the Kotliči springs in the middle of Rakov Škocjan and a smaller part reaches Zelške Jame, which would be the most logical direction.

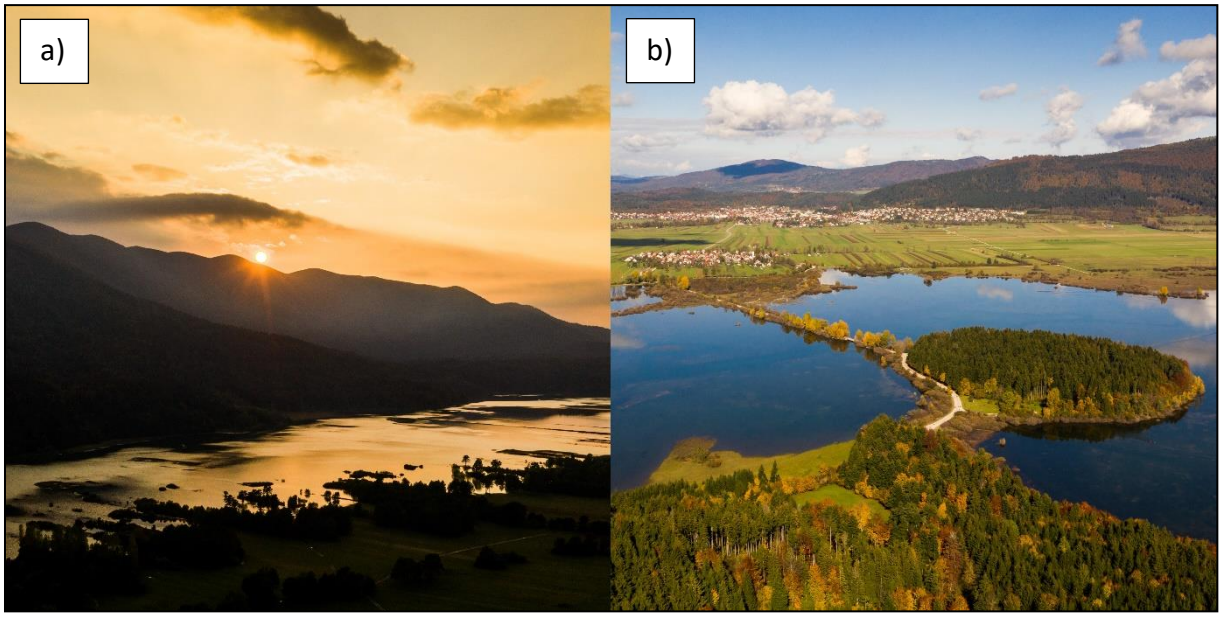


Fig. 3.8: Cerkniško Jezero. a) Lake and Javorniki Mountains at sunset. b) View toward the village of Dolenje jezero (Photos: M. Blatnik; RI-SI-EPOS).

In the last centuries, several plans were made to change the hydrological behaviour of the polje, but none was completed. In the 1960s, a plan to transform Cerkniško Jezero into a permanent lake was initiated. The entrances to the caves Velika and Mala Karlovica were closed with concrete walls and a 30 m tunnel was built to connect Karlovica to the surface. However, a minor impact on water retention during dry periods was found assessed (Shaw & Čuk 2015).

The analysis of long-term meteorological data on the Cerkniško polje and its recharge area showed that the annual amount of precipitation in the last 70 years didn't change significantly, but its distribution over the year is more uneven – there is an increase in autumns (which were already abundant with rain before), whereas other seasons of the year have less rain (Blatnik *et al.* 2024, 2025a). The general amount of snow is lower, which results in lower snow retention. Additionally,

the mean annual temperature is increasing, which means that evapotranspiration is also increasing. The result is lower effective precipitation (Fig. 3.9) with more uneven seasonal distribution (Fig. 3.10), which altogether with past human interventions modify significantly the hydrological dynamics on surface flows and lake on the Cerkniško Polje.

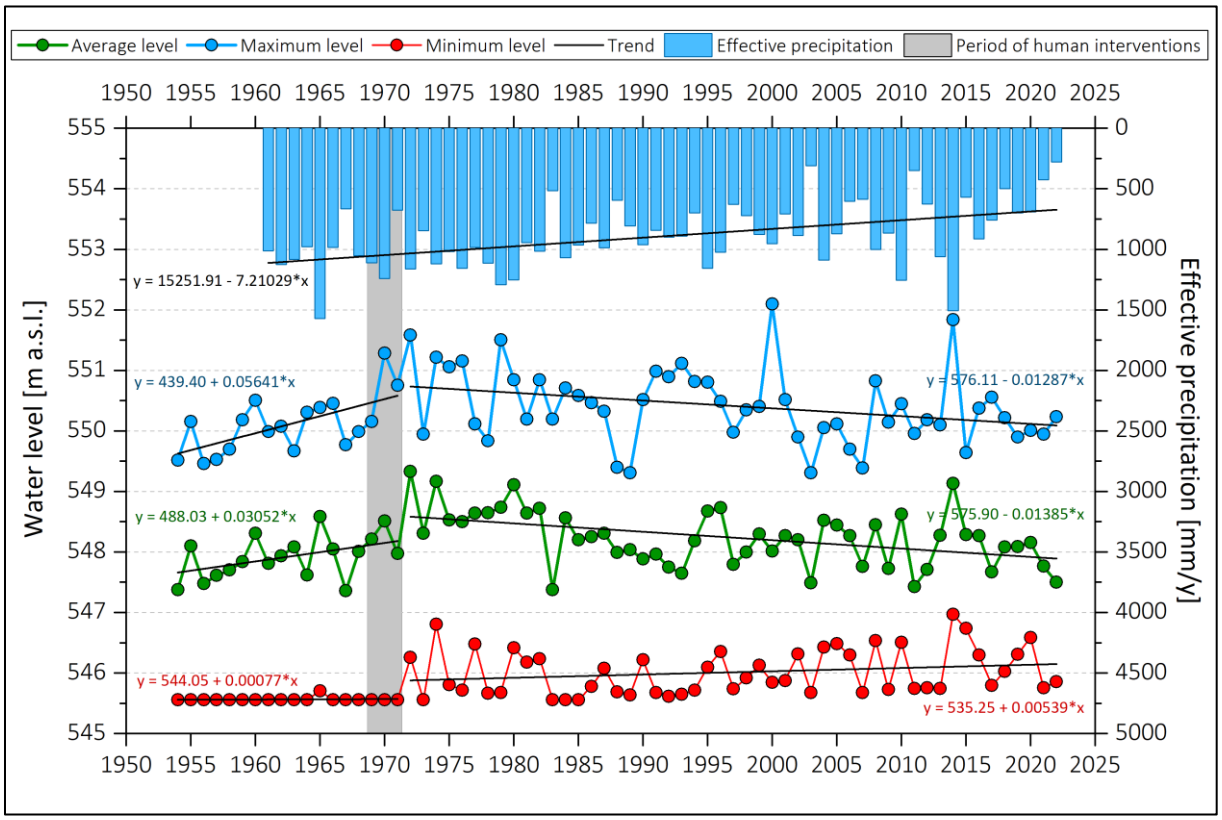


Fig. 3.9: Average, minimum and maximum water levels for individual years and calculated trends for the Dolenje Jezero hydrological station, 1954–2022. The grey belt indicates a period with the most intensive human activities for extended flooding periods.

Long term hydrological measurements on the Cerkniško polje (implemented at the hydrological station Dolenje Jezero) show that before 1970 the general water level was low (human interventions were focused to the more efficient drainage), whereas in the 1970s the water level was significantly higher due to the permanent lake generation experiment). After abandoning the experiment, some artificial barriers have been removed so the water level was gradually dropping. From 1980 on, the pattern in the water level dynamics was mostly following the meteorological dynamics (Blatnik *et al.* 2024, 2025b; Fig. 3.9). The changes in the seasonal water level dynamics is mostly represented by the increase or stagnation of the water level in autumns and winter, whereas during springs and summers significant drop in the water level is observed (Fig. 3.10). This unfortunately results in the higher frequency of hydrological extremes, which are represented in more frequent very high floods and also more frequent and longer droughts. These changes further affect the biodiversity and habitat types distribution and composition, where some changes were already noted (Blatnik *et al.* 2024, 2025b).

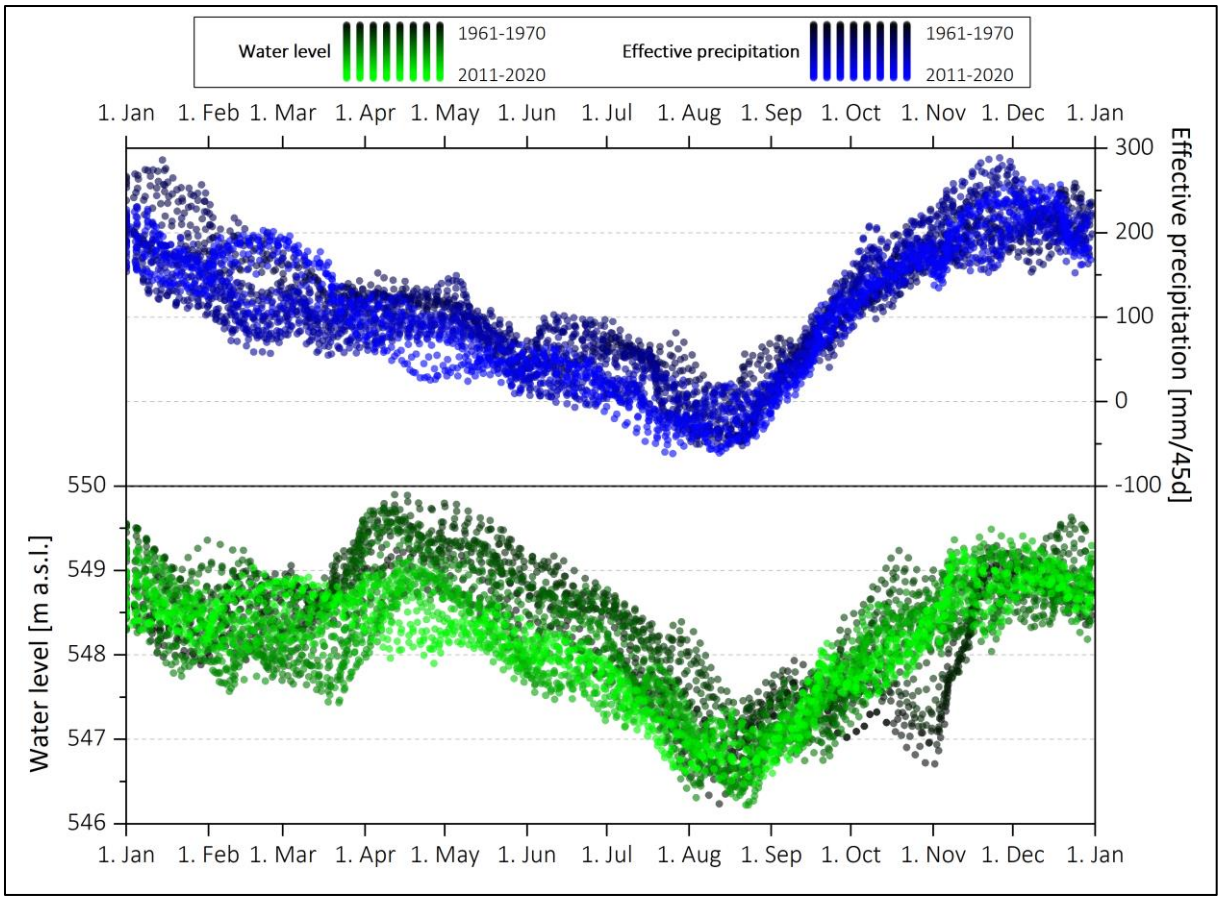


Fig. 3.10: Distribution of the effective precipitation (blue dots) and water level (green dots) over the year according to moving averages for 10-year periods between 1961 and 2022.

RAKOV ŠKOCJAN KARST VALLEY

After sinking in in the main ponors of Cerkniško Polje, the water surfaces in an about 1.5 km long and 200 m wide karst valley called Rakov Škocjan (Fig. 3.11). On the upstream side (SE) the water emerges as the Rak River from the cave Zelške Jame. Zelške Jame is about 5 km long and ends in the large collapse doline of Velika Šujca, where the water arrives from Cerkniško Polje via the Karlovica cave system. The entrance area of Zelške Jame is a fragmented system of channels and collapse dolines. The most prominent feature is Mali Naravni Most (Small Natural Bridge; Fig. 3.12a), where an impressive narrow arch, which was part of the former cave ceiling, crosses the collapse doline (Gams 2004).

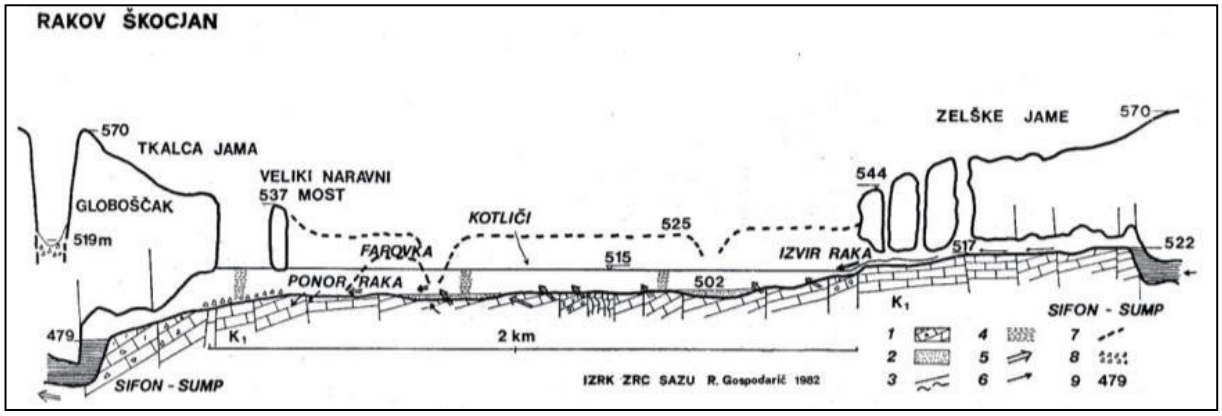


Fig. 3.11: Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring: 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.

Downstream, the valley widens and several springs (Fig. 3.12b) located along the SW side of the valley (e.g. Kotliči, Prunkovec) form perennial or intermittent tributaries of the Rak River. The valley narrows an impressive natural bridge called Veliki Naravni Most (Big Natural Bridge; Fig. 3.13b). The height of the bridge is comprised 9.5 and 17 m, its width is between 15 and 23 m and the length is of 56 m. The rocky arch is made of thick-bedded and anticline-folded Lower Cretaceous limestone.

Fig. 3.12: Rakov Škocjan karst valley. a) The arch of Mali Naravni Most. b) Kotliči spring at the beginning of a hydrological event (Photos: M. Blatnik).

After Veliki Naravni Most, the channel opens into a 150 m long canyon that ends at the entrance to Tkalca Jama, an almost 3 km long explored cave that drains the water towards Planinsko Polje. The connections of the Rak with the water from Cerkniško Polje and with the Unica Springs at Planinsko Polje have been proven by several tracer campaigns under different hydrological conditions (Gabrovšek *et al.* 2010; Ravbar *et al.* 2012). An important flow constriction is present before the first siphon of Tkalca Jama and allows flooding to occur regularly in the Rakov Škocjan karst valley. The floods can reach a height of 19 m above the cave entrance (located at 496 m; Fig. 3.13c), and large parts of the Rakov Škocjan karst valley are frequently inundated (Drole 2015; Fig 3.13a). Before World War 1, Rakov Škocjan was a private park owned by the Windischgrätz family,

while between the First and Second World Wars the Italians used it as a military site. Since 1949 Rakov Škocjan has been is a Landscape Park open to the public.

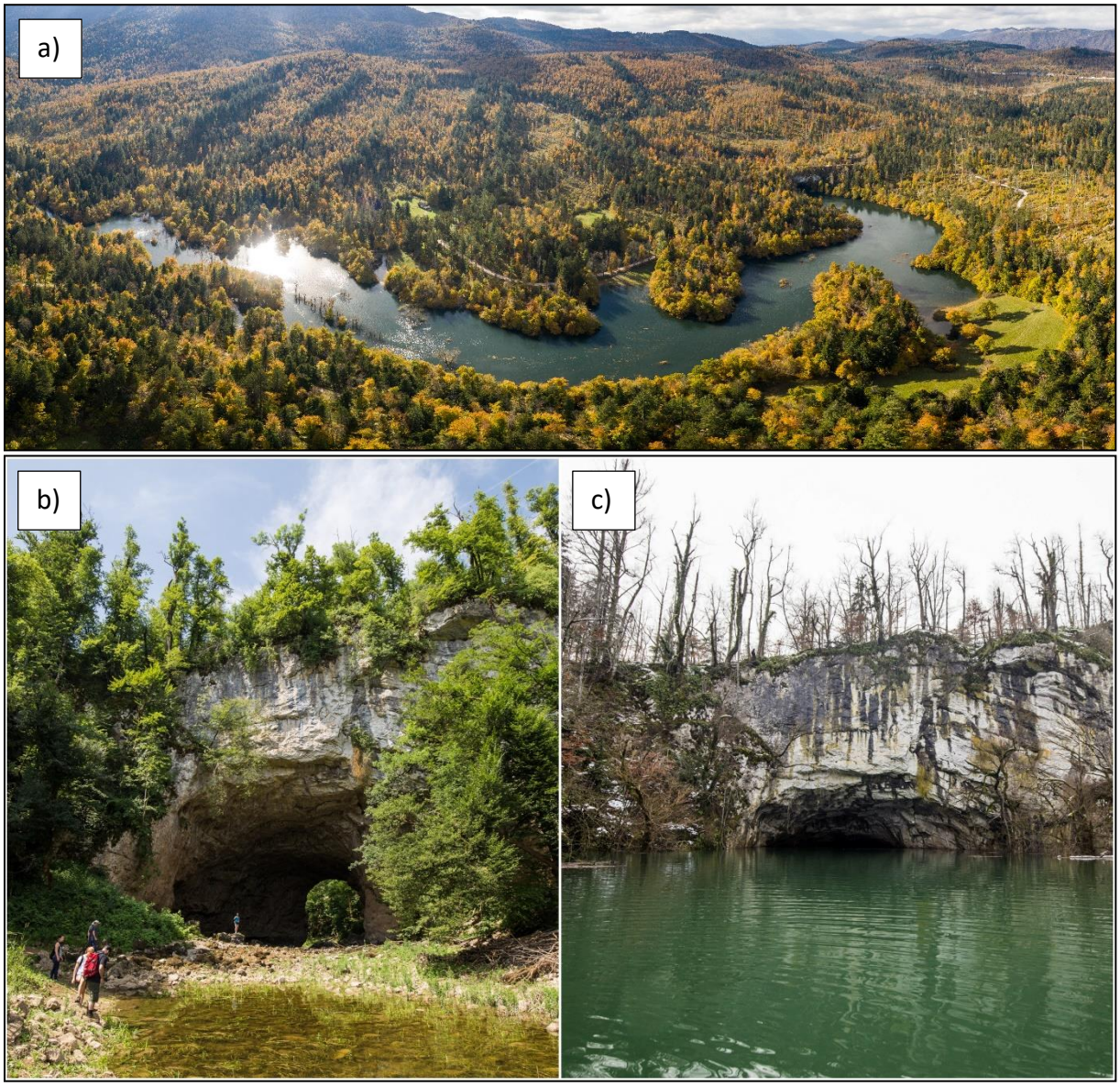


Fig. 3.13: a) Flooded Rakov Škocjan Karst Valley in October 2020, b) Veliki Naravni Most (Big Natural Bridge) during dry period in summer; and c) during high water event in winter (Photos: M. Blatnik; RI-SI-LifeWatch).

PLANINSKO POLJE

Planinsko Polje is a typical example of overflow structural polje (Gams 1978; Šušteršič 1996). The polje largest springs are located on its southern side and recharge the Unica River that sinks in two major outflow zones located along the polje eastern and northern borders (Savnik 1960) (Fig. 3.14). The polje surface is slightly undulating and about 10 km^2 large, with a bottom elevation mostly comprised between 444.5 m and 450 m (Blatnik *et al.* 2017). Apart from the wetlands close to the Unica, the polje is used for field crops and grass. Three settlements are located on the elevated slopes around Planinsko Polje, which is surrounded by forested karst plains at elevations between 520 m and 600 m. and by mountains reaching up to 1.000 m after.

Planinsko Polje has formed along the Idrija Fault Zone. Its southern and western borders mostly consist of Upper Triassic Main Dolomite, while its two main springs are located within a band of cretaceous limestone in the south. The average thickness of the alluvium cover is about 4 m (Breznik 1961; Ravnik 1976). The polje bedrock base is dominantly Upper Triassic Main Dolomite, whereas its eastern and northern sides include most of the ponors and are composed of highly karstified Cretaceous limestone (Čar 1982).

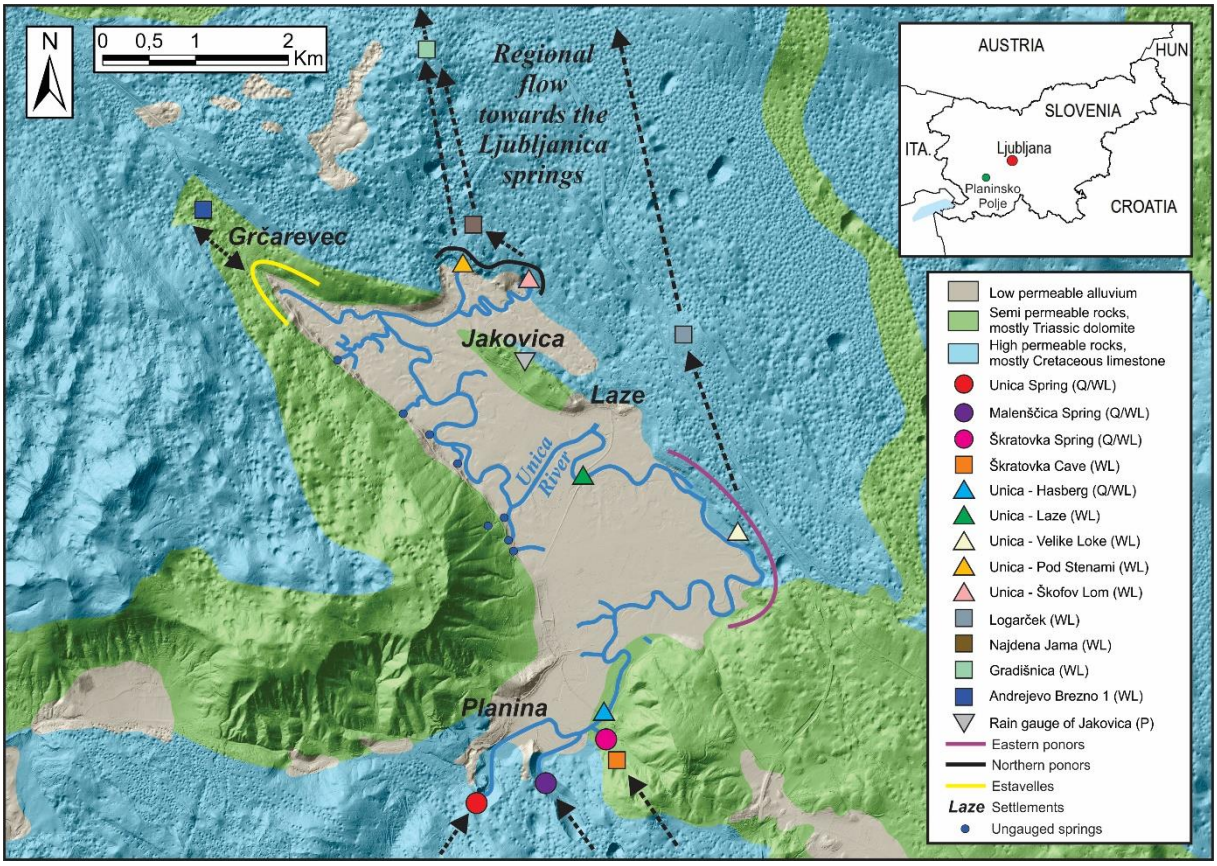


Fig. 3.14: Hydrogeological map of Planinsko Polje and the monitoring network that has been installed in its surrounding area. The upper right insert shows the regional position of the area in Slovenia.

Besides Planinska Jama, the most important recharge input is the Malenščica spring (Q_{min} = 1.1 m^3/s, Q_{mean} = 6.7 m^3/s, Q_{max} = 9.9 m^3/s; Frantar 2008), which receives water from Rakov Škocjan and the Javorniki mountains. The Malenščica spring is used as a water supply for more than 21,000 inhabitants (Petrič 2010). The Unica River flows rather uninterrupted over the polje's surface for the first 7 km (Fig. 3.15a). Along its course in proximity to the eastern border, it loses water along a 2 km long reach due to the presence of several groups of ponors and zones of intense leakage (Fig. 3.15b). The water sinks into well-expressed ponors, along lines of diffuse discharge into fractures and small dissolutional openings, as well as into small blind valleys entrenched into the sediment (Fig. 3.16). A study carried out by Blatnik *et al.* (2017) revealed new details on the location and capacity of the eastern ponor zone, with a total outflow capacity of about 18 m^3/s and individual outflow ranging between 1.0 and 5.6 m^3/s at each group of ponors. After 2 km of flow along the eastern border, the river crosses the polje and follows the western border. Then the Unica turns northeast towards the second ponor zone that are distributed along the polje northern border. The capacity of the northern group of ponors was estimated between 40 and 60 m^3/s (Šušteršič 2002).

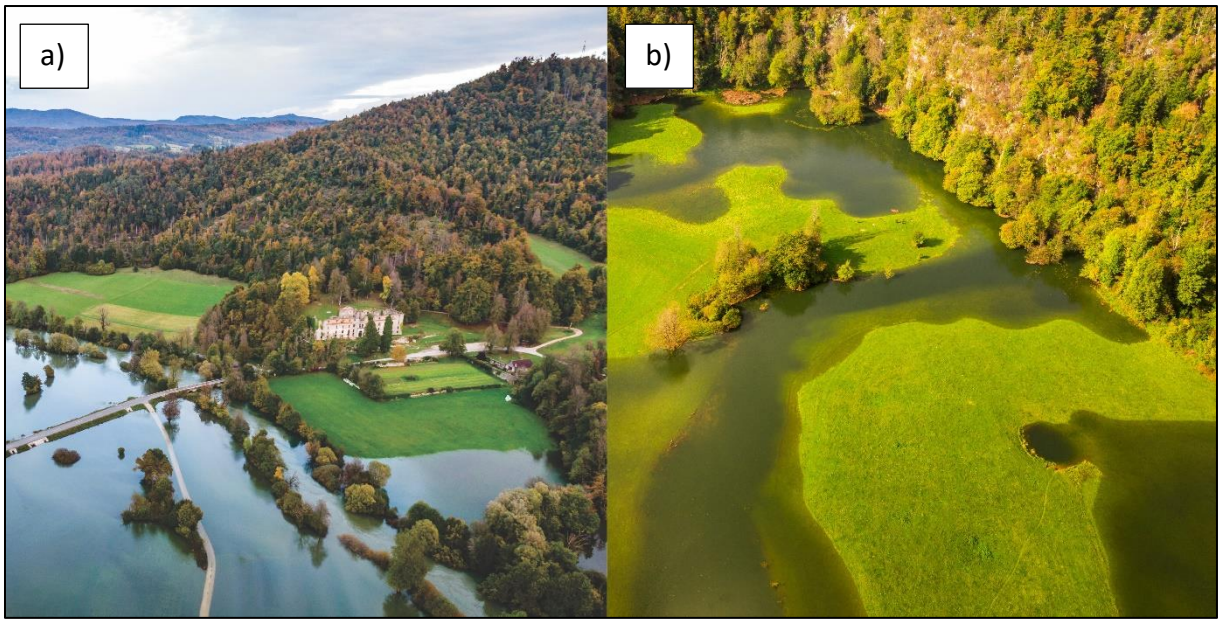


Fig. 3.15: Flooded Planinsko Polje. (a) Hasberg Bridge and castle. (b) Northern ponors (Photos: M. Blatnik; RI-SI-LifeWatch).

Similarly to Cerkniško Polje, Planinsko Polje can be flooded up to several times per year (Kovačič & Ravbar 2010). The period with the greatest probability that an extreme flood occurs is the coldest part of the year, tied to the mid-autumn rainfall peak, winter rains and snowmelting (Fig. 3.15a & Fig. 3.17). Although historical data are difficult to compare to current regular measurements, several extreme floods have been recorded in the past such as in 1801, in 1851/52; when the water level presumably reached an elevation between 456 and 458 m; and in 1923 when water level reached 453.4 m (Gams 1980). In February 2014, the floods reached an altitude of 453.2 m and 72 million cube meters of water were stored in the polje (Frantar & Ulaga 2015). The lake extended over 10.3 km^2 and more than forty houses and other facilities have been flooded (Mihevc 2014).

Fig. 3.16: Two of the many ponors draining Planinsko Polje. (a) Velike Loke located at the eastern border. (b) So-called Putick's Well (Putickova štirna) located at the terminal outflow zone at the northern border (Photos: M. Blatnik).

During the period between 1954 and 2014, high waters on the polje occurred on average 37.9 days per year (Ravbar *et al.* 2018). The longest periods the polje has been overflown were recorded in 1960 (altogether 137 days) and in 2014 (altogether 126 days). An event of high waters lasts on average for ten days, but can also be as long as 78 days such as the flood that occurred in autumn and winter 2000/01 (Ravbar *et al.* 2018).

Fig. 3.17: Planinsko Polje under various hydrological situations (Photos: M. Blatnik).

In a recently published work, Mayaud *et al.* (2019) listed and tested the parameters that could potentially control flooding in poljes. Lately, the same authors reconstructed the polje water (Mayaud *et al.* 2022). To do so, water levels measured on the polje surface and ponor zones, a new rating curve of the Unica at Planinska Jama and a 1 m resolution DEM of the polje surface have been used (Fig. 3.18).

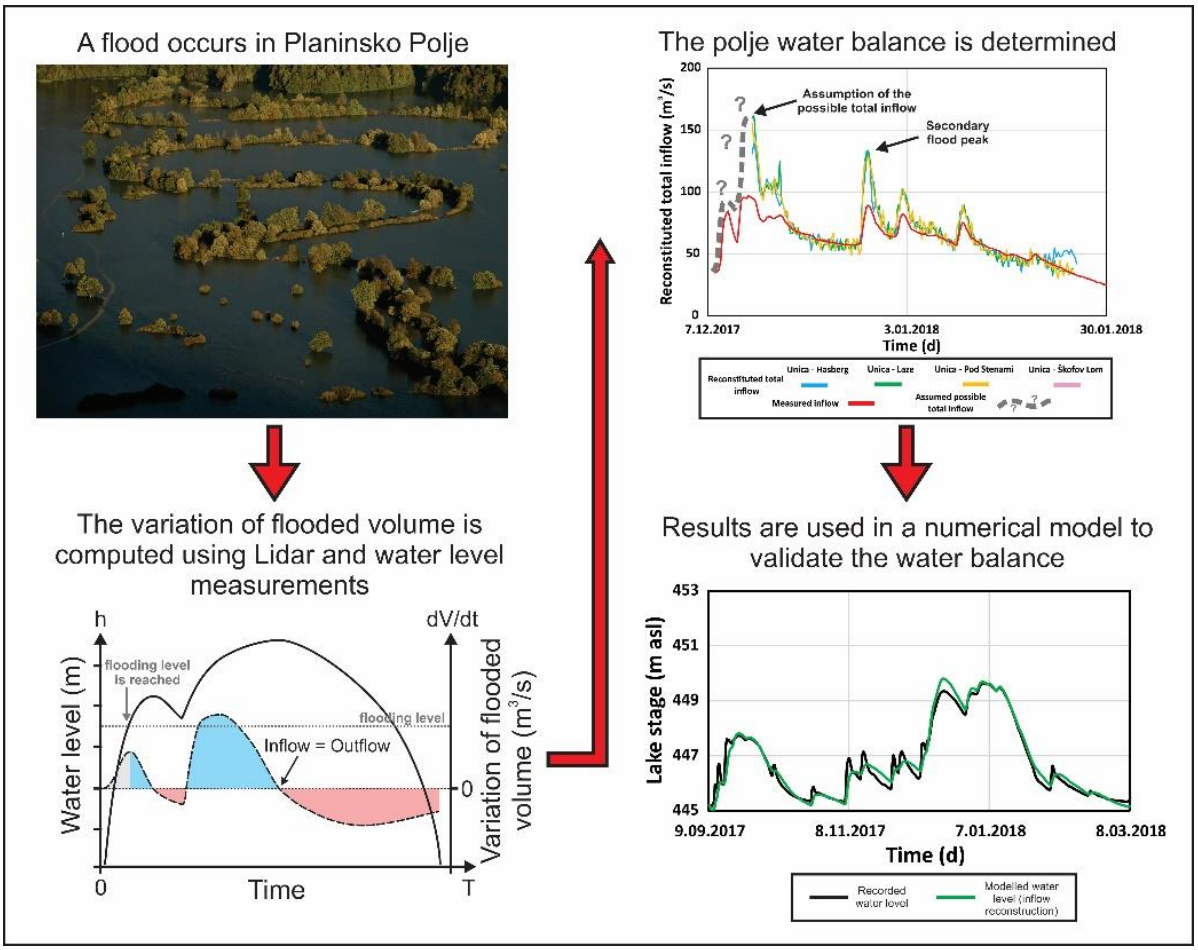


Fig. 3.18: Procedure employed to reconstruct the water balance of Planinsko Polje (Mayaud et al. 2022).

Water level and temperature have been monitored in all active caves between Planinsko Polje and Ljubljana basin in years from 2006 to 2009 and from 2015 on (Turk 2010; Gabrovšek & Turk 2010; Blatnik *et al.* 2019; Blatnik *et al.* 2020). Data loggers have been installed in 8 caves (Logarček, Vetrovna Jama, Najdena Jama, Gradišnica, Gašpinova Jama, Brezno pod Lipovcem, Andrejevo Brezno 1, Veliko Brezno v Grudnovi Dolini) and three ponors on the rim of Planinsko Polje (Velike Loke, Pod Stenami, Škofov Lom). Fig. 3.19 presents the recorded dynamics of underground water in March and April 2018.

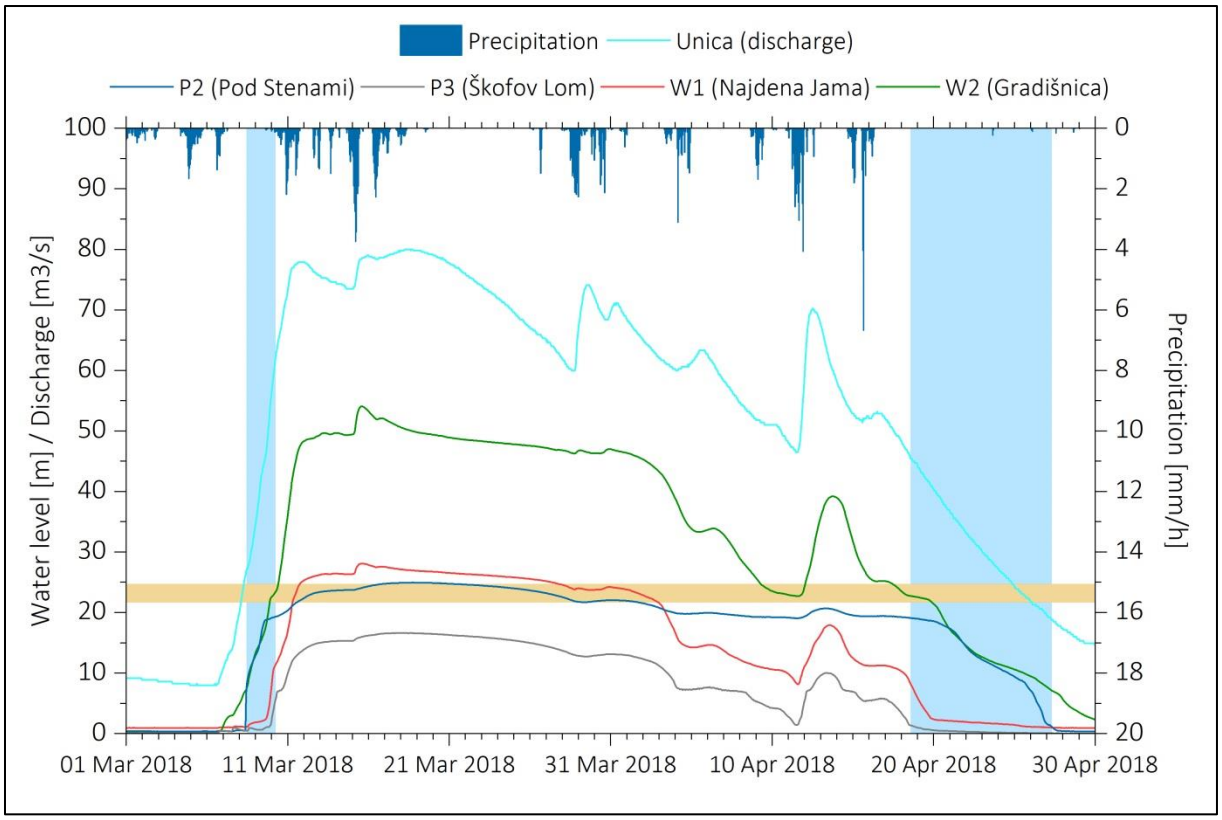


Fig. 3.19: Water level dynamic in selected caves between Planinsko Polje and Ljubljanica springs during high water event in March and April 2018. Blue areas denote different response of water level change; orange area denotes temporal slower increase (decrease of water level in cave Gradišnica).

PLANINSKA JAMA

Planinska Jama (Planina Cave) is a large spring cave located on the southern edge of Planinsko Polje (Fig. 3.20a). The cave is about 6.6 km long and consists mostly of large active river passages with cross-sections often larger than 100 m^2 (Fig. 3.21). The cave is known to be the confluence of two important regional rivers (Fig. 3.20b & Fig. 3.21): the Pivka River, which drains a large allogenic catchment through the Postojnska Jama (Gabrovšek *et al.* 2010; Kaufmann *et al.* 2016, Kogovšek 2022) and reaches the confluence with the cave via the Pivka Branch, and the Rak River, which carries water from Rakov Škocjan and Cerkniško Polje via the Rak Branch. Finally, a large amount of water also flows into the Rak Branch via the siphon of the Javornik Current, which is located below the Mysterious Lake (Fig. 3.21) (Kaufmann *et al.* 2020). The water exits the cave under the common name Unica River with a discharge between 0.2 and 90 m^3/s (Kogovšek 2022).

The different parts of the aquifer that feed the Unica spring show considerable differences in water contribution (Savnik 1960, Kogovšek 2022). During high water conditions, there is a groundwater divide in the Javorniki Mountains. The water discharges through the western, eastern and northern edges of the massif. Then the nearby Malenščica spring (Fig. 3.21), which is mainly fed by the the autogenic Javorniki water and allogenic water from the Rakov Škocjan reaches a maximum discharge of 9-10 m^3/s (Kogovšek 1999; Kovačič 2010, 2011). As the spring is damped, the Rak Branch is activated and acts as an overflow, while the Unica spring also receives water from the Pivka Branch. At low-flow, after the Cerkniško Jezero is drained, the outflow is solely directed towards the Malenščica spring, while the Unica spring is fed exclusively by the Pivka Branch (Kaufmann *et al.*

2020, Kogovšek 2022). The inversion of the flow direction between the Mysterious Lake and the Malenščica spring was numerically simulated with a pipe flow model (Kaufmann *et al.* 2020).

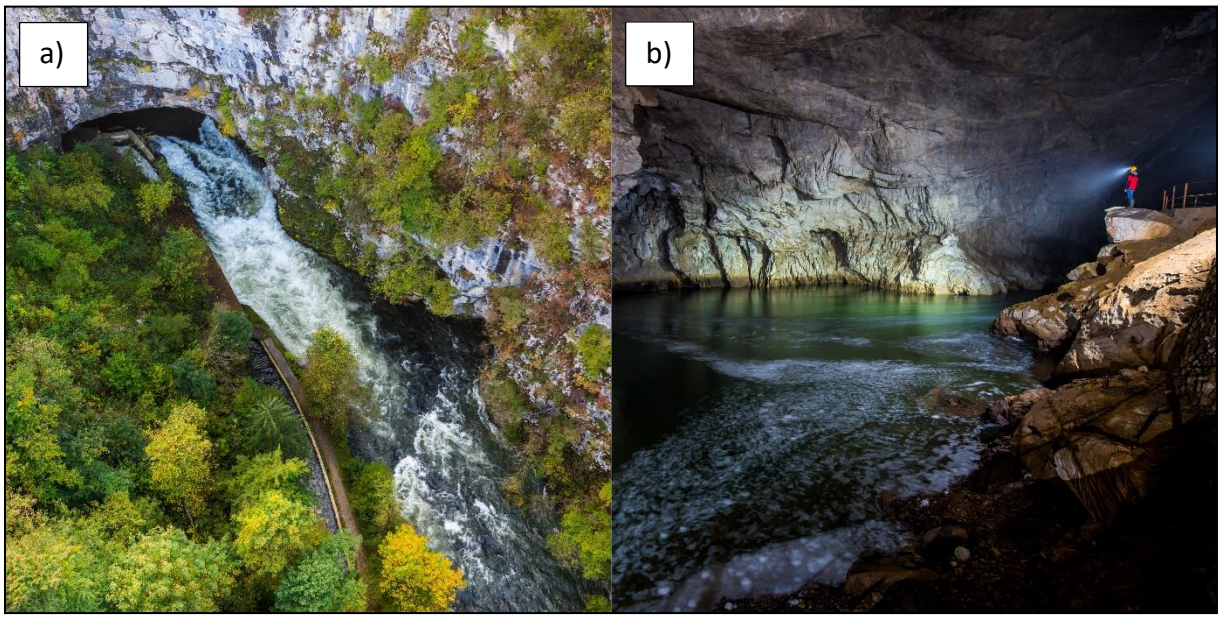


Fig. 3.20: Planinska Jama. a) Cave entrance (Photo: M. Blatnik; RI-SI-EPOS). b) Confluence of the Pivka and Rak Branches (Photo: M. Blatnik).

There are also differences in flow velocities between low and high flow conditions (Petrič *et al.* 2018). In general, the apparent dominant flow velocities in the karst aquifer are five times higher during high water (between 20 and 25 m/h) than during low water conditions (~ 4 m/h). In the well-developed conduit networks of Karlovica-Zelške Jame, Tkalca-Planinska Jama and Postojnska-Planinska Jama, flow velocities were up to fifty or even ninety times higher during high water (between 170 and 1000 m/h) compared to the velocities observed during low water (~ 4-23 m/h) (Petrič *et al.* 2018).

The research conducted in Planinska Jama over the last three years focused mainly on studying the hydrological behaviour of the Javornik Current (Gabrovšek *et al.* 2019), a partially explored siphon that connects to the Rak Branch in the so-called Mysterious Lake (Fig. 3.20b & Fig. 3.21). For this purpose, water pressure, electrical conductivity and water temperature were automatically recorded in both Mysterious Lake and the Javornik Current sump. The main objective was to find out whether the water coming out of the siphon is suitable for human consumption, to be used as a back-up reservoir for the municipalities of Postojna and Pivka (Gabrovšek *et al.* 2019).

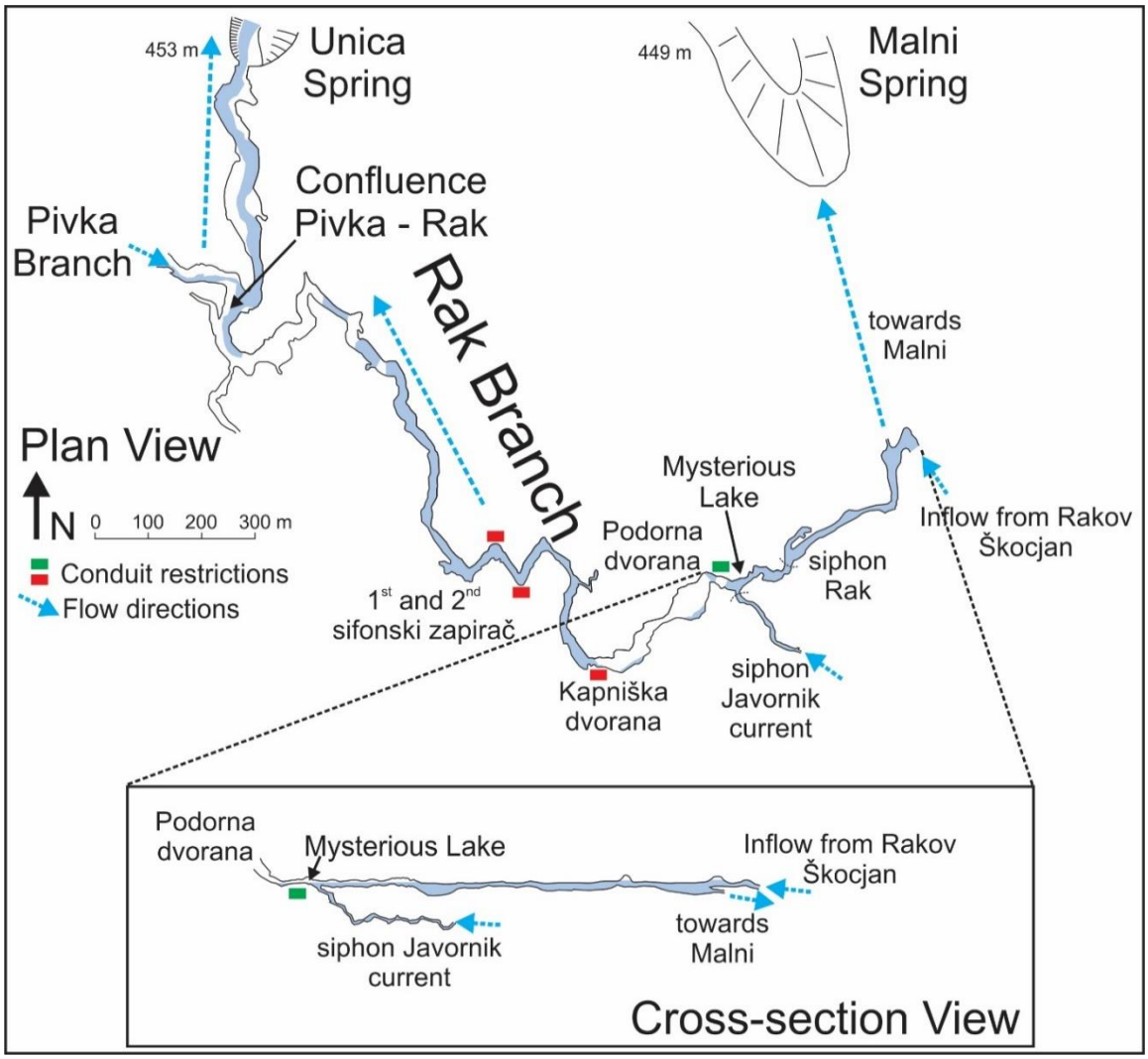


*Fig. 3.21: Plan and cross-section view of the explored passages of the Rak Branch. The constrictions described in the text are indicated in red and green (*Gams 2004; Kaufmann *et al.* 2020*).*

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Whole-day field trip (D):

ŠKOCJANSKE JAME AND KRAŠKI ROB (KARST EDGE)

Friday, June 20th 2025, 8:30–16:00

Nadja Zupan Hajna, Franci Gabrovšek

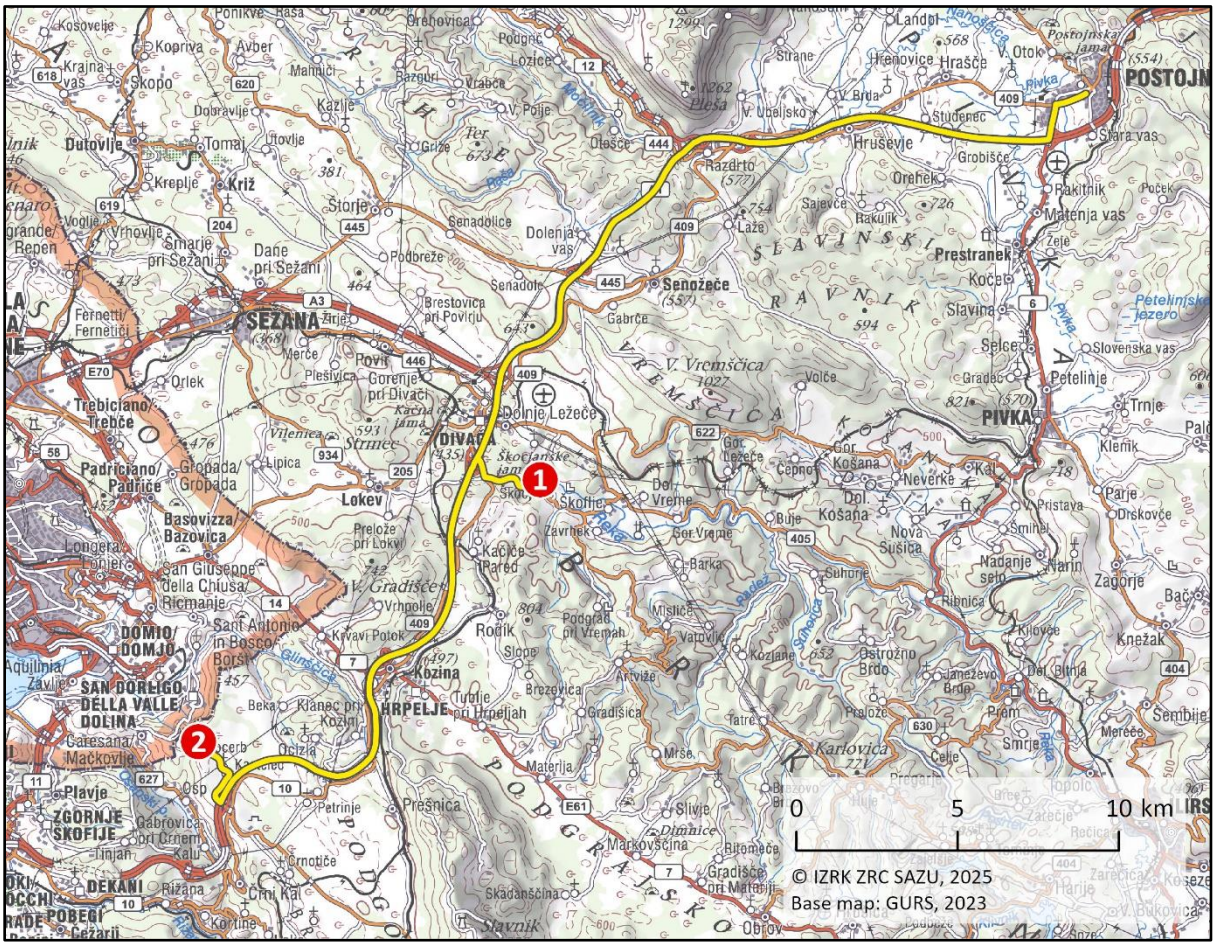
Stops:

1 – Reka River ponor

2 – Floods in Škocjanske Jame (Škocjan Caves)

3 – Paleofloods in Tiha Jama (Škocjan Caves)

4 – Kraški Rob (Karst Edge)



Škocjanske Jame in Kraški Rob

Celodnevna ekskurzija (D); petek, 20. junij 2025

Škocjanske jame so že same po sebi izjemen naravni fenomen, v katerih ne manjka lokalnih in globalnih ekstremov vseh vrst. Velika časovna spremenljivost dotoka reke Reke in velika prostorska spremenljivost prepustnosti kraškega sistema med Škocjanom in izviri ob Tržaškem zalivu botrujeta tudi do preko sto metrov visokim dvigom podzemne vode, ki jih v jamah vzdolž podzemnega toka Reke spremljamo s samodejnimi instrumenti. O visokih poplavah v preteklosti pa nam pričajo poplavni sedimenti, ki jih najdemo tudi v prerezih sige.

Zahodni rob Kraškega planotastega sveta in severozahodni rob Podgorskega krasa, znanega kot Kraški rob, se dvigata nad Tržaškim zalivom. Ta izrazita geomorfna stopnja je nastala tam, kjer so bile karbonatne plasti narinjene nad flišne kamnine. Izraz Kraški rob običajno označuje prepadne stene in strma karbonatna pobočja, ki potekajo vzdolž celotnega narivnega pasu, od izliva reke Timave do Učke na Hrvaškem.

REGIONAL SETTINGS

The Škocjanske Jame (Škocjan Caves) are located at the SE edge of the Kras (Karst Plateau; Fig. Fig. 4.1). The Kras Plateau is 40 km long and up to 13 km wide; latitude and longitude 45°45''N and 14°00''E cross the Kras near the village of Divača. The main part of the plateau is essentially leveled, inclined slightly to the northwest, with numerous dolines, caves and other karst features. The Kras plateau became a textbook example of this type of landscape because of its exceptional karst phenomena, and explorations were carried out in the 19th century. The name Kras in the German form of the word (der Karst) became an international scientific term.

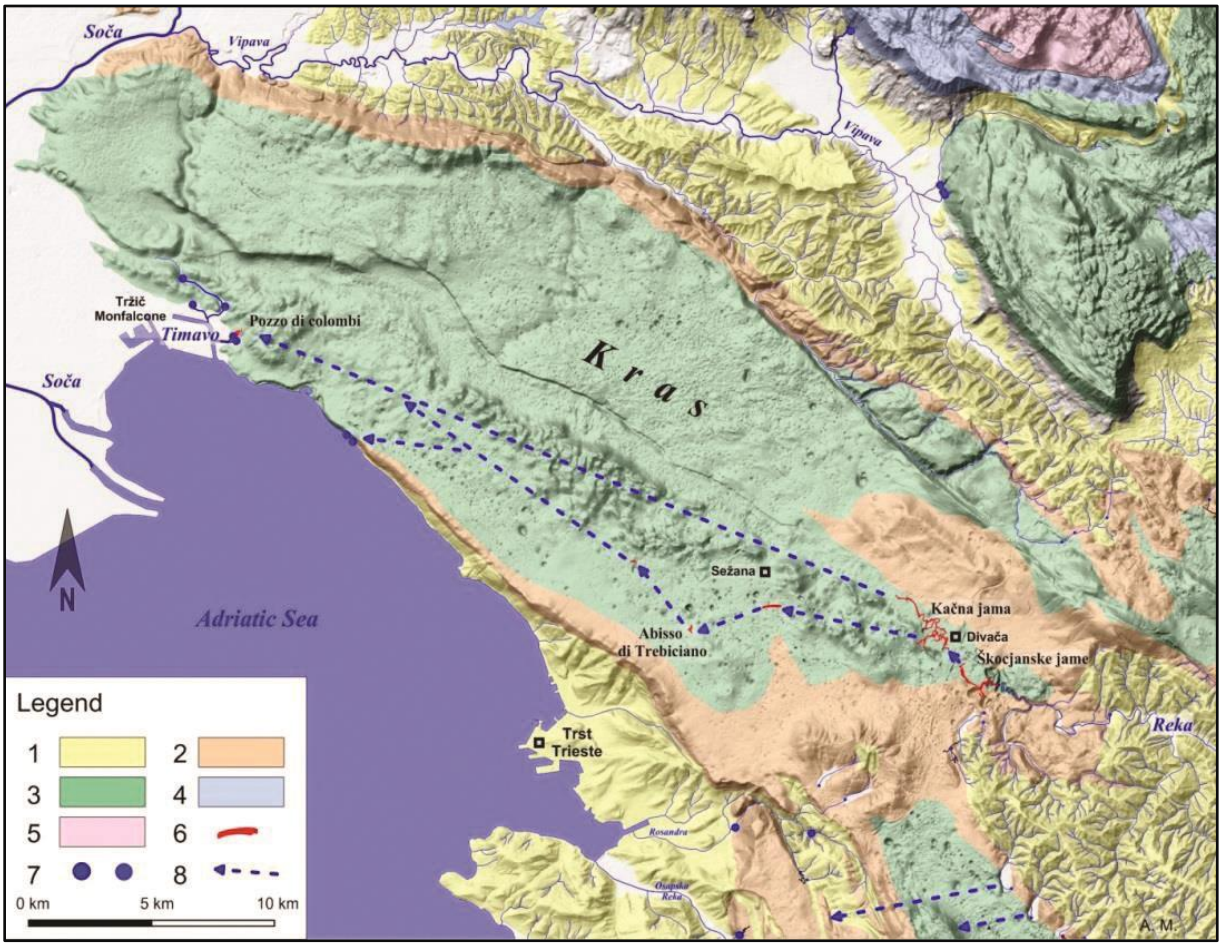


Fig. 4.1: Lithology, hydrology and morphology of the Kras Plateau, with two distinct dry valleys crossing the plateau. *Legend: 1. Eocene flysch; 2. Paleocene limestone; 3. Cretaceous limestone and dolomitic limestone; 4. Jurassic limestone and dolomite; 5. Triassic dolomite; 6. important cave; 7. springs; 8. supposed flow of underground rivers. Source of data: Geodetski oddelek ARSO.*

The Škocjanske Jame (in English Škocjan Caves), a more than 6 km long system of caves and collapse dolines (Fig. 4.2) in the Divaški Kras (Divača Karst) of southwestern Slovenia, are a world-renowned natural site. Recognized as a UNESCO World Heritage Site since 1986, the caves are famous for their extraordinary underground canyon—one of the largest in the world. In addition, they hold historical importance for 19th-century studies that contributed to the understanding of karst phenomena, the development of karst terminology, and the establishment of speleology and karstology as scientific disciplines.

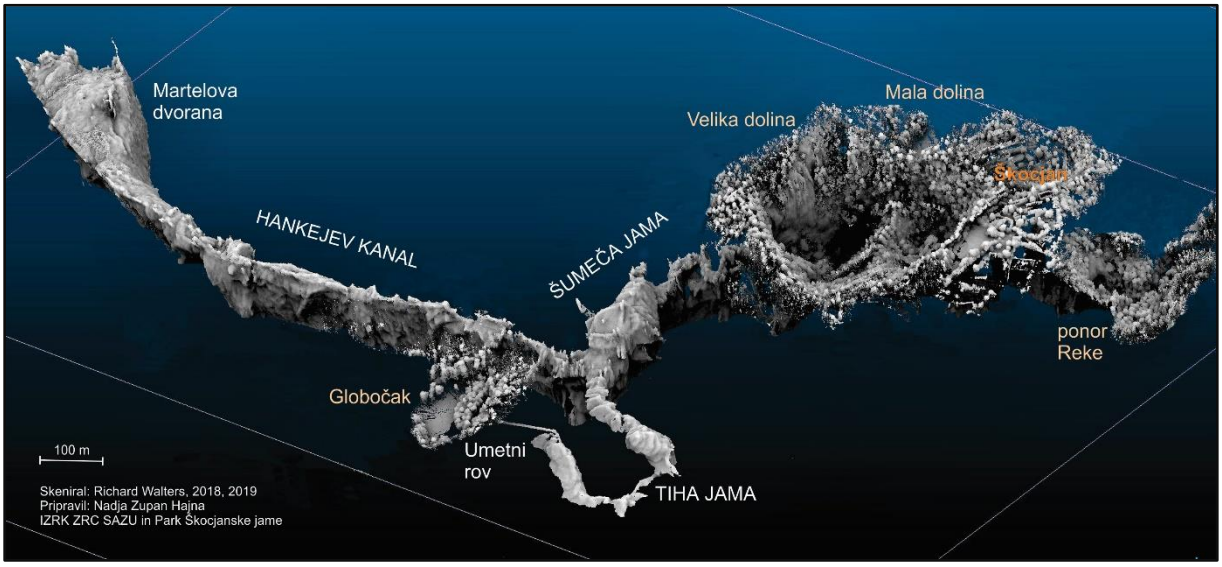


Fig. 4.2: 3D model of Škocjanske Jame made in Cloud Compare. View from NW: collapse dolines Velika and Mala Dolina and Globočak with main parts of the cave: Šumeča Jama, Hankejev Kanal and Martelova Dvorana (Walters & Zupan Hajna 2020).

The location of the cave system is strongly influenced by the contact between permeable Cretaceous and Palaeocene carbonate rocks and impermeable Eocene flysch. According to early geological studies, the system developed in bedded Turonian (K_2^2), massive Senonian (K_2^3), and thin-bedded Palaeocene (K_2^4 + Pc) limestones. More recent geological mapping of the surface and subsurface at a scale of 1:50,000 (Fig. 4.3) has revealed that the stratigraphic sequence in the Škocjanske Jame area comprises three lithostratigraphic units (Jurkovšek *et al.* 1996; Jurkovšek et *al.* 2013). The oldest rocks, belonging to the Sežana Formation (K_2^{2-4}), are 400–500 m thick and consist mostly of bedded limestones with rare rudist biostromes. Overlying this formation is the Lipica Formation (K_2^{4-5}), 250–400 m thick, comprising bedded and massive limestones with rudist biostromes and bioherms. The youngest unit is the Liburnian Formation (K-Pc), composed of bedded limestones containing the foraminiferal genus Alveolinae, with a thickness of 50–300 m. The boundary between the Lipica and Liburnian Formations is a disconformity, representing a regional discordance.

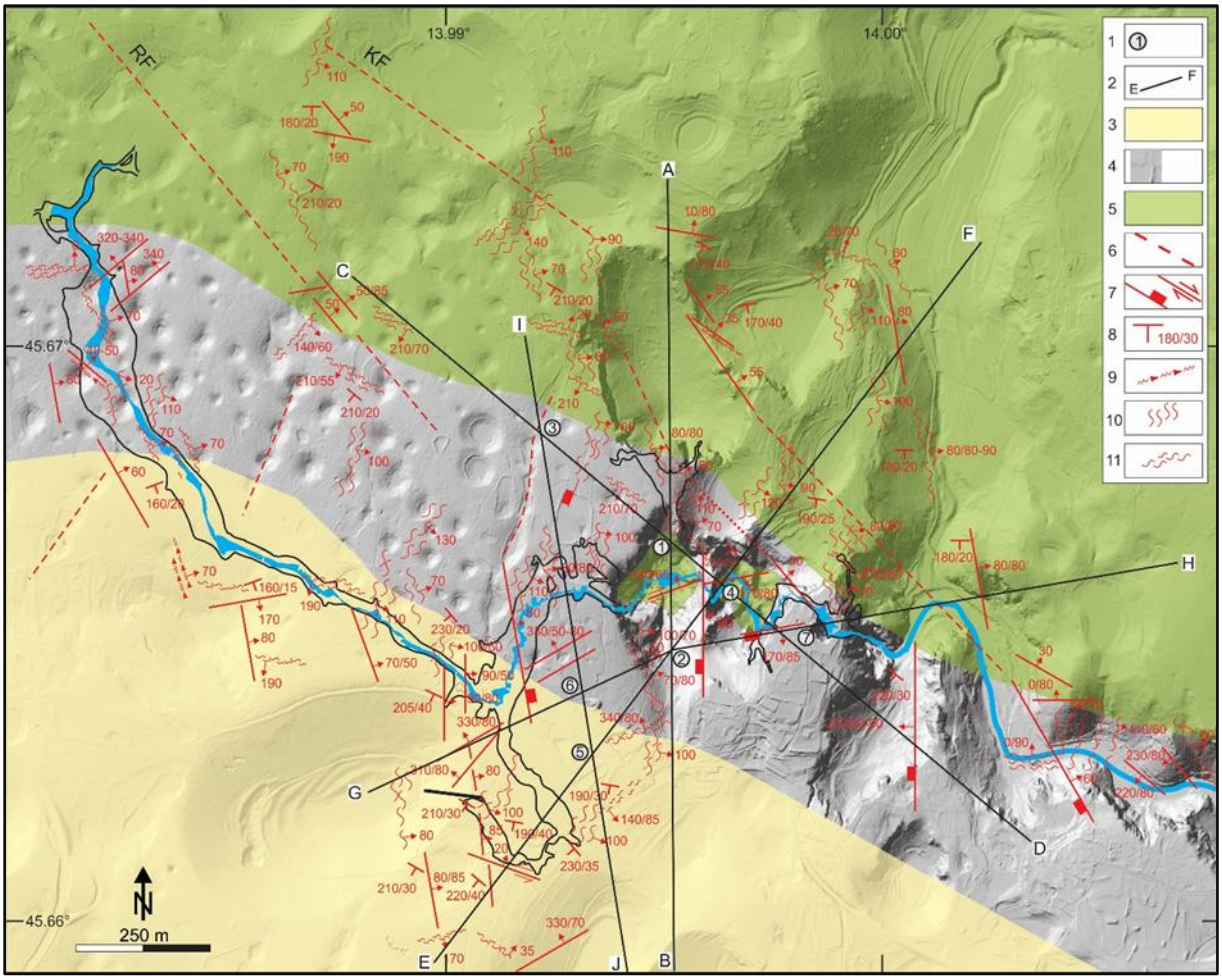


Fig. 4.3: Geological map of the surface above the Škocjan Caves system (Šebela & Novak 2023), hill-shade morphology (ARSO 2025a), and Škocjan Caves map with the River Reka. 1 – reference crossing point number of longitudinal profiles on ground-plan and longitudinal profiles, 2 – course of longitudinal profile, 3 – Liburnian Formation (K-Pc), 4 – Lipica Formation (K_2^{4-5}), 5 – Sežana Formation (K_2^{2-4}), 6 – supposed fault trace at the surface, 7 – vertical and horizontal displacements along faults, 8 – dip direction and dip angle of bedding planes, 9 – crushed zone, 10 – broken zone, 11 – fissured zone.

The passages of Škocjanske Jame developed within a 300 m-thick sequence of Cretaceous and Palaeocene limestones (Šebela 2009). The Reka, particularly within Šumeča Jama and Hankejev Kanal (Hanke's Channel) flows predominantly through a 130 m-thick segment of the Lipica Formation (K_2^{4-5}), following the direction of bedding. Bedding planes affected by interbedding slips (Knez 1996; Mihevc 2001; Šebela 2009) appear to have functioned as inception horizons, favouring the early development of cave passages. Beddings in the area exhibit a Dinaric strike orientation, trending NW–SE and generally dipping towards the southwest. The region belongs to the geotectonic unit known as the Trieste–Komen Plateau, and more specifically lies on the southwestern flank of a regional anticlinal fold structure (Gospodarič 1965; Jurkovšek *et al.* 2013). Many faults run parallel to the strike (NW–SE), while others intersect it obliquely (NE–SW).

Tectonically, the area lies on the Adria Microplate, which was overthrust by the External Dinaric thrust belt at the end of the Eocene (Celarc *et al.* 2012). During the Miocene, the Adria Microplate experienced segmentation and counter-clockwise rotation, accompanied by

underthrusting beneath the Dinarides. The degradation of the Adriatic–Dinaric carbonate platform and the deposition of clastic flysch sediments occurred during the Eocene.

Two major regional faults in the area are the Raša Fault and Divača Fault, both oriented NW–SE and currently considered active (Atanackov *et al.* 2021). The Raša Fault underwent multiphase kinematic evolution: initially a reverse fault with southwest-directed overthrusting, later partially reactivated by gravitational forces, and ultimately transformed into a strike-slip fault (Jurkovšek *et al.* 1996). The surface trace of the Divača Fault lies approximately 1 km north of Škocjanske Jame, and its broader deformation zone functions as a shear zone. Local evidence indicates overthrusting, normal faulting, and horizontal displacement (Jurkovšek *et al.* 1996).

ABOUT THE UNDERGROUND FLOW OF REKA TIMAVO SYSTEM

The Škocjanske Jame area is defined by the Reka and its ponor, located at an elevation of 314 m. After entering the cave system, the river flows underground for another 35 km to the Timavo springs near Trieste (Fig. 4.4). The cave system contains extensive passages and large collapse chambers developed across several inclined levels. After sinking into the system, the Reka flows 250–300 m below the surface. The lower, active part of the system begins with an underground passage just after the ponor (Mahorčičeva and Mariničeva Jama), averaging 30 × 40 m in cross-section. This passage is interrupted by two major collapse dolines: Mala Dolina and Velika Dolina. The river continues through a 2.6 km-long underground canyon, 10–60 m wide and 80–145 m high (Šumeča Jama and Hankejev Kanal), eventually reaching Martelova Dvorana at 214 m above sea level. Beyond this point, the Reka descends further through flooded passages towards Kačna Jama.

Downstream, the underground river can be accessed in several caves (Fig. 4.4), including Brezno treh generacij, Kačna Jama, Brezno v Kanjeducah, Jama Sežanske Reke, Jama v Strašinkini dolini, Labodnica (Abisso di Trebiciano), Abisso Skilan, and Pozzo di Colombi. Further to the northwest, no caves are currently known to carry the active flow of the Reka. The vadose zone is approximately 300 m thick, and caves have developed at nearly all elevations from the surface to sea level and below.

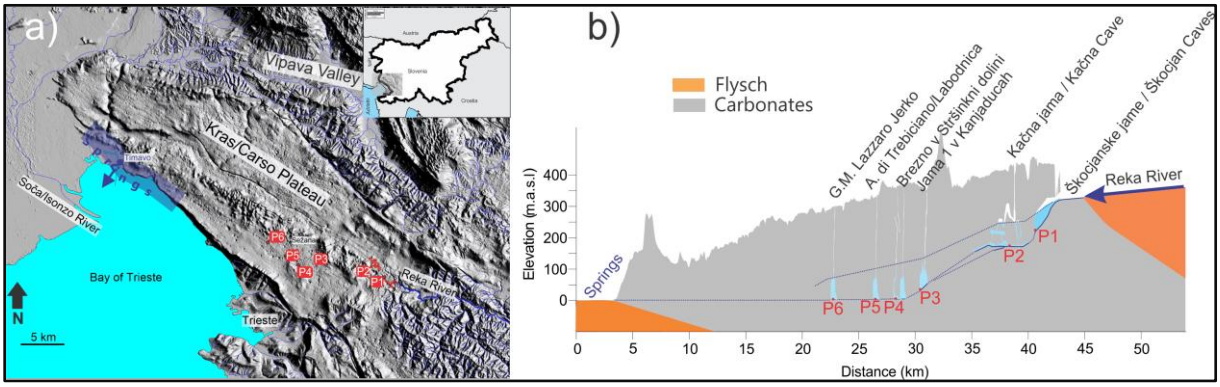


Fig. 4.4: DEM terrain visualization (a) and topographic profile (b) of the Kras/Karst Plateau with the position of some caves with access to groundwater flow. The dotted blue lines in the profile show base level and flood level at the observation points (Gabrovšek et al. 2018).

HYDROLOGY OF REKA AND GROUNDWATER FLOW CONNECTIONS

Flood events associated with the Reka exert a significant influence on the active part of the Škocjanske Jame system, affecting flow dynamics, enhancing erosive power, and controlling sediment transport and deposition within the cave passages. Before reaching the Škocjan area, the river flows approximately 50 km through a valley incised into low-permeability Eocene flysch (Fig. 4.1). The catchment area of the Reka exceeds 365 km², with about 60% of surface runoff occurring on flysch terrains (Peric & Hribar 2010).

Between 1992 and 2021, the lowest recorded discharge of the Reka at the Cerkvenikov Mlin hydrological station was 0.25 m³/s, while the mean discharge was 7.89 m³/s (ARSO 2025b). During extreme high-water events, discharge can exceed 300 m³/s. As the Reka reaches the contact with the carbonate bedrock, it begins to lose water through several sinks located immediately downstream of the lithological boundary. Under very low flow conditions, the entire discharge sinks at this point; otherwise, the river continues for another 7 km within a limestone valley before finally sinking underground into the cave system.

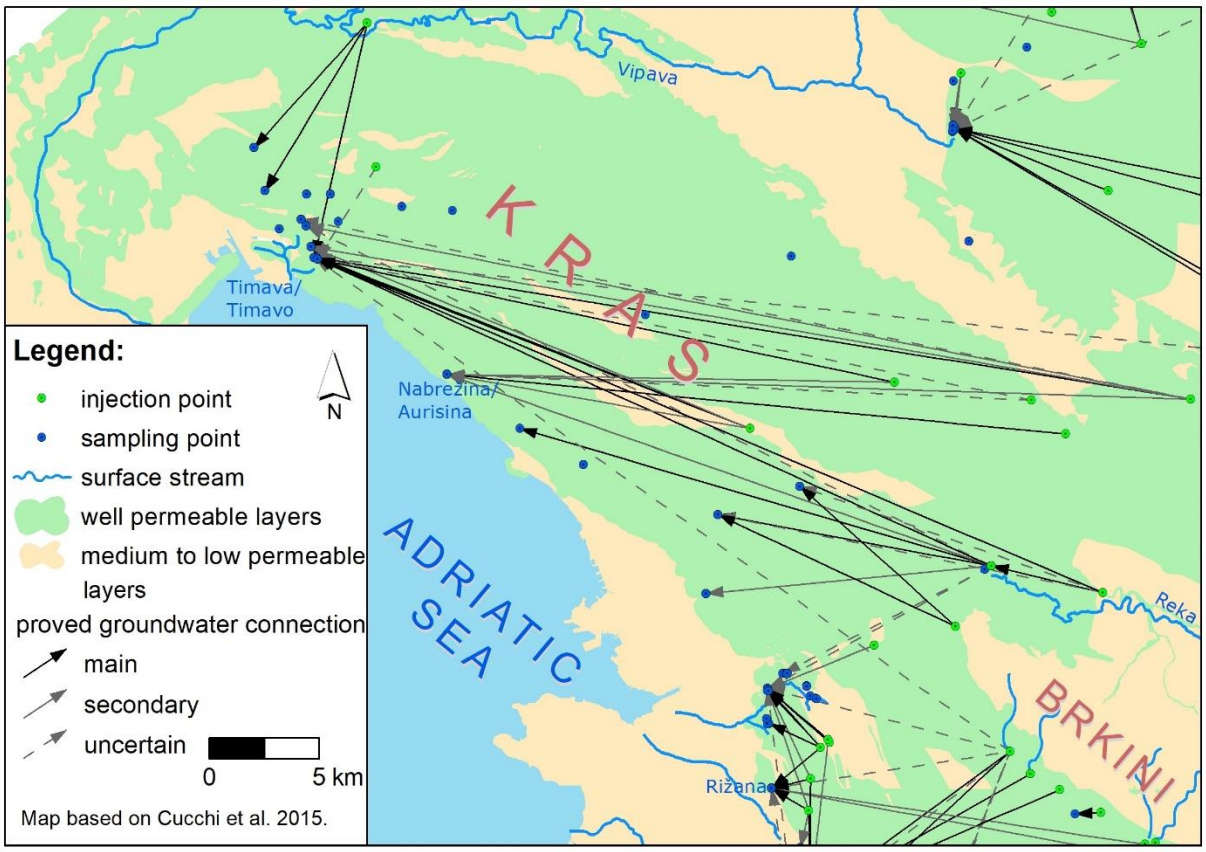


Fig. 4.5: Hydrogeological map of the Karst Plateau with proved groundwater connections (based on Cucchi et al. 2015).

From the cave, groundwater flows towards a coastal spring belt between the Nabrežina/Aurisina and Timava/Timavo springs in the Gulf of Trieste (Fig. 4.5). The main springs of the Timavo River have a minimum discharge of 7.4 m³/s, a maximum of 158 m³/s, and a mean of 29.3 m³/s (Gemiti 1995). The first tracer tests in the Classical Karst were conducted as early as the late 16th century, first successful tracing with fluorescent dye (confirming the connection to Timavo) was done

in 1891. Many subsequent tracer tests in of the 20th century confirmed the hydrological connection between the Reka at Škocjanske Jame and the aforementioned springs (Timeus 1928; Mosetti 1965; Gemiti 1998; Galli 2012; Peric 2012). Tracers were also detected in intermediate karst caves, such as Jama 1 v Kanjaducah and Labodnica/Abisso di Trebiciano (Fig. 4.4). The determined flow velocities—based on the duration of tracer transport and the linear distance between injection and emergence points—varied between 47 and 204 m/h, depending on hydrological conditions (Turpaud *et al.* 2018).

FLOODS IN ŠKOCJAN CAVES: OBSERVATIONS, ANALYSES AND MODELLING

The Reka River enters the karst aquifer at Škocjanske jame. Its subterranean course can currently be traced through at least nine additional caves between Škocjanske jame and a series of coastal springs located between Aurisina and Duino on the northwestern shore of Trieste Bay, with the Timavo Springs being the most voluminous (Fig. 4.5).

Systematic monitoring of water level and other hydrological parameters in the Reka–Timavo underground system was initiated more than 25 years ago using autonomous data loggers (Cucchi and Zini 2002), and was later expanded by Gabrovšek and Peric (2006). The interpretations and models presented herein are based on the synthesis by Gabrovšek *et al.* (2018).

The upstream portion of the system comprises Škocjanske jame and Kačna jama (Snake's Cave), whose cross-section is illustrated in Fig. 4.6.

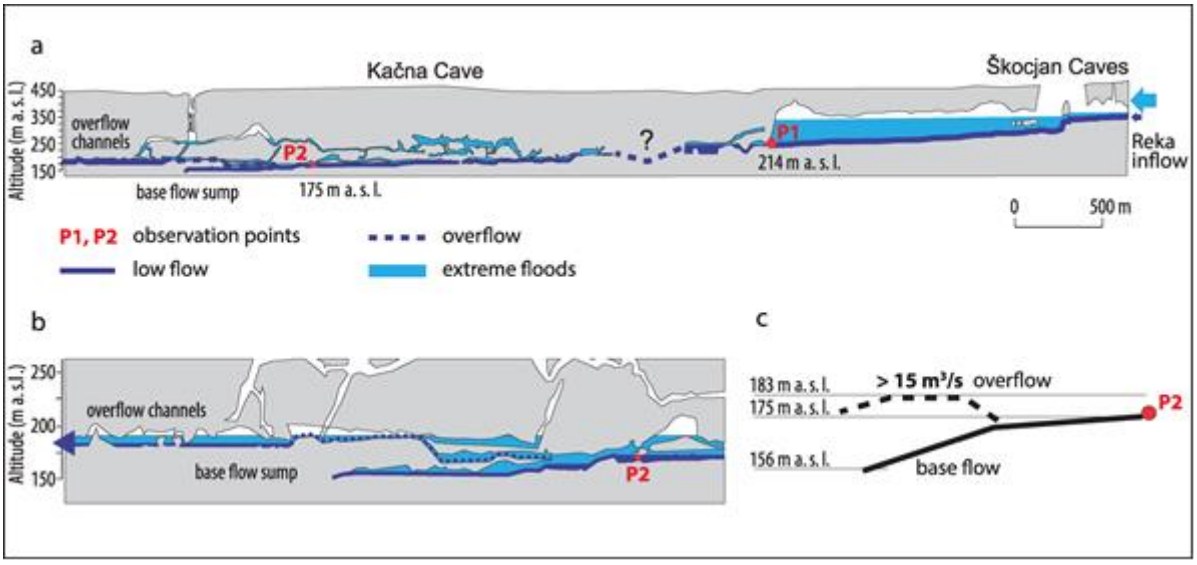


Fig. 4.6: a) Cross-section through Škocjanske Jame and Kačna Jama *with the position of observation points P1 and P2. Dark blue lines/regions indicate low flow water positions, and the pale blue shows the floodwater situation. b) Detailed view of the region of P2 in Kačna* Jama*. c) Flow routing at low flow (solid line) and high flow (dotted line) behind P2 (from Blatnik et al. 2020).*

The Reka reaches the flysch–limestone boundary about 7 km upstream from the Škocjanske Jame and initially flows through a canyon (Fig. 4.6). At the entrance to the Škocjanske Jame, the canyon turns into an underground channel with a cross-section of 30 m by 40 m, which is after few hundred meters interrupted by collapse dolines from where the river continues along an underground canyon; 2.6 km long, 10 m to 60 m wide and 80 m to 145 m high. In Martelova Dvorana, the channel is

interrupted by a Cross-Dinaric fault, and the cross-sectional area drops abruptly by roughly three orders of magnitude, to "only" several tens of square meters. Here, at 214 m, is the position of the first observation station P1. From here, the flow follows a sequence of channels (with a cross-section of several tens of m^2) and continues into a sump, which is still unexplored, but the connection to another sump 800 m NW in the Kačna Jama is certain. Kačna Jama can be entered from the surface through a 186 m-deep shaft that connects to a complex system of epiphreatic and vadose channels, distributed along at least two distinct levels. The cave is over 20 km long and 280 m deep. The lower epiphreatic level is dominated by the flow of the Reka River, which mostly flows in an open channel during low to medium hydrological conditions, when water leaves the cave through the terminal sump at 156 m Observation station P2 in Kačna Jama is in the section called Brzice (translated from the Slovene by rapids), about 300 m upstream from the sump, at 175 m. When the outflow capacity of the sump is exceeded, water flows along a system of overflow channels following the SE–NW (Dinaric) trend. More than 2 km of the overflow channels, interrupted by perched sumps, have been explored. Historical markings (organic debris) of floods in Kačna Jama reach over 100 m above the base flow level (Fig. 4.6).

FLOOD RESPONSE

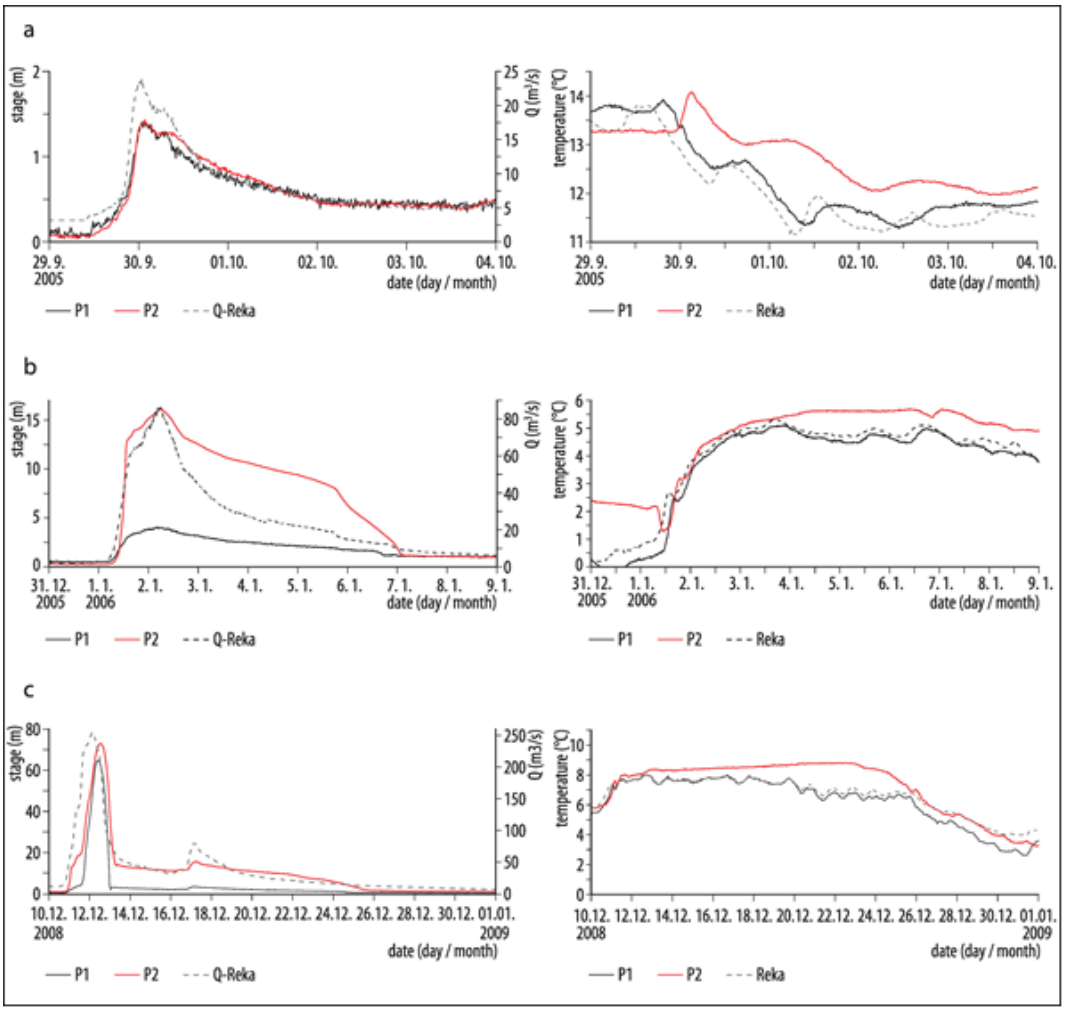


Fig. 4.7: Stage and temperature hydrographs at Škocjanske Jame (P1) and Kačna Jama *(P2) during small (a), medium (b) and large (c) flood events (from Blatnik et al. 2020). Note that the range of stage axis differs between the cases.*

Fig. 4.7 shows the response of the water level in Škocjanske Jame (P1) and Kačna Jama (P2) during three events with different peak flows and peak levels. During a small event, comparable responses at both locations are recorded (Qmax = 23 m^3/s, Fig. 4.7a). In a medium event (Qmax = 85 m^3/s, Fig. 4.7b), the level at P1 rises to 4 m, while the level at P2 shows a steep rise to 15 m and slow recession (-2 m/day), as long as the flow rate is above 15 m^3/s. Finally, it recedes at the rate of about -4 m/day to the base level. During a large event (Qmax = 250 m^3/s, Fig. 4.7c) stage rises vigorously to 65 m at P1 and 73 m at P2, where it drops rapidly almost to the base level when the discharge drops below 100 m^3/s, while at P2 stays elevated until Q> 15 m^3/s. During the rising stage of the medium and large events, inflection at about 13 m can be observed at P2, suggesting an overflow level.

The interpretation of the response and stage-discharge curves is based on the known geometry and base flow directions in Kačna Jama (Fig. 4.8). There, the flow at low stage enters a narrow channel, which ends in a sump at 156 m. The limited capacity of this outflow back-floods this part of the cave and diverts water into large galleries positioned about 9 m above the instrument. This obvious overflow resolves the first inflection in Kačna Jama (Fig. 4.7b & Fig. 4.7c).

The situation is additionally clarified in Fig. 4.8, which shows the level at P1 and P2 as a function of the Reka flow rate for the entire observation period. For Q<100 m^3/s, P1 stays below 4 m, while the level at P2 rises above 10 m for Q>20 m^3/s. When flow is higher than 130 m^3/s, a steep rise with similar characteristics at both locations is observed.

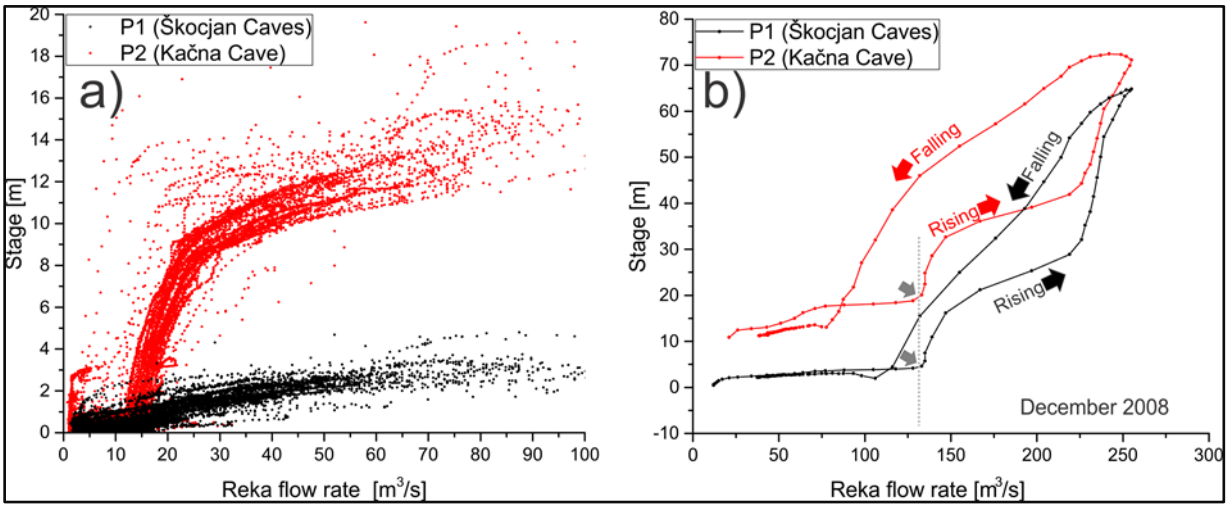


Fig. 4.8: Stage at P1 and P2 as a function of Reka flow rate (from Blatnik et al. 2020). a) Entire cloud of data points for Q<100 m^3/s. b) Situation at large flood event of December 2008. Note the common inflection towards steep rise at about 130 m^3/s, marked by grey arrows.

However, a more interesting question is what causes large floods in Kačna Jama and particularly in Škocjanske Jame, where the major inflection in the stage-discharge curve occurs at about 130 m^3/s (Fig. 4.8b). This inflection is always slightly preceded by a major inflection in Kačna Jama (grey arrows in Fig. 4.8b), which suggests that the back-flooding is triggered by the constriction behind the observation point in Kačna Jama.

Another insight is given by Fig. 4.9 which shows the relation between heads at both points. Two major floods from December 2008 and February 2009, deviate as large loops.

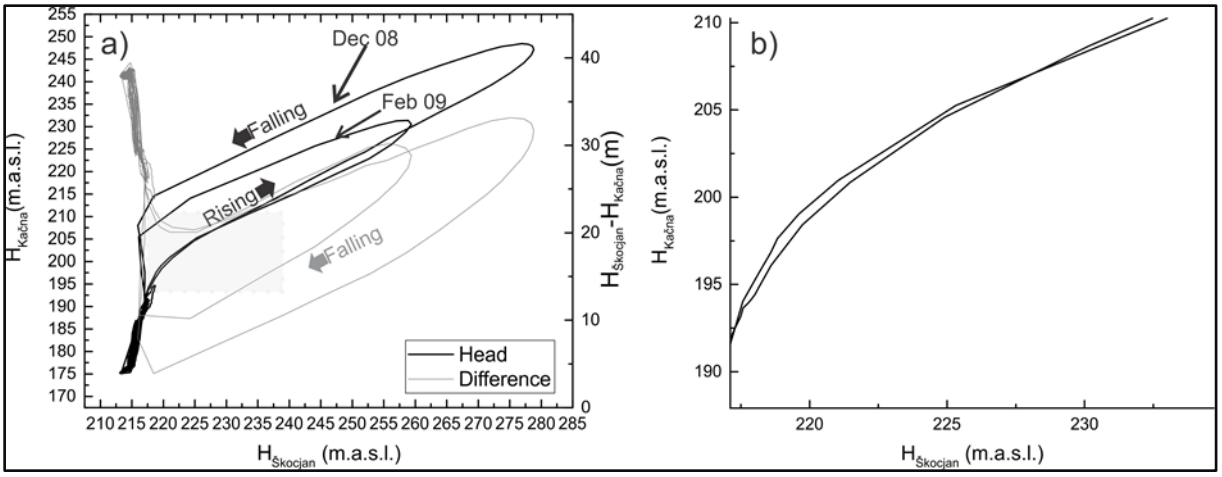


Fig. 4.9: a) Black curve: the relation between heads in Škocjanske Jame (P1) and head in Kačna Jama *(P2) (from Blatnik et al. 2020). The grey curve shows difference $H_{Škocjan}$-$H_{Kačna}$. b) Rising stage of the curve in the region marked by a rectangle in the Fig. a.*

During the rising stages of both flood events, the heads at both caves start to correlate, when the head in Kačna Jama rises above 190 m. Only a small deviation between both floods occurs during further increase (Fig. 4.9b). In general, the loops in such correlation plots are caused by time delay between response at the points and/or by the stored water between both points, which becomes the sole reason when both points are fully hydraulically connected. In this case the additional flow of the stored water results in slower recession at the downstream point, as compared to the upstream point. Larger floods may store more water between the points, which makes their hysteresis larger, as can be seen in Fig. 4.9a.

Note that the rate of head rise at P1 becomes higher compared to the rate at P2, when it is reached by backflooding. The reason for this is that there are several conduits between both points that become pressurized when backflooded, resulting in a large head-drop along them.

SWMM MODEL OF THE HYDRAULIC RESPONSE TO HIGH RECHARGE EVENTS

We have modelled the flood propagation through Škocjanske Jame and Kačna Jama with Storm Water Management Model (SWMM). The model is based on the one presented by Gabrovšek *et al.* (2018), but only the first part of the system, relevant for P1 and P2, is taken and optimized manually. The plan-view of the model is shown in Fig. 4.10a and the cross-section at different flood stages in Fig. 4.10c. Fig. 4.10b shows the observed and modelled response at P1 and P2 during the period of the February 2009 flood. Despite the fact that the model's geometry is highly simplified and partially unknown, the model captures all characteristics of the observations. Four stages of the flood event are shown in Fig. 4.10c: 1) before the flood, when all the water is drained by the low water sump beyond P2, 2) when the overflow is active and P2 is already backflooded, but the response at P1 is still small, 3) at the peak, where all conduits are pressurized and, 4) when P1 has dropped almost to base level and P2 is still high.

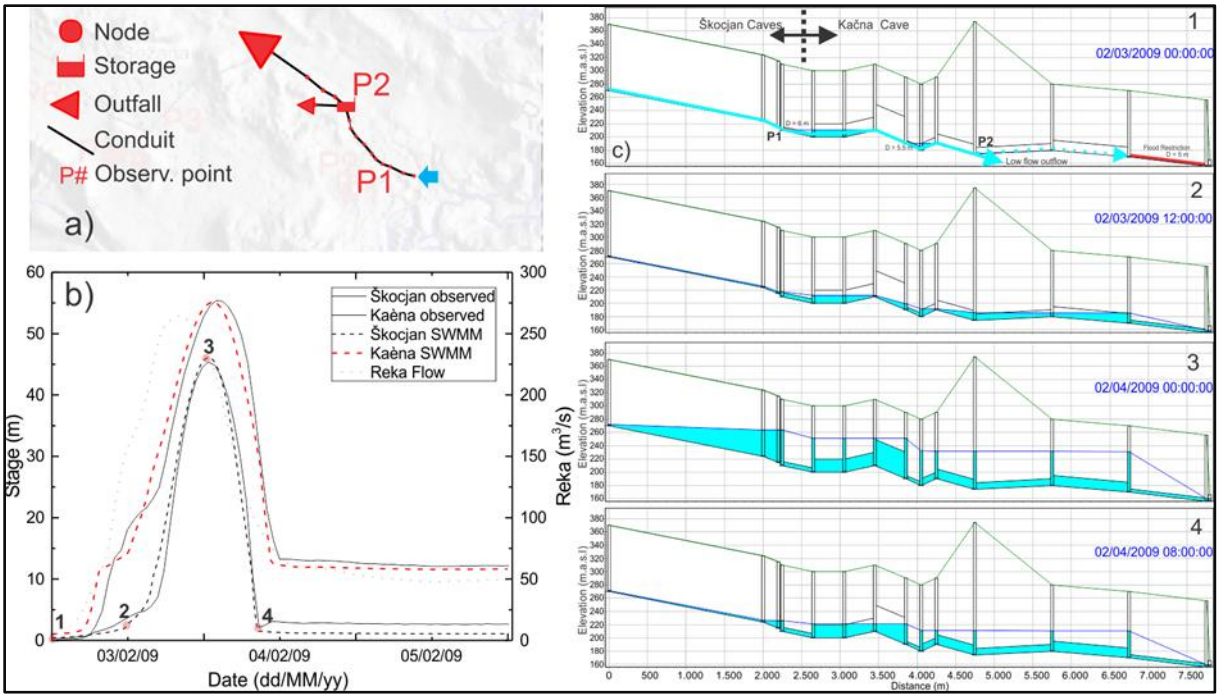


Fig. 4.10: a) Plan view of the SWMM model (from Blatnik et al. 2020). b) Modelled (dashed lines) and observed (full lines) responses at P1 and P2 during the flood event in February 2009. The recharge is shown by grey dotted line. Points 1-4 show four the positions of stages presented in the Fig. 4.10c. c) Cross-section of the model at four stages during flood event. Pale blue regions denote the water level; dark blue lines show total had along the profile.

FLOOD EVENT OF FEBRUARY 2019

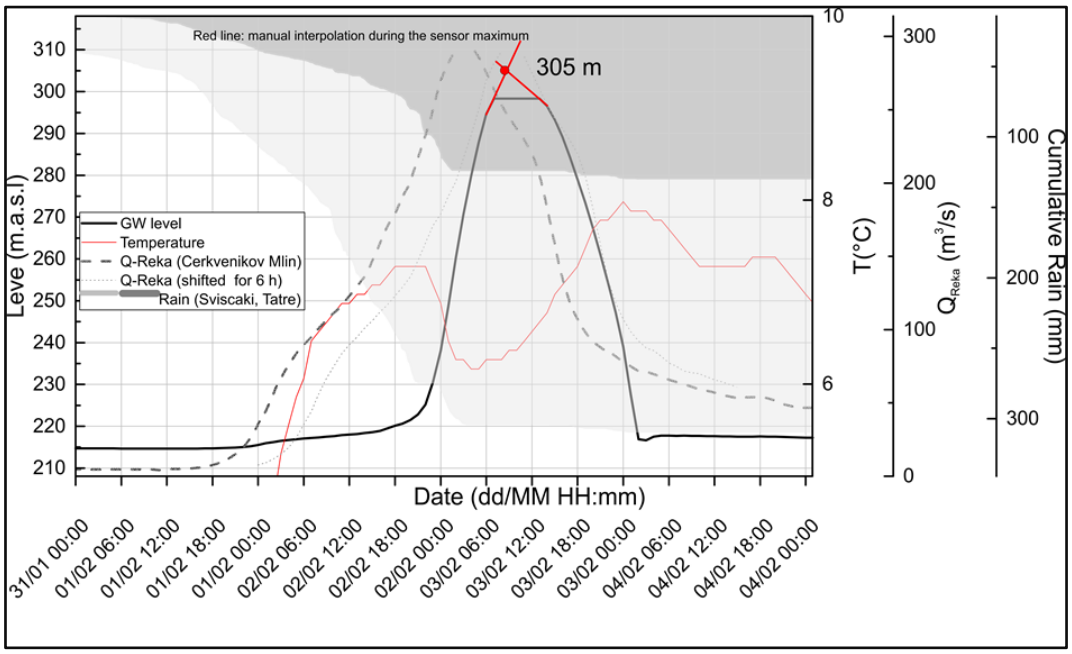


Fig. 4.11: The flood event of February 2019: Cumulative rain at two stations, discharge of the Reka River and level and temperature in Martel's Chamber (from Blatnik et al. 2020). Dotted grey line shows discharge shifted for six hours, an estimated travel time from gaging station to Martel's Chamber.

Between January 27th and February 4th 2019, over 300 mm (almost 200 mm in the most intensive 30 h period) of rain fell in the mountainous region of Mt. Snežnik and about 150 mm in the area of Škocjan. The discharge of the Reka River at the Cerkvenikov Mlin gauging station peaked at 300 m^3/s. During the event the water in Škocjanske Jame rose at rates up to 10 m/h and reached a level of 305 m in Martel's Chamber (Fig. 4.12 & Fig. 4.13) and about 307.5 m in Šumeča Jama. The flood was the largest in the last 50 years. High water caused severe damage to infrastructure and deposited a considerable amount of mud; at some places the thickness of fresh deposits was above 50 cm (Fig. 4.13).

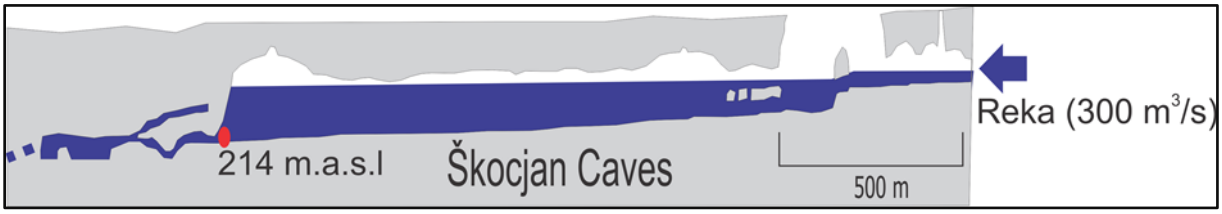


Fig. 4.12: A simplified extended elevation of Škocjanske Jame with approximate maximal water level during the flood of February 2019 (from Blatnik et al. 2020).

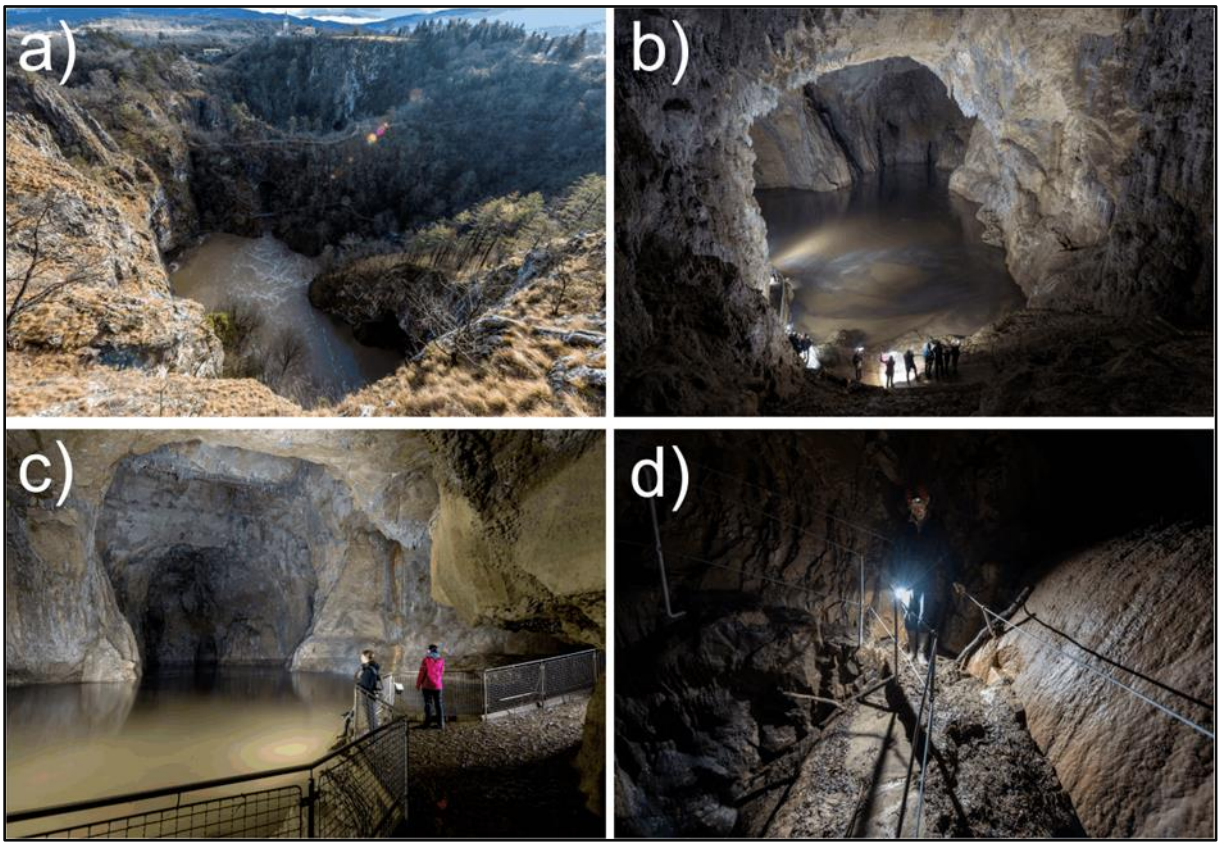


Fig. 4.13: Photos of the 2019 flood. a) Velika Dolina collapse valley (Photo: B. Lozej). b,c) Šumeča Jama (Rumouring Cave; Photos: B. Lozej) d) Flood deposits on the footpath in Hankejev Kanal (Photo: F. Gabrovšek).

From July 2018, we also performed a time-lapse gravity observation with a gPhone gravimeter (herein referred as SK1) positioned on the surface above Škocjanske Jame. The idea was to observe gravimetric response due to mass changes caused by flooding (Pivetta *et al.* 2021).

The gravimeter was installed in a building near the information center, approximately 250 m from the Šumeča Jama (Rumoring Cave). The raw gravimetric have to be processed to remove signals of tidal and non-tidal origin and atmospheric signals in order to obtain the residual, i.e. the gravity variations caused solely by the flood event. Fig. 4.14a & Fig 4.14b show the map of Škocjanske Jame with elevations of streambed and the ceiling, and flooded region at two different water levels. Fig. 4.14c & Fig. 4.14d & Fig. 4.14e show the measured and modelled water level, the gravimetric response and the stored volume. The "whole model" version includes also water stored in collapse dolines and Reka Canyon prior to the ponor. Inclusion of these parts produced a much better fit to gravimetric data. The hydraulic and gravimetric model used in this work also included an improved geometry of Škocjanske Jame based on 25 cross-sections of the Reka Canyon made with laser profiler.

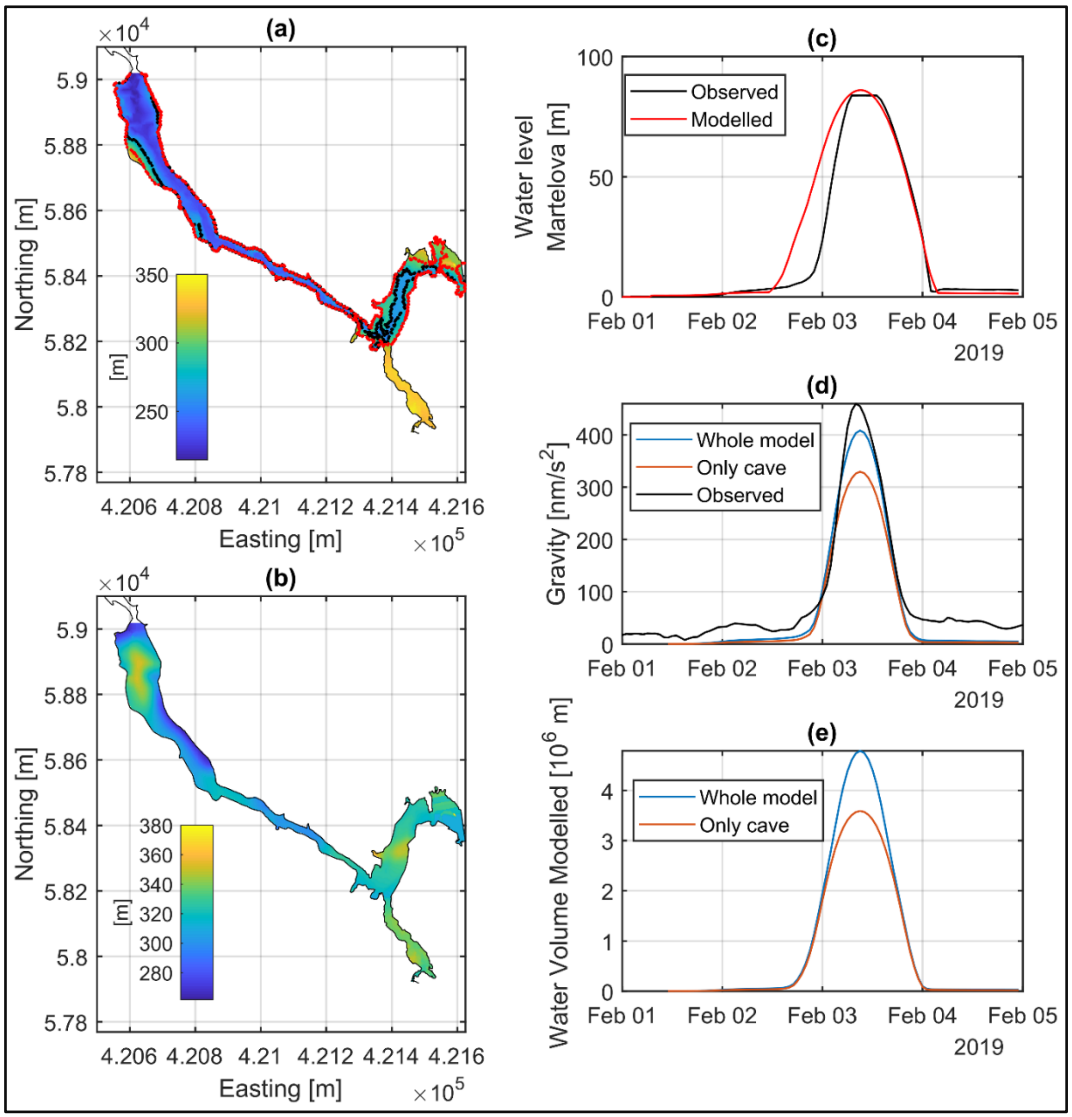


Fig. 4.14: Hydrological and gravitational response to flood event (from Pivetta et al. 2021). (a) Elevation of the streambed during low flow (m) where the Reka flows; the red and black outlines show the flooded

area when the water level in P1 is respectively 86 and 50 m. (b) Elevation (m) of the ceiling of the cave. (c) Observed (black) and modelled (red) time series of the water at P1 (d) black: observed gravity residual; blue: modelled gravity transient for the whole model, which includes the flooded areas out of the cave; red: gravity effect of the solely masses inside the cave. (e) Stored water volume during the flood; the color code as in (d).

COLLAPSE DOLINES

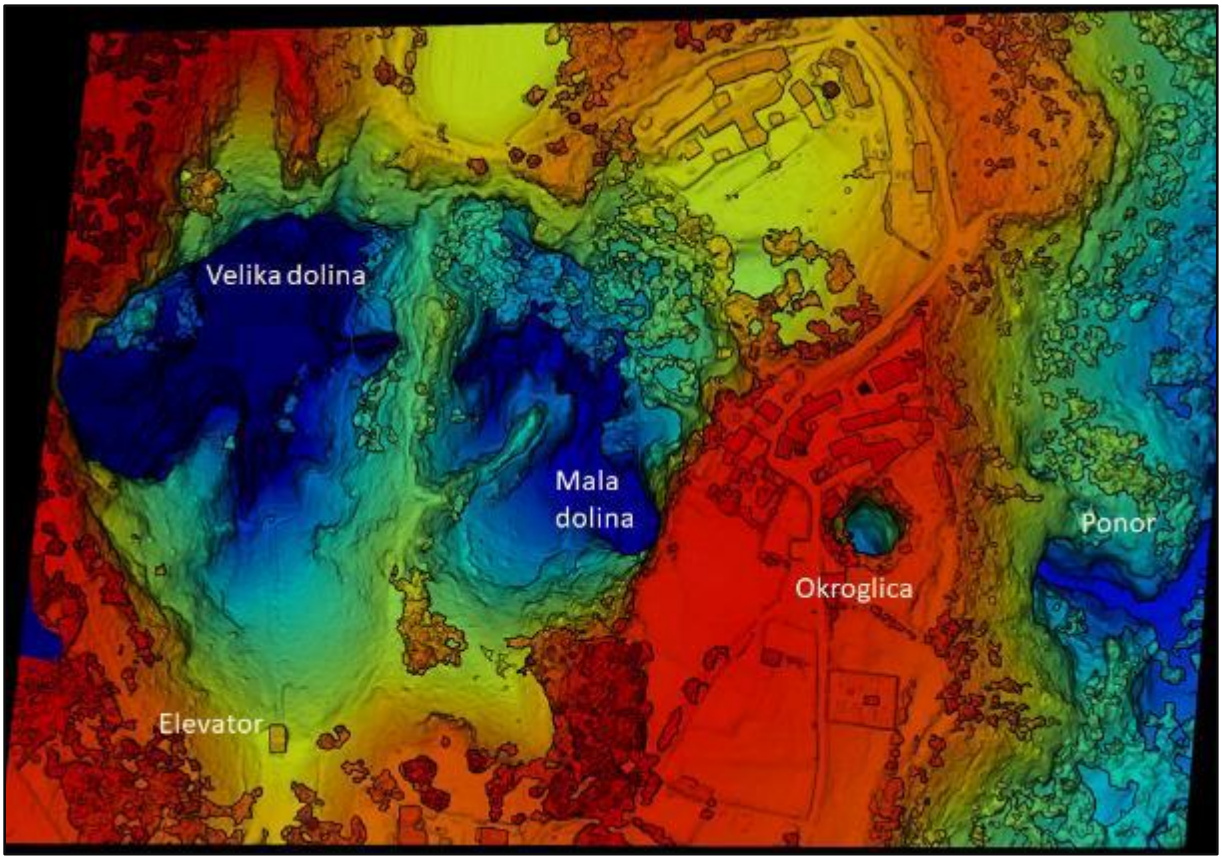


Fig. 4.15: DEM of ponor and collapse dolines from drone images (Walters & Zupan Hajna 2020).

In the collapse dolines above Škocjanske Jame and the Divača Karst, intense collapse occurs only where caves intersect tectonically fractured zones within the height range of regular flooding (Mihevc 2001, 2009; Gabrovšek & Stepišnik 2011). In several cases, collapse chambers have formed at different levels along the same fractured zone, indicating that collapse is not merely due to mechanical failure of fractured rock, but a specific speleogenetic process. Flood oscillations promote water intrusion and dissolution along fractures, gradually widening them and destabilizing the rock. Collapse material is then removed by both, chemical and mechanical erosion. Once chambers rise above the flood zone, the process slows or stops, often due to flowstone sealing fissures. The formation of large collapse chambers and dolines is thus the result of multiple interacting factors and cannot be explained by simple ceiling failure alone. This process represents a distinct form of cave development and surface geomorphology.

TIHA JAMA

Tiha Jama is a dry passage in the Škocjanske Jame, located approximately 50 m above the active river flow in Šumeča Jama. It extends (Fig. 4.16) from Müllerjeva Dvorana (Müller Hall, 308 m) through Velika Dvorana (Great Hall, 333–323 m), Labirint (Labyrinth, 323–310 m), and Podorna Dvorana (Collapse Hall, 315 m), terminating in Paradiž (Paradise, 343 m). It is connected to the collapse doline Globočak via an artificial tunnel (Umetni rov; entrance at 365 m). The listed elevations refer approximately to the bottoms of the passages.

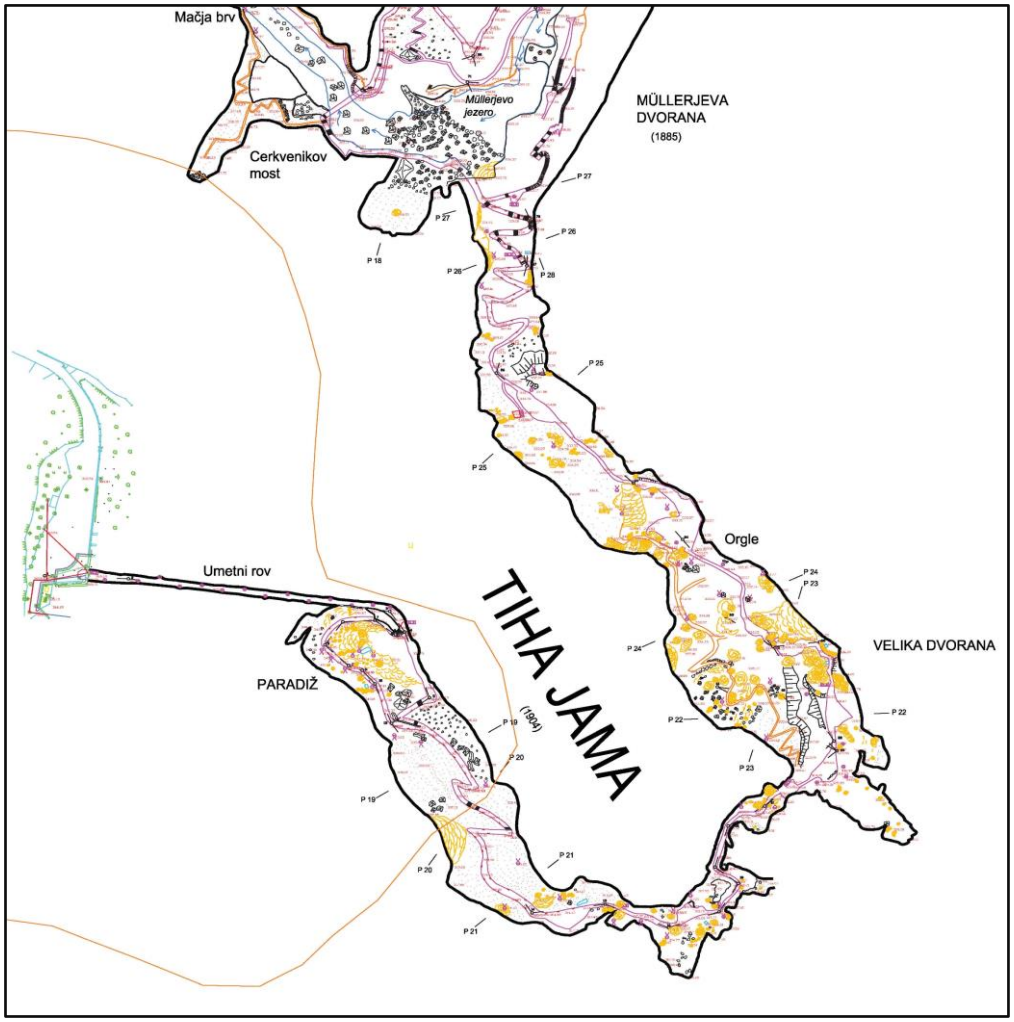


Fig. 4.16: Ground plan of Tiha Jama, with locations of Velika Dvorana, Labirint, Podorna Dvorana, Paradiž and artificial tunnel (Umetni rov) to collapse doline Globočak.

The passage was initially developed in bedded Cretaceous limestone, transitioning downstream into tectonically deformed Paleogene limestone (Gospodarič, 1983, 1984). Its morphology is shaped by thin-bedded limestone and north–south faulting, which fracture the ceiling and walls. The passage floor is entirely covered by clastic sediments, primarily silts, sands, and gravel from flooding events.

Tiha Jama is genetically complex (Gams, 1967/68; Mihevc, 2001) due to the lithological transition and the presence of various cave development phases – from phreatic conduits (visible in ceiling and wall features) to collapse chambers and sediment-filled passages. The longitudinal profile

shows a gradual elevation drop with erosional channels cut into collapse material, especially in the Velika Dvorana.

PALEOFLOODS AND SEDIMENTS

Floods usually reach up to 30 m. The largest known flood in the previous century raised the groundwater table level for 132 m. The historically recorded flood levels in Mullerjeva dvorana are presented on Fig. 4.17.

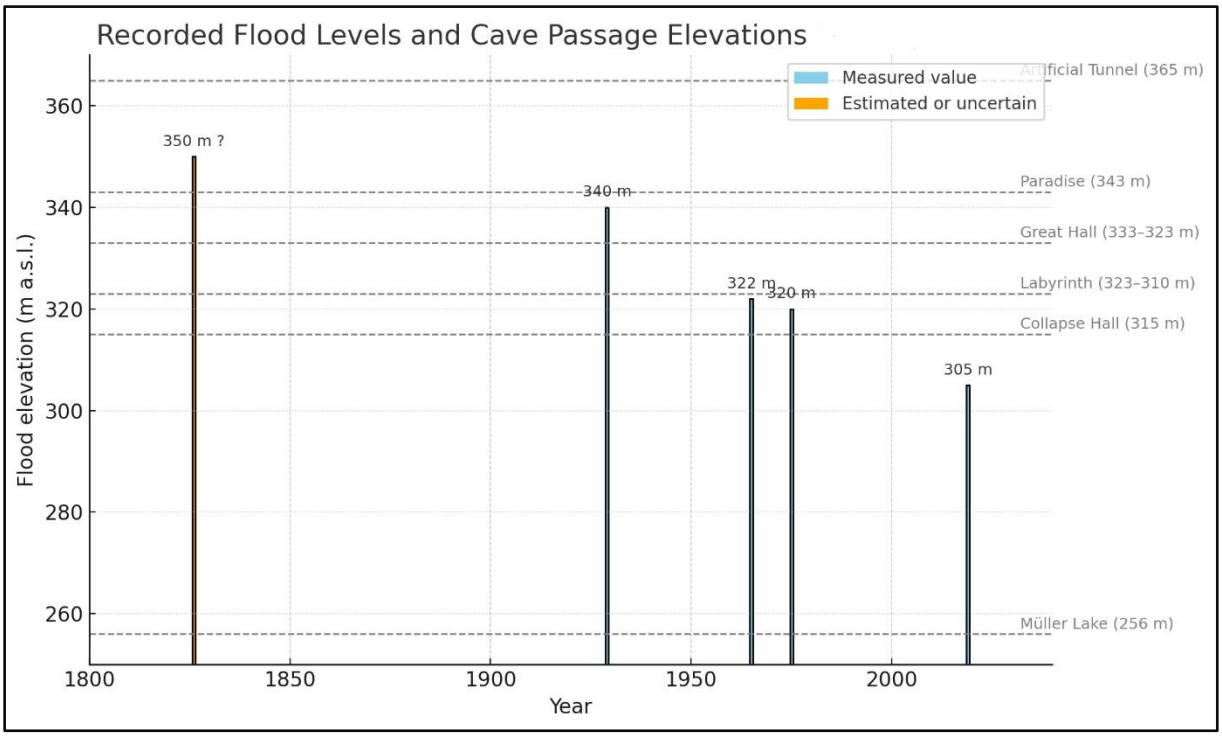


Fig. 4.17: Historically recorded flood levels in Mullerjeva Dvorana and levels of the lowest passages bottoms in parts of Tiha Jama.

The Reka and its tributaries form a typical allogenic sinking river system that transports alluvium into the Škocjanske Jame. Along the riverbed, from the ponor to the siphon, various types of clastic sediments are deposited. Flysch sandstone pebbles predominate throughout the system, while limestone pebbles become dominant near the siphon (Kranjc, 1989). Flood-deposited clays and silts are composed mainly of quartz, plagioclase, and clay minerals (Zupan Hajna, 1995). A fluvial sediment profile located at 334 m at the entrance of Tiha Jama consists of quartz, muscovite, and clay minerals, which correspond to the composition of modern flood loam. In 2024, the speleothem samples were sampled in Tiha Jama to date flood events, analyses are in progress.

Relict deposits in Černigojeva Dvorana (334 m) include chert (Gospodarič, 1984), flysch sandstone, and limestone pebbles. Similar sediment types with comparable mineralogy have been found in unroofed caves above Škocjanske Jame and are dated to approximately 5 million years (Zupan Hajna *et al.* 2024).

KRAŠKI ROB (KARST EDGE)

The western edge of the Kras Plateau and the northwestern margin of the Podgorski kras (Podgora Karst), known as the Karst Edge (Kraški Rob), rises above Trieste Bay (Fig. 4.18). This prominent geomorphic step formed where carbonate layers were thrusted over flysch rocks (Placer *et al.* 2010). The term Kraški rob generally refers to the escarpment of vertical cliffs and steep carbonate slopes that extends along the entire underthrust belt, from the Timavo River mouth to Učka Mountain in Croatia. These cliffs mark the boundary between the Kras and Čičarija and the flysch terrain of the Istrian and Trieste coastal areas. The name Kraški rob came into common use only at the end of the 20th century and now specifically refers to the cliffs above the Osp and Upper Rižana river valleys.

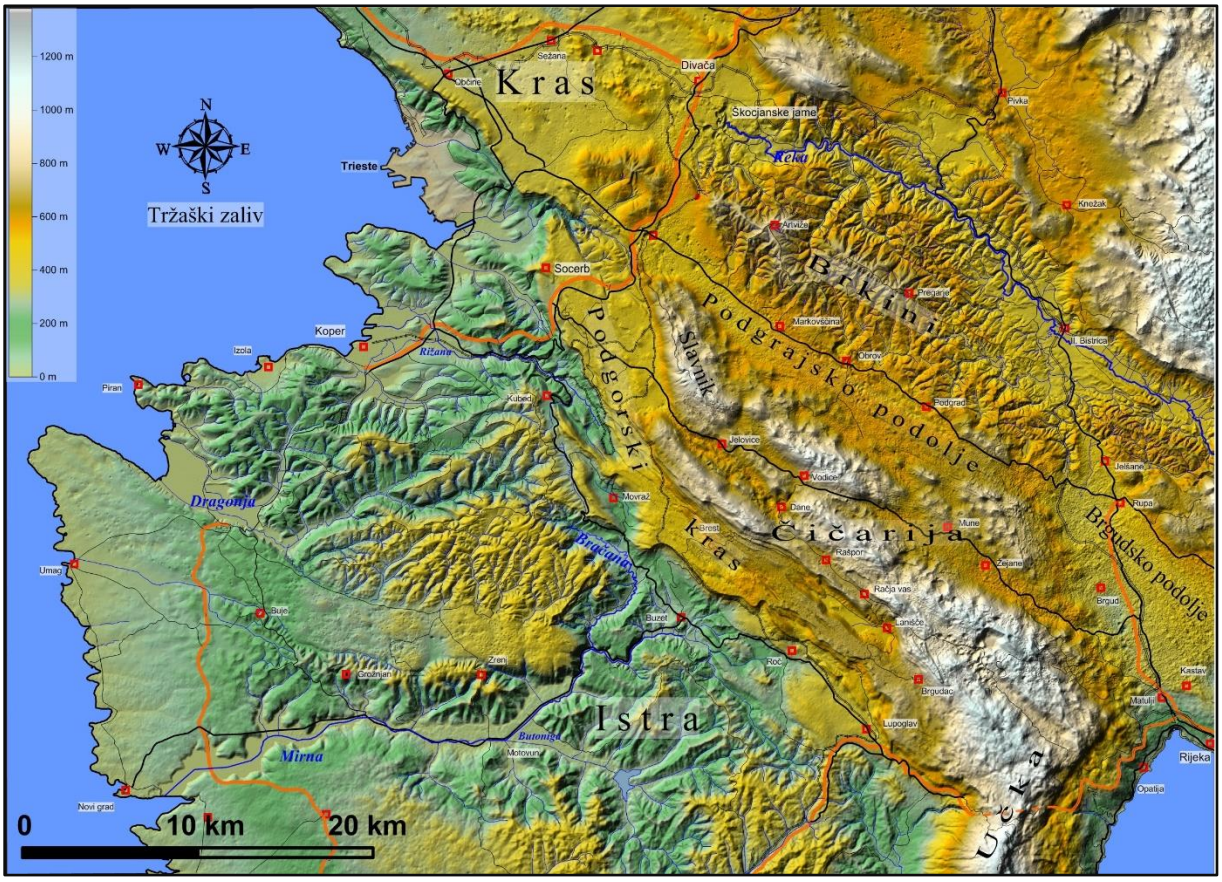


Fig. 4.18: Kraški Rob (Karst Edge) – the western Kras Plateau and northwestern Podgora Karst rising above Trieste Bay.

Behind the edge the Podgorski Kras is located, a plateau about 5 km wide, extending NW–SE along the foothills of Slavnik Mountain. Its elevation ranges from 500 to 450 m, with a gently inclined surface dissected by numerous dolines and unroofed caves (Zupan Hajna *et al.* 2020). The plateau descends through several structural steps to the flysch-filled Rižana and Ospaska Reka valleys. The karst springs of the Rižana and Osapska rivers, with peak discharges of several cubic meters per second, emerge below the structural edge at 50–100 m. More than 90 caves are known on the plateau, the deepest reaching 150 m. The unroofed cave in the Črnotiče Quarry, situated at the plateau's edge, contains allogenic cave sediments dated by paleomagnetic analysis to >1.77–>5 Ma (Zupan Hajna *et al.* 2020).

The village and fortress of Socerb are named after a 3rd-century hermit and martyr, St. Socerb, who lived in a cave later transformed into a pilgrimage church. St. Socerb is also the patron saint of

Slovenian cavers. The fortress was built after 1382, following the Habsburg acquisition of Trieste from the Venetian Republic. Trieste, a key port in the Austro-Hungarian Empire, began its rapid expansion in 1719 when it was declared a free port. Due to increasing water demand in the 19th century, deep karst shafts were explored, including Labodnica (Abisso di Trebiciano) in 1841. This cave, at 320 m deep, was the world's deepest known cave for 60 years. The railway from Vienna reached Trieste in 1857. In 1893, the Deutschen und Österreichischen Alpenverein established a local section focused on speleology. This society explored Škocjanske Jame and many others, publishing maps and assisting many scientists and explorer such as Alfred Penck, Jovan Cvijić, E.A. Martel, Franz Kraus, and more. Pioneers like Anton Hanke, Joseph Marinitsch, Friedrich Muller, and Karl Moser played key roles. Italian and Slovene caving societies soon followed. Today, Trieste is likely the city with the highest number of caving societies in the world.

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ABSTRACTS
IZVLEČKI

*sorted according to the family names of the first authors
**for any grammatical errors is responsible the corresponding author
*razporejeno glede na priimke navedenih prvih avtorjev
**za slovnične napake je odgovoren glavni avtor prispevka

The Tej cyclone flash flood recorded in an underground river in SW Dhofar, Oman
Zapis ciklonskih bliskovitih poplav skozi jamo v Omanu

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The cave system connecting Sha'at Sinkhole and Ain Nakbat Spring is a major through-cave in SW Dhofar, close to the border with Yemen. The Sha'at Sinkhole is located at an altitude of 838 m, downstream of a wadi draining a semi-impermeable catchment area of 5 km^2. A large conduit 3.2 km long, which includes an 800 m sump that has not yet been crossed, leads to the Nakbat Spring, almost 400 m below. Due to the semi-arid environment on the edge of the Rub al-Khali desert, the wadi upstream of Sha'at is dry most of the year, and Ain Nakbat only discharges a few L/s at low water. Recharge takes place in July and August during the Khareef, with occult rainfall from the very attenuated edge of the monsoon. Exceptionally, Indian Ocean cyclones can reach this region, bringing heavy rainfall and flooding with less than decadal frequency. The temperature and water level recorded at the Nakbat Spring over a year using a Reefnet datalogger, provide an insight into the Khareef's recharge, and in particular the passage of cyclone Tej in October 2023, which dumped 250-300 mm in 36 h. Observed values from a dozen cumulative rain gauges, combined with spatial analysis of satellite weather grids (ERA5, GPM) with 30–60 min time steps, enable us to reconstruct the spatial field of the rainfall event and its chronological sequence. Comparison of the rainfall and the data at the spring allows us to characterize the effect of the Khareef recharge over a 6-week period, with a lag time of 3 days and propagation velocities through the cave system of around 43 m/h. During cyclone Tej, the Nakbat Spring experienced almost instantaneous flooding of more than 1 m at the outlet, with a lag time of 8 h decreasing as the event progressed, and propagation velocities increasing from 200 to 1300 m/h under the effect of pressure transfer once the conduits were flooded.

Keywords: *Flashfloods, cyclone, cave hydrodynamic, flooding*
Ključne besede: *Hudourniške poplave, ciklon, hidrodinamika jam, poplavljanje*

From atmosphere to cave: tracing the journey of the climate signal in Nova Grgosova Cave, Croatia
Od atmosfere do podzemlja: sledenje podnebnim signalom v jami Nova Grgosova (Hrvaška)

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Geochemical properties of speleothems offer valuable insights into past climate and environmental conditions, sometimes at high, sub-annual resolution. However, the climate signal preserved in speleothems is not always straightforward to interpret, as it may be altered by a range of complex processes occurring in the soil, epikarst, and cave atmosphere during its journey from the atmosphere to the speleothem. To ensure reliable palaeoclimate reconstructions, site-specific cave monitoring campaigns are typically carried out. At Nova Grgosova Cave in Croatia, an ongoing, nearly three-year-long cave monitoring campaign has been undertaken. This mid-latitudinal continental cave is developed in biolithic carbonate bedrock characterized by high primary porosity, limited or absent primary discontinuities, and moderate secondary porosity. A comprehensive suite of parameters has been monitored, including the cave air microclimate parameters, along with the elemental, isotopic, and organic composition of precipitation, soil water, and drip water. In this presentation, we provide an overview of the data collected to date, with a particular focus on interpreting the timing of recharge.

This is accomplished by integrating a large dataset of drip rate measurements with daily-resolution meteorological data. Our findings not only provide critical context for the robust interpretation of speleothem-based palaeoclimate records at this site but also shed new light on the complex role of the soil and epikarst zones in karst groundwater recharge dynamics.

Keywords: *Cave monitoring, recharge, drip rate, epikarst, Nova Grgosova Cave*
Ključne besede: *Opazovanje jam, napajanje, kapljanje, epikras, jama Nova Grgosova*

Knowledge gaps and challenges towards an open-access European map of groundwater vulnerability in karst regions

Vrzel v znanju in izzivi na poti k odprto dostopnemu evropskemu zemljevidu ranljivosti kraških vodonosnikov

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Karst aquifers are subject to fast transport or by-pass infiltration of dissolved compounds released on the top surface. Nevertheless, in Europe, more than 50% of the land in karst regions (defined by WOKAM) is used for agriculture (identified by CORINE Land Cover). There should be a great awareness of the possible leaching pathways in karst regions and special attention on the local agricultural practices. However, specific guidance for growers on agriculture practices or on how to use the monitoring data generated in karst aquifers to direct best management efforts is still missing. Generating such guidelines is complicated by the significant variation in conditions across karst regions (e.g., topsoil depth, land use, karst type), which directly affects groundwater vulnerability. It is, therefore, imperative to identify the most vulnerable sites for developing appropriate agricultural guidelines and efficiently steering stewardship activities. Creating a comprehensive, reliable and open-access map of karst groundwater vulnerability may represent a cornerstone for developing targeted best management practices for pesticide use in these sensitive regions, focusing first on the intrinsically most vulnerable areas. To achieve that vulnerability map, a long and winding harmonisation process is needed, carefully balancing the needs for accuracy, scalability and representativeness with the data availability and the local knowledge of the karst systems. This work is carried out using QGIS 3.40. To obtain a sufficient resolution at the European scale, great care is given to the mapping methods, using robust spatial interpolators, resampling algorithms and an optimal resolution. A thorough assessment of input data must be made, sometimes leading to the choice of a proxy when a parameter is not available at a sufficient resolution on such a large extent. Finally, for the successful integration of local knowledge of karst systems on a continental level, the support of the karst experts network will be crucial.

Keywords: *Groundwater vulnerability, Karst, GIS, Europe*
Ključne besede: *Ranljivost podzemne vode, kras, GIS, Evropa*

Morphological indicators of speleogenesis of selected caves in the Plitvice Lakes National Park (Croatia)

Morfološki indikatorji speleogeneze izbranih jam v Narodnem parku Plitvička jezera (Hrvaška)

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The morphological characteristics of caves are often indicating the conditions and processes of speleogenesis. Sometimes these conditions are spatially and temporally uniform, but sometimes they change and leave different traces in the cave morphology. The aim of this study was to determine the conditions of speleogenesis for selected caves in the Plitvice Lakes National Park in Croatia based on morphological indicators. The Park area is a very well-known karst area, mainly because of its tufa barriers, waterfalls and dammed lakes. The entire drainage system continues with the karst river Korana, which has cut a deep canyon. About 200 caves are known in the area of the park and the exploration is still ongoing. For this study, eight caves in the Korana canyon and its immediate surroundings were selected. The basic approach was to analyse the cave morphology. In addition to considering macromorphological and mesomorphological features and morphometric data, the main method was detailed geospeleological mapping. For each cave, mapping of structural elements, speleogens, water bodies, cave deposits and speleothem formations was carried out. The results indicate that the cave channels were mainly formed by drainage along several formative bedding planes, supported by tectonic influences. Morphology and sedimentary remains indicate pronounced fluctuations in the groundwater level, which in turn was controlled by the change of canyon incision phases and the accumulation of tufa in it. It was found that some caves may have formed (or at least developed in one phase) as an underground bypass of water flow due to the growth of tufa barriers in the river canyon. The formation of some caves and their present-day characteristics were also strongly influenced by the lowering of the karst surface.

Keywords: Caves, speleogens, canyon incision, tufa barriers, Plitvice lakes NP, Croatia
Ključne beside: *Jame, speleogeni, kanjonski vrez, lehnjakove pregrade, NP Plitvička jezera, Hrvaška*

Karstologists on the Trail of the First Hominins in Southern Africa (South Africa and Botswana). Human Origins in Botswana Karst Research Program (*Homini'Karst*)

Krasoslovci na poti prvih homininov v južni Afriki (Južna Afrika in Bocvana). Človeški izvor v programu raziskovanja krasa v Bocvani (Homini'Karst)

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In the northeast of South Africa, not far from Johannesburg, UNESCO has designated a small karst region as the "Cradle of Humankind." This title was not given because the oldest fossils of our lineage were found there, but rather due to the exceptional density of such remains: more than a third of all ancient hominin fossils discovered in Africa have been unearthed in this area! In 2005, we launched an interdisciplinary research program that allowed us to better understand these karst systems and how they function. First, it was essential to place the formation of caves such as Sterkfontein within the broader geological and geomorphological history of Africa. We then focused on studying the fossil-rich infillings, which offered key insights into sediment deposition processes and the taphonomy of bone remains, as well as enabling the development of new dating techniques consistent with these

processes. One major outcome was the proposal of a new dating for the *Australopithecus* specimen known as Little Foot—the most complete to date—found in the Silberberg Grotto. Now dated to 3.7 million years, this finding aligns with the pace of geomorphological evolution, the associated fauna, and the revised dating of other fossil deposits within the cave and nearby sites. These interdisciplinary results now make it possible to compare the evolutionary trajectories of hominin fossils in East and Southern Africa. Furthermore, they open up unprecedented research opportunities: every karst formation in Southern Africa may potentially conceal another fragment of the Cradle of Humankind. Using the South African cave model, we have developed methods and tools to locate such fossil sites among the thousands of known—and yet undiscovered—caves still awaiting study in this vast region. To date, the most promising sites have been found in Botswana. There, we identified not only geological features similar to those of South Africa's fossil-bearing karsts, but also a remarkably high concentration of faunal bones. The discovery of even a single ancient hominin remain in this region would support the hypothesis that nearly the entire African continent could be considered part of humanity's cradle—and would open exciting new prospects for karst research across Africa.

Keywords: *Karst, archaeology, paleontology, hominins, breccia, South Africa, Botswana*
Ključne besede: *Kras, arheologija, paleontologija, hominini, breča, Južna Afrika, Bocvana*

Microclimatic controls on CO_2 dynamics in caves: insights from Samograd Cave (Croatia)

Vpliv mikroklimatskih dejavnikov na dinamiko CO_2 v jamah: primer jame Samograd (Hrvaška)

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This study explores spatial and temporal variations in air temperature and CO_2 in Samograd Cave (Croatia) based on a 3-year monthly monitoring program (2021–2024). Samograd is a morphologically simple cave, with a single 345 m-long, up to 32 m high and 25 m wide passage, some 53 m below the surface. The cave climate shows a seasonal bimodality controlled by its morphology and temperature-induced convective airflow. In winter, cold outside air enters the cave, lowering temperature and CO_2 levels. In summer, reduced ventilation and soil-derived CO_2 input lead to CO_2 accumulation. As a show cave, tourism (spring to autumn) contributes to the CO_2 budget, though to a lesser extent. Air temperature distribution reflects the cave's four-zone structure: (I) a dynamic entrance zone, (II) a transition zone, (III) a cold zone at the passage's lowest point, and (IV) a stable zone. Temperature variability decreases from zones I–III (SD=1.336–1.022°C), with zone III showing winter cold air retention (T=3.2–7.2°C). Zone IV, at the passage's end, due to reduced winter air inflow and highest position, was the most stable and warmest (T=7.7–8.4°C; SD=0.308°C). CO_2 levels follow a similar gradient, peaking in zone III (414–2,487 ppm), where the passage's concave shape traps CO_2. Maximum CO_2 lags peak temperatures by about two months, indicating delayed soil-to-cave transfer or gradual accumulation in stagnant air conditions. CO_2 concentrations progressively increased, tracking global trends, yet shaped by morphology and ventilation. We hypothesize that vadose zone caves act as CO_2 conveyor belts moving CO_2 generated in soil to the atmosphere, potentially affecting CO_2 dynamics.

This work has been supported by Croatian Science Foundation under the project "Dynamics and distribution of CO_2 in karst vadose and epiphreatic zone (CARDIKARST)" (IPS-2022-02-2260).

Keywords: *Cave microclimate, CO_2, temperature-driven circulation*
Ključne besede: *Mikroklima jam, CO_2, temperaturno pogojeno kroženje*

Exploiting karst water resources in the face of climate change crises; the Creuse valley aquifer system (Jura)

Trajnostno koriščenje kraških vodnih virov ob podnebnih spremembah: primer vodonosnika v dolini Creuse (Jura)

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Karst is a dynamic environment, highly sensitive to climatic and environmental variations, which record these changes in their morphologies and structures. In the Franco-Swiss Jura, the karst plateau, located along the overthrust fold of Lomont–Mont Terry, is a key site for understanding landscape evolution from the Little Ice Age (LIA) to the present. As a mid-altitude karst region, this area developed a unique territory through optimized water management, supporting agriculture, industry, and urbanization. As early as the 19th century, scientists such as Cuvier, Thurmann, Agassiz, and Marcoux precisely described its geological and environmental framework. Hydraulic developments helped sustain the local economy during the climatic crises at the end of the LIA. From the 1950s onward, territorial expansion increased water demand, requiring sustainable and high-quality resources. Research was conducted by the BRGM (French Geological Survey), regional water authorities, and speleologists to identify new water sources, particularly through tracer tests and karst network exploration. The Creuse Valley karst system was thus identified as a viable solution. However, droughts and severe floods exposed the limitations of small aquifers and the need for reliable infrastructure. A development program was implemented to reduce pollution and establish sustainable water catchment systems, meeting the needs of local populations, agriculture, and industry. Today, climate warming worsens prolonged seasonal droughts, while floods degrade water quality. This presentation outlines the exploitation of this vital resource for 10,000 inhabitants and the challenges posed by the current climatic context.

Keywords: *Karst aquifer, speleological exploration, water ressources management*
Ključne besede: *Kraški vodonosnik, speleološko raziskovanje, upravljanje vodnih virov*

Karst Mountains of Euro-Mediterranean and their groundwater potential in a changing climate

Kraška gorovja Evro-sredozemlja in njihov potencial podzemnih voda v razmerah podnebnih sprememb

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Karst springs are groundwater systems that provide drinking water to a significant portion of the population living in countries around the Mediterranean. A significant part of the Alpine-Himalayan mountain belt is composed of Mesozoic and Cenozoic carbonates, and many karst aquifers, especially in the Mediterranean belt, are fed by these mountainous systems. Changes in the hydrodynamics of mountainous karst aquifers during climate change threaten the surrounding ecosystems that depend on these systems. Hydrological models are needed to predict the impact of climate change on groundwater. In order to apply hydrological models, high quality data with high spatial and/or

temporal resolution are needed. Difficulties in data accessibility or organisation have hampered the progress in karst research and the elucidation of karst processes in large-scale hydrological studies. Based on this, the aim was to improve data accessibility for the Euro-Mediterranean region in order to identify and understand karst resources and the impacts of climate change. Within the scope of this study, a large number of karst spring discharge data spread over a wide geographical area including the Atlas, Pyrenees, Apennines, Alps, Dinarids, Carpathians, Taurus and Zagros were accessed. In these regions, a spring discharge dataset has been created in which the data available in the open access of the relevant institutions are collected. It is expected that the dataset compiled within the scope of this study will be frequently used in local or regional modelling studies, provide more efficient and effective management of karst groundwater and encourage international and interdisciplinary cooperations.

Keywords: *Karst hydrology, snow, groundwater, climate change*
Ključne besede*: Kraška hidrologija, sneg, podtalnica, podnebne spremembe*

Impact of hydroclimatic extremes on karst water resources and water quality: contribution of continental and regional analyses

Vplivi hidroklimatskih ekstremnih pojavov na kraške vodne vire in kakovost vode: pomen celinskih in regionalnih analiz

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In hydrology, the analysis of extremes helps to better assess the resilience of hydrosystems to climate change. Dry extremes or exceptional floods are considered in relation to normality or a standard range of variability. Firstly, in the case of karst basins, it is interesting to question their hydrological variability, compared with other types of aquifers. Using hydrological signatures—metrics that quantify various aspects of hydrological behaviour—we have highlighted the importance of inter-basin groundwater flows and surface water/groundwater interactions in karst basins, compared with non-karst basins. These flows influence therefore the regulation of karst hydrosystems, but also their hydrological response during flood events, which justifies adapting conventional hydrological models. Secondly, the question of extremes arises in terms of long-term hydroclimatic trends and their impact on water resources in karst systems. A recent study we carried out on long-term hydrological dataset (over 40 years) from around 50 karst springs in Europe enabled us to investigate changes in flow rates, seasonality and low and high water conditions. Results show that the sensitivity of karst aquifers to climate change does not depend on their degree of karstification. The evolution of trends for highest and lowest flows over the different periods indicates potential process changes in the last 20 years, with springs that exhibit positive high flow and negative low flow trends. This is a strong indication for changes in the partitioning of concentrated and diffuse recharge, suggesting alterations in precipitation patterns. A third question concerns physico-chemical extremes, and in particular the impact of climate change on water quality. A focus on the Jura massif shows that the nitrate peaks observed during autumn floods are directly linked to the intensity of previous drought periods. A more detailed analysis of the processes involved shows that the origin of these flushes, generally attributed to nitrogen residues in the soil during dry periods, is not the result of a by-pass from the soil, but is linked to the mobilisation of older water already stored in the infiltration zone. These three questions are addressed by means of examples of large-scale analyses (continental and regional), which can then be used to work more locally on the processes involved, and to propose valuable insights for assessing the resilience of hydrosystems in the future.

Keywords: *Extreme, hydrological variability, large scale, trends*
Ključne besede*: Ekstremno, hidrološka spremenljivost, velika merila, trendi*

Wildfire hazard and vulnerability assessment in the cross-border karst landscape under climate change

Ocena nevarnosti in ranljivosti požarov v naravi v čezmejni kraški pokrajini v kontekstu podnebnih sprememb

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The global climate change is not a future problem. Its contribution is already evident in the increased frequency of natural hazards worldwide, and the Kras/Carso Plateau on the border between Slovenia and Italy is no exception to this trend. The large wildfire of 2022 underlined the need for adaptive strategies and enhanced the cooperation between both countries. Such measures are essential to reduce wildfire risk and strengthen regional resilience and ecological health of this cross-border area. In this context, within the KarstFirewall 5.0 project, we assessed and mapped wildfire hazard probability and vulnerability under current (1981–2010) and near-future (2011–2040) climate conditions. Specifically, we selected 11 predictors reflecting anthropogenic, environmental, climatic and topographic characteristics to determine wildfire hazard probability using Maxent modelling and to assess wildfire vulnerability employing Multi-Criteria Decision Analysis (MCDA). We used past wildfire ignition points to train and test the Maxent models and to validate the MCDA-based vulnerability assessment. Maxent identified 16% of the area as significantly or extremely high hazard under current climate conditions, while vulnerability mapping classified 93% of the area as significantly or extremely high vulnerable. Under the near-future climate scenarios, hazard is expected to decrease, while the extreme vulnerability areas are predicted to increase by 5%. Despite using the same input predictors, the results differed significantly in terms of the area distribution of the high value classes. This is due to the fact that Maxent-based hazard analysis emphasizes wildfire likelihood based on past events, while MCDA-based vulnerability analysis distributes high-vulnerable areas more evenly using static factors. Furthermore, both analyses identified distance to roads and land use as key predictors. The fact that a significant proportion of fires ignited within 50 meters of roads (67.4%), railways (14.1%) and settlements (16.2%), highlights the important role of anthropogenic factors in wildfire risk. On the other hand, wildfires occurred most frequently in grassland and overgrown areas (39.8%) and deciduous forests (36.9%), underscoring the importance of fuel availability. Overall, the results provide a valuable foundation for future wildfire risk reduction and management strategies, with each analyses contributing different perspectives into wildfire dynamics in the region.

Keywords: *Wildfire, natural hazards, vulnerability, Maxent, Multi-Criteria Decision Analysis, GIS*
Ključne besede: *Požar v naravi, naravne nesreče, ranljivost, Maxent, večkriterijsko odločanje, GIS*

Flash flood event recorded by atmospheric changes in the Bue Marino cave (Dorgali, Italy)

Hudourniška poplava zaznana preko atmosferskih sprememb v jami Bue Marino (Dorgali, Italija)

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The central-eastern part of Sardinia is characterized by significant carbonate banks that reach the Tyrrhenian Sea with imposing cliffs. Under specific meteorological conditions, heavy rainfall can generate significant flood events within the karst systems present in the area, activating fluviokarstic

canyons. The Bue Marino tourist cave (Dorgali) can also be affected by important flash flood phenomena as it is hydrologically connected to the vast Codula Ilune karst system that extends for over 70 km in across territory of Baunei, Urzulei and Dorgali. Recently, the physical monitoring carried out in the cave by the Italian National Research Council (CNR) as part of the Showcave Project, has highlighted unusual and significant oscillations of the environmental parameters, in particular for CO_2 and temperature. Such oscillations have been related with the occurrence of a flood event in the cave (confirmed by water marks observed after the event) and were found more significant than those induced by tourist attendance. Therefore, research is underway aimed at identify the hydrological and meteorological conditions able to generate flash flood events in the Bue Marino cave, the magnitude of floods that might occur and the potential implications for tourist safety.

Keywords: *Flash flood, cave atmosphere, showcave, safety*
Ključne besede*: Hudourniška poplava, jamsko ozračje, turistična jama, varnost*

Geomorphological mapping and terrestrial LiDAR scanning of speleogenetic features in the cave under Babji Zob, Julian Alps, Slovenia

Geomorfološko kartiranje in LiDAR-skeniranje speleogenetskih oblik v jami Babji zob, Julijske Alpe, Slovenija

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Terrestrial laser scanning (TLS) has emerged as a valuable method in geomorphological fieldwork, offering high-resolution spatial data for the examination of cave morphology and speleogenesis. In the Babji Zob Cave (Reg. Nr. 125), situated on the Jelovica Karst Plateau in the Julian Alps of Slovenia, a terrestrial laser scanner was used to generate a comprehensive 3D dataset of the cave's internal structure. A total of 71 scan positions were acquired to document the full 350-meter length of the cave. The resulting 3D reconstruction supports the analysis of speleogenetic geomorphology as well as selected morphometric measurements. Based on this data, a simplified geomorphological map highlighting the cave's medium-scale speleogenetic features was created. The aim of the research was to correlate features that may share a common origin and could be related to hypogene speleogenesis. This included analyzing the connections between floor features such as feeder channels and vertical shafts, wall features like niches and wall channels, and ceiling features such as multi-cupolas, ceiling pockets, and vertical shafts/outlets. Since cave genesis in this area occurs at different stages of development, the potential overprinting of features by epigenic speleogenesis was also taken into consideration.

Keywords: speleogenetic features, LiDAR scan, geomorphological mapping, hypogene speleogenesis, Julian Alps
Ključne besede*: Geomorfološko kartiranje in LiDAR-skeniranje speleogenetskih oblik v jami Babji zob, Julijske Alpe, Slovenija*

Direct Numerical Investigation of Flow Dynamics in Karst Conduits

Neposredna numerična raziskava dinamike toka v kraških kanalih

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Karst aquifers, with their intricate conduit networks, play a crucial role in groundwater flow and contaminant transport. Their complex geometry, characterised by branching conduits, varied cross-sections, and notable wall roughness ($k/D = 10^{-1}$), presents challenges in predicting flow patterns, friction losses, and turbulence onset. This work examines flow behaviour in representative karst conduits to identify key geometrical and fluid mechanical parameters, such as average cross-sectional areas, cave centrelines, friction factors, and velocity distributions, using direct numerical simulations over a broad range of flow conditions ($Re = 1–10^3$). These variables are critical for upscaling methods, enabling simulation of entire karst networks without resolving every conduit in detail. A combination of finite-volume and spectral element methods is employed: finite-volume for laminar flows in complex geometries and spectral element methods for capturing turbulence at higher Reynolds numbers. Conduit geometries are reconstructed from high-resolution LiDAR scans, preserving rough walls, branching, and variable cross-sections. An immersed boundary model with a ray-tracing algorithm ensures accurate boundary representation and enforcement of boundary conditions. The numerical framework is validated against classical problems, including laminar and turbulent pipe flow, where the immersed boundary method accurately reproduces friction factors and velocity profiles. Simulations in a wavy channel show that laminar flow persists in certain conduit sections, yielding smooth centreline velocities and predictable friction losses. However, irregularities disrupt the flow field, introducing spatial variations absent in smooth-channel conditions. The results further reveal an earlier-than-expected transition to turbulence at $Re \leq 1000$, suggesting that standard empirical correlations, such as the Moody chart and Darcy-Weisbach formulations, may not fully account for the effects of complex conduit geometry. The intricate structure and roughness of karst conduits significantly alter flow dynamics, deviating from classical behaviour. Extracting quantitative data—velocity profiles, turbulence statistics, and friction factors—remains challenging, necessitating alternative approaches to capture key flow characteristics in karst systems effectively.

Keywords: *Karst conduit, transitional flow, simulation*
Ključne besede*: Kraški kanal, prehodni tok, simulacija*

Sustainability of drinking water supply in a Mediterranean city in the context of climate change. Study case: Montpellier (France) and Beni Mellal (Oum Er Rabia basin, Morocco)

Trajnostna oskrba s pitno vodo v sredozemskih mestih ob podnebnih spremembah: primer Montpellierja (Francija) in Beni Mellala (povodje reke Oum Er Rabia, Maroko)

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The Mediterranean basin is particularly vulnerable to climate change. These changes lead to disruptions in the hydrological cycle, potentially impacting groundwater resources and their 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 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 hydrogeological catchments of the Asserdoune karst spring, located north of Morocco, is actively used to supply Beni Mellal (280,000 residents in 2024) with drinking water, the Lez one, situated I South of France, is used to supply Montpellier (more than 300,000 residents). The main objective of this research is to assess eventual long-term trends in the climatic (rainfall, temperature, potential evapotranspiration) and hydrological variables (spring and river discharges); a focus on the interrelationship between these different parameters is also performed to understand the hydroclimatic trend and temporal evolution of this highly anthropized aquifer. The analysis combines measurements of local soil and hydrogeological variables, with the climate reanalysis ERA5 since 1940 (for Morocco), COMEPHORE since 1997 and SAFRAN since 1958 (for France). The trend analysis results indicated a strong increase of temperature and evapotranspiration associated, but no significant changes in precipitation totals from the different datasets.

Keywords: *Mediterranean basin, karst, water ressource, climate change*
Ključne besede*: Sredozemski bazen, kras, vodni vir, podnebne spremembe*

Geomorphology of caves and their ancient use on the Sheikh Said cliff, Tell El Amarna Area, Egypt

Geomorfološke značilnosti jam in njihova pretekla raba na klifu Skeikh Said, območje Tell El Amarna, Egipt

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The study area is Sheikh Said Cliff in the northern part of the Tell El-Amarna archaeological site, which is located in the southern part of Minya Governorate, Upper Egypt. Geological structure is represented by the Minya Formation, which is primarily characterized by the Eocene limestone that is affected by several structural features, especially faults and folds. There are also large amounts of sedimentary deposits ranging from the Middle Eocene and Pleistocene to the Holocene. Tell El-Amarna area is an important area due to various activities that ancient Egyptians performed in this karstic area. In addition to numerous naturally developed karst caves, the Sheikh Said Cliff features many hand-dug caves, which were used as cemeteries, and due to the harder accessibility, they had an important protective role. Ancient people also inhabited some caves and stored crops in them. This research aims to monitor naturally developed caves in the cliff, study the factors of their formation during the past climatological and hydrological conditions, and examine the role of geological structure. The goal is also to characterize the areas with man-made caves. We also aim to study the morphological characteristics of these caves and classify them according to their morphological and genetic features, uses, and stages of their geomorphological chronology. We expect that natural caves developed in the areas with more soluble rocks, along fractures and bedding planes, whereas man-made caves are more characteristic for softer rocks (which are easier for digging) and also locations, which were more convenient for their human use. This research will improve the knowledge about the karst geomorphology of the area which was not well studied before.

Keywords: *Karst geomorphology, geology, caves, human activities, Tell El Amarna, Egypt*
Ključne besede*: Gomorfologija krasa, geologija, jame, človekove dejavnosti, Tell El Amarna, Egipt*

Dispersion and deformation of a mixing front in heterogeneous media: reaction hotspots nad the propagation of karst

Razpršitev in deformacija mešalnega čela v heterogenem mediju: reakcijska žarišča in zakrasevanje

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Heterogeneity of mixing fronts leads to dispersion, mixing and reaction hotsports that facilitate the propagation of karst. We investigate the dispersion and deformation of a front in heterogeneous porous media. Mixing and reaction hotspots are related to regions of maximum interface deformation. We analyze the deformation process and focus on a line that disperses and deformes.

Keywords: *Karst, deformation, mixing rates*
Ključne besede*: kras, deformacije, histrosti mešanja voda*

Modelling flow and transport to assess the influence of subsurface geometry on Alpine karst aquifer vulnerability

Modeliranje pretoka in transporta za oceno vpliva podpovršinske zgradbe na ranljivost alpskega kraškega vodonosnika

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Karst areas are important drinking water resources whose purity must be guaranteed. Most methods for assessing vulnerability consider it to be constant in time and space. This is a simplification that needs to be extended, as the behaviour of an aquifer also depends on its structure and the hydrological conditions. The heterogeneous underground drainage network can lead to unimpeded and rapid flow, which favours the contamination of springs. Often the unknown subsurface drainage pathways can only be assessed by studying the response of the discharge parameters to a precipitation event or by exploring caves. Therefore, the behaviour of an Alpine karst system was investigated by numerical modelling using simple geometries found in Alpine karst systems. The results show that the structure of the conduit system and the hydrological conditions are responsible for the discharge behaviour. In summary, three different characteristics of the simple models could be recognised: (1) discharge and concentration signals are neither lowered nor delayed in a model with a single vertical conduit; (2) discharge and concentration signals are lowered but not delayed in a model with a constriction (e.g., due to a sediment plug) and (3) discharge and concentration signals are lowered and delayed in a model with a reservoir. The applicability of these simple models to natural conditions was demonstrated using data from a tracer experiment.

Keywords: *Alpine karst system, numerical flow and transport modelling, vulnerability, overflow, MODFLOW 6, tracer test*
Ključne besede*: Alpski kraški sistem, numerično modeliranje pretoka in transporta, ranljivost, prelivanje, MODFLOW 6, test s sledilom*

Preliminary assessment of groundwater recharge in karst areas using the mGROWA-SI model

Preliminarna ocena napajanja podzemne vode na kraških območjih z uporabo modela mGROWA-SI

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The mGROWA model is a deterministic, grid-based distributed hydrological water balance model. Model simplifies hydrological processes by approximating fundamental hydro- and thermodynamic principles aligned with the spatial resolution typically available in hydrological datasets. mGROWA model integrates a detailed simulation of the soil water balance and runoff formation while distinguishing between surface and subsurface flow components, such as groundwater recharge. The runoff separation on consolidated rocks is made with the use of BFI values. These were calculated as the ratio of mean annual groundwater discharge to total discharge, using the MoMLR method based on long-term monthly low flows, in karst with the correction using the Kille method. The spatial BFI distribution was made with GIS to merge it with various hydrogeological site characteristics.

In our study, we investigated groundwater recharge estimation in karst aquifers using the mGROWA-SI model. The catchment area of the Unica springs, a binary karst aquifer system covering an area of approximately 820 km^2, was chosen as the test area. In the GROWA-SI model, the BFI values in the individual cells of the catchment area are determined on the basis of the hydrogeological properties of the rocks. For the Unica catchment, these values range between 0.11 and 0.97. The mean value of 0.44 differs significantly from the BFI value of 0.58, which was calculated using hydrological analysis methods based on long-term discharge data from the Unica springs. In order to evaluate the differences in BFI values for different hydrogeological rock types, the comparison was extended to three smaller and hydrogeologically limited subunits of the Unica catchment consisting of different rock types (well karstified limestones, poorly permeable dolomites with a surface drainage network, very poorly permeable flysch with intergranular aquifers of low yield in alluvial deposits of the surface stream). We compared the BFI values used in the mGROWA-SI model with the values calculated by hydrological analyses at the gauging stations draining the above-mentioned smaller areas. The obtained differences indicate a great diversity in the functioning of the aquifers and the division into direct and base flow, which depends not only on the hydrogeological rock types in the catchment area, but also on other factors. These are preliminary results, and further analysis is planned to refine the interpretation of BFI variability across different hydrogeological settings. In the current phase of research, the possibility of including additional criteria and methods for determining the proportion of groundwater recharge in the mGROWA-SI model is being examined.

Keywords: *Groundwater recharge, mGROWA-SI, water balance model, karst, Slovenia*
Ključne besede: *Napajanje podzemne vode, mGROWA-SI, model vodne bilance, kras, Slovenija*

Investigation of the phreatic karst zone using magnetotelluric measurements

Preučevanje freatične cone v kraškem okolju z uporabo magnetoteluričnih meritev

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The phreatic zone (water-saturated zone) plays a key role in groundwater dynamics in karst systems. In the Alps, delineating the top of the phreatic zone is difficult due to limited access, which is why

assumptions often have to be made for hydrological models. Only springs and rare deep caves reaching siphons can provide information about the vadose–phreatic transition. The springs provide localised data and reflect minimum heights. Thus, the spatial and seasonal fluctuation of the phreatic zone throughout the karst is unknown to many karst aquifers. The aim of this work was therefore to test the applicability of magnetotelluric (MT) measurements in an Alpine karst massif in order to detect water saturation differences with depth at specific points in time. The study site was the Hochschwab karst plateau, whose summit reaches 2277 m above sea level (m a.s.l.), where springs on the northern and southern edges provide information about the minimum altitude of the phreatic zone (lowest spring at 650 m a.s.l.). During the exploration of a 1127 m deep shaft cave a siphon was not yet reached, representing an upper depth limit (895 m a.s.l.). MT measurements were carried out at three different locations on the karst plateau between 1880 and 2200 m a.s.l. and on a lower planation surface at 1360 m a.s.l. Spring discharge was compared to the MT results during the measurements. From these measurements, conclusions can be drawn about the current top of the phreatic zone at the time of each MT measurement. A correlation between the MT and discharge measurements was observed and the inversion images show that the water saturation increases with depth. MT measurements have thus proved to be a good way of investigating the phreatic zone and provide valuable insights into water saturation and storage in an alpine karst area.

Keywords: *Karst, phreatic zone, geophysics, magnetotelluric*
Ključne besede*: Kras, freatična cona, geofizika, magnetotelurika*

Speleothem oxygen and carbon isotopes point to strong NAO teleconnection during the onset of MIS 6 in the Sudety Mountains (Central Europe)

Izotopi kisika in ogljika v speleotemih kažejo na močno telekonekcijo NAO med nastopom MIS 6 v Sudetih (Srednja Evropa)

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A combined isotopic record from the speleothems from close-located Niedźwiedzia and Miniaturka caves (Sudety Mountains) was correlated with global and others European records to determine longitudinal climate patterns during Saalian glaciation (MIS 8–6). The age-depth model indicates continuous speleothem deposition from ~250 ka to maximum cooling during MIS 6 (Warta Stage) of about 140 ka. The covariance values of $\delta^{18}O$ and $\delta^{13}C$ suggest that the record did not pass Handy test, but due to its good correlation with the LR04 global isotopic stack, it may still be useful for climate reconstruction. The isotopic record indicates mild interglacial conditions between 250 and 225 ka. The relatively low $\delta^{13}C$ values suggest intensive development of forest vegetation during this period. Around 225 ka, an increase in $\delta^{13}C$ indicates less vegetation activity, but the lack of significant change in $\delta^{18}O$ suggests lower precipitation rather than temperature as a factor driving this change. This change can be correlated with MIS 7d characterized by lower temperatures across Europe, the presence of Eurasian ice sheets and near-stadial conditions. The subsequent decrease in $\delta^{13}C$ corresponded to milder conditions during MIS 7c and MIS 7a. The MIS 7–6 transition, marked in Miniaturka Cave by an increase in both $\delta^{18}O$ and $\delta^{13}C$ (an increase of 0.8 and 5 ‰, respectively), was dated to 192–183 $\pm$ 5 ka which is in good agreement with the timing of this transition determined for the Alpine record from the Spannagel Cave (197.1–191.4 $\pm$ 0.3 ka). On the other hand, the correlation with Tatra records and with records from the Low Tatras is not so obvious, and a clear offset of changes in isotopic values is observed. This shows that climatic conditions in the Sudety at the end of MIS 7 and during MIS 6 were more similar to those in Western Europe than to those of the Central European regions lying within the Carpathian Mountains.

Keywords: *Saalian glaciation, climatic conditions, vegetation development, isotopic record, MIS 7d, Warta Stage*
Ključne besede*: Saalska poledenitev, podnebne razmere, razvoj vegetacije, izotopski zapis, MIS 7d, stopnja Warta*

Cave sulfate minerals and speleogenesis - an insight from the perspective of sulfur and oxygen stable isotopes

Sulfatni minerali in speleogeneza jam: vpogled skozi analizo stabilnih izotopov žvepla in kisika

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The presence of sulfate minerals in the cave environment may be related to different sulfur sources and may be the result of different processes occurring with the participation of this element. Sulfur contained in these minerals can derived from sulfide oxidation, dissolution of evaporites in interbedded or overlying limestones, decomposition of bat guano, or post volcanic activities. To verify the hypotheses about the origin of the studied sulfate minerals, a dual isotopic approach of S and O in sulfates can be used. Sulfates derived from various S sources are usually characterized by different sulfur and oxygen isotopic signatures, also various biogeochemical processes involving sulfates lead to changes their isotopic composition and SO_4^{2-} concentrations in the studied system. $\delta^{34}S$ values provide information on the source and reaction pathway of sulfur involved in the initial stage of sulfate reduction (biotic/abiotic), but obtain very limited information on the secondary processes of oxidation during sulfate formation. Oxygen isotopic composition of sulfates provide information of the source and reaction pathway of oxygen involved in this secondary stage of the oxidation of sulfides; independent of information obtained due to origin of sulfur in sulfides. Different types of speleogenesis are associated with different environmental conditions, which is reflected, among others, in the isotopic composition of the minerals occurring in the cave. Our research focuses on the Mravljetovo brezno v Gošarjevih rupah (MBGR) cave, and one of the research paths undertaken to deeper investigate dedolomitization and its relationship with the MBGR speleogenesis is the research focused on the analysis of geochemical and isotopic data from the studied area. Here we compare the results of $\delta^{34}S$ and $\delta^{18}O$ values obtained for MBGR cave gypsum minerals ($\delta^{34}S_{SO4}$ from 10.3‰ to 14.0‰; $\delta^{18}O_{SO4}$ from −0.3‰ to 2.2‰) with the results from other caves that were formed and developed in different conditions.

Keywords: *Sulfate, gypsum, stable isotopes, speleogenesis*
Ključne besede*: sulfat, sadra, stabilni izotopi, speleogeneza*

Morphogenesis at the very edge of the Dinaric Karst - an example of the Ozalj region (Croatia)

Morfogeneza na skrajnem robu Dinarskega krasa – primer območja Ozalj (Hrvaška)

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The Ozalj region is situated in northeastern Croatia, on the border of two megageomorphological regions: the Pannonian Basin and the Dinaric Alps. This transitional zone is characterised by high lithological heterogeneity, with frequent alternation of different rock types, both carbonate and non-carbonate, over short distances. This lithological setting enabled contact karst development. In this research, the downstream section of Raduhovo stream and the surrounding area were analysed. The research methodology includes both GIS-based and field survey landform analyses and geomorphological mapping, as well as geospeleological mapping of caves found in the area. Several caves within the study area provide additional insight into subsurface hydrological and geomorphological dynamics. Based on the obtained data, conceptual models of the geomorphological evolution of the area are proposed, offering a better understanding of landscape development in a contact karst setting. The results contribute to broader discussions on karst development in transitional geomorphological environments.

Keywords: *Morphogenesis, contact karst, geospeleology, Dinaric Karst, Croatia*
Ključne besede*: morfogeneza, kontaktni kras, geospeleologija, Dinarski kras, Hrvaška*

Advancing Contaminant Transport Modeling in Karst Systems: Integrating Eulerian and Lagrangian Approaches in openKARST

Izpopolnjevanje modeliranja prenosa onesnaževal v kraških sistemih: združevanje Eulerjevega in Lagrangeovega pristopa v okviru orodja openKARST

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Contaminant transport in karst systems is highly dynamic, as pollutants can move rapidly through fractures and conduits with minimal attenuation, often leading to an immediate and strong response at karst springs. However, some contaminants temporarily enter less mobile zones before slowly returning to the main flow path, resulting in prolonged, low-concentration breakthroughs. This process explains the characteristic steep rising and long-tailed falling limbs commonly observed in tracer breakthrough curves. Modeling such complex transport behavior in karst aquifers remains a significant challenge due to the heterogeneity and rapid flow dynamics of conduit networks. openKARST, an open-source Python-based framework for simulating free-surface and pressurized flows in karst systems, provides a flexible platform for advancing transport modeling. This study expands openKARST by integrating multiple Eulerian and Lagrangian transport models, including the advective-dispersion equation, particle tracking with different routing rules, and time-domain random walks. These enhancements enable more realistic simulations of solute transport, capturing key processes such as non-Fickian dispersion, retention, and delayed breakthrough. Improving transport modeling in karst environments is essential for water resource management, groundwater protection, and risk assessment, particularly where rapid and unpredictable contaminant movement poses significant challenges.

Keywords: *Karst aquifers, Contaminant transport, Tracer breakthrough curves, Numerical modeling, Particle tracking*

***Ključne besede**: kraški vodonosniki, transport onesnažil, prebojne krivulje sledil, numerično modeliranje, sledenje delcem*

Conditioning of flood pulses produced by intense or prolonged rainfall events during transfer through underground conduits

Pogojevanje poplavnih pulzov ob intenzivnih ali dolgotrajnih padavinah med pretokom skozi podzemne kraške kanale

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Springs in Castleton, Derbyshire, UK, drain a mixed allogenic-autogenic karst catchment of c. 13.5 km^2 within which there are some 30 km of explored conduit (caves) and a much greater length of smaller tributary conduits. As part of a long-term study, hydraulic head is measured at five underground sites and water depth is measured at three springs fed by the conduits, and in a river fed by the springs. To accurately represent the hydrological complexity measurements are made at short intervals (2–4 minutes). In October 2023, Storm Babet brought heavy and persistent rain (80–100 mm) to the English Peak District and there was widespread surface and underground flooding, including property in Castleton. As expected, the conduits fed by sinking streams from the allogenic catchment responded rapidly to recharge but there was also a rapid response from the autogenic catchment where there are no surface streams and only a small number of dolines. Underground there were large increases in hydraulic head (up to 35 m) that resulted in two types of flow switching. Firstly, the increased head at the input end of one phreatic conduit system removed an underwater permeability barrier in a relatively low elevation conduit resulting in a dramatic increase in flow out of the conduit and a corresponding decrease in flow from a linked higher elevation conduit that had dominated before the storm. Secondly, increased head upstream of two conduits with limited hydraulic conductivity allowed water to spill over into conduits that were inactive prior to the storm. Surprisingly, the complex signals measured underground were not apparent in the spring hydrographs. Nevertheless, it is suggested that as intense/prolonged rainfall events become more common, changes within conduits may make the spring response (and hence flood risk) harder to predict.

Keywords: Castleton, flood-pulse, flow-switching, spring discharge
***Ključne besede**: Castleton, poplavni val, preklapljanje pretoka, izdatnost izvira*

Subsidence in Muttenz (Switzerland) and its causes

Ugrezanje tal v Muttenzu (Švica) in njegovi vzroki

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The village of Muttenz in northern Switzerland, nearby Basel, is subsiding, partially in an alarming fast rate (>1 cm/year). The causes of this subsidence was not known and difficult to evaluate, because three possible karstifiable layers are found in the underground. Investigations across several years yielded the surprising result that the subsidence is anthropogenically induced, however it was not at all expected. The lecture details the causes and effects and brings to light that modification of nature may bring unexpected results.

Keywords: *Subsidence, Switzerland, karst, groundwater, infiltration*
***Ključne besede**: Ugrezanje, Švica, kras, podzemna voda, infiltracija*

Scalable flow modeling in karstic media through graph simplification
Skalirano modeliranje toka v kraških medijih z uporabo poenostavljenih grafov

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Karst aquifers are characterized by highly heterogeneous and complex conduit networks, making the modeling of groundwater flows particularly challenging, especially under unsaturated flow conditions. In this work, we model these systems as resistive graphs, where nodes represent junctions and edges simulate hydraulic conductance through karst conduits. The governing equations take the form of nonlinear Laplacian systems and can involve graphs with tens of thousands of nodes. To enable efficient computation and scale transition, we propose a coarsening strategy that simplifies the graph while preserving key global hydraulic properties. Our approach relies on the concept of effective resistance to guide the simplification process, ensuring that the reduced network maintains comparable flow behavior between designated zones. We assess the performance of the coarsened graphs by comparing their flow responses to those of the original fine-scale networks. Preliminary results show that significant reductions in graph size are possible with limited loss in accuracy, providing a promising framework for multi-scale modeling of karst systems. This method paves the way for computationally efficient simulations of large-scale subsurface flow, and for better understanding of flow redistribution in evolving karst architectures. Figure 1 illustrates a subgraph extracted from a complex conduit network and its corresponding coarsened version obtained through our effective resistance-based simplification method.

Keywords: Networks, graph theory, upscaling, coarsening
Ključne besede*: Omrežja, teorija grafov, povečevanje merila, grobljenje*

Flood management needs as a challenge for geoconservation in a geopark. Case study of Gurgo di Andria in MurGEopark (Southern Italy)
Upravljanje poplav kot izziv za naravovarstva v geoparkih: primer Gurgo di Andria v geoparku MurGEopark (južna Italija)

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The protection of the territory in Italy is guaranteed by the European Landscape Convention of the Council of Europe (the Florence Convention), by national and regional laws on protected areas, and by those that protect from hydrogeological hazard. Regional rules protect geological features, geosites, valleys, dunes and caves among them, considering these as perceptible components of the landscape, rather than a complex system in evolution and subject to morphogenetic dynamics involving aspects of geomorphological and hydraulic hazard. Having splitted landscape and hazard aspects sometimes leads to some inconsistency in the evaluation of the potential impacts of projects on the dynamics of the territory and, consequently, on the economic and social ones. The karst areas of Apulia region (Southern Italy) undergo also hydraulic hazard resulting from extreme weather events that affect the surface drainage consisting of generally dry valleys, which have not always been considered, in the past, in urban planning. In 2024, a preliminary project was revived, necessary for the reduction of the hydraulic risk of the city of Andria, crossed by a torrent in an artificial riverbed with flow limits; between two alternatives, it opts for the most economical solution from the point of view of the cost of the

works, consisting in the excavation of an artificial channel for the excess flood waters that, instead of being conveyed into the sea, would be conveyed into one of the five large collapse sinkholes that are part of the geological heritage of the region. The Italian Society of Environmental Geology (SIGEA) has therefore opened a discussion with the Municipality of Andria, the Regional Council of Puglia, local associations and individual citizens, to reconsider the plan in the current constraints, looking at the sinkhole as a geosite with caves of historical-archaeological interest, in a network of geosites supporting a geopark recognized by UNESCO that offers prospects for sustainable development, support for environmental education and job creation.

Keywords: Geosites, flood management, geoconservation, MurGEopark
***Ključne besede**: Geotočke, upravljanje poplav, geoohranjanje, MurGEopark*

Dissolved carbonate exports in the Chevaline river (Choranche, Vercors). Period 2008–2018
Izvor raztopljenih karbonatov v reki Chevaline (Choranche, Vercors) v obdobju 2008–2018

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Here we present some preliminary results on the export of dissolved carbonates in a mid-mountain underground river: Chevaline (Vercors, France). A hydrometric station (2008–2018) records water levels, temperatures, and conductivities (every 30 minutes). Water levels are converted into flow rates and conductivity is converted into dissolved carbonate concentrations. This allows us to calculate dissolved carbonate flow rates. The underground river is subject to significant encrustation. Some of the calcite is deposited upstream of the measuring station and some far downstream. The measurements we propose do not account for all the dynamics of karst dissolution. However, they do allow us to analyze the dissolved export downstream of this mid-mountain karst system. The flow distribution shows a strong asymmetry with flows varying from 0 to 3.6 m^3/s. The median is 37.7 l/s. The same distribution of dissolved carbonate exports is observed with carbonate flows ranging from 0 to 880 g/s. The amplitude of carbonate concentrations is limited to between 186 and 296 mg/l. It is the quantity of water that controls carbonate flows, not the carbonate content. We then analyze the evolution of dissolved exports over 10 years. Dissolved carbonate exports show variations ranging from single to double during this period (min: 415 t, max: 923 t). We then recalculate these dissolved exports according to the four hydrological situations of equal duration: low water, low flow, high flow, and floods. Floods represent an average of 25% of the hydrological time over 10 years. They account for 63% to 78% of chemical erosion.

Keywords: *Carbonate flow, chemical erosion, underground river, Vercors*
***Ključne besede**: Pretok skozi karbonate, kemična erozija, podzemna reka, Vercors*

Geomorphological characteristics of shallow karst depressions (dayas) on the Nullarbor Plain
Geomorfološke značilnosti plitvih kraških kotanj (dayasov) na uravnavi Nullarbor

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Dayas are shallow karst depressions infilled with aeolian sediments, commonly considered a type of doline. Their diameters range from several tens of meters to over one kilometer, but are typically only a few meters deep. These subtle landforms develop on planar to gently undulating surfaces within

semi-arid to arid karst environments, such as the Nullarbor plain in southern Australia. The underlying bedrock typically comprises relatively young limestones, often capped by calcrete, or evaporites. The sedimentary infill inhibits infiltration, leading to surface runoff accumulation during intense rainfall and the formation of ephemeral lakes. Semi-automated remote sensing based on a digital elevation model (TandemX), radiometric maps, satellite imagery, and terrain visualizations, indicates that dayas are among the most frequent surface landforms on the Nullarbor Plain. Four distinct types have been identified. Simple circular dayas (1) are the most common, exhibiting circular or elliptical shapes, variable in size, and sporadically scattered across the landscape. In the northern and eastern parts, daya formation has been influenced by paleo-drainage networks, creating the drainage-channel type (2). These dayas tend to be elongated and are interconnected by shallow channels. Such linear alignments frequently terminate in a larger, centripetal type (3), characterized by a distinctive star-shaped morphology formed by converging inflow channels. In the southern parts, the terrain is dominated by ridges and swales, interpreted as relict dune fields, where wind-aligned dayas (4) have developed. These occur both in the swales, where they are larger, circular or elongated, and often form a continuous floor, and on the ridges, where they are smaller and primarily circular. The morphogenesis of dayas remains only partly understood; however, current evidence suggests a polygenetic origin involving the combined influence of karstic, aeolian, and fluvial geomorphic processes—particularly flash floods—alongside tectonic activity, lithology, and relict landforms.

Keywords: *Geomorphological analysis, arid karst, dayas, remote sensing*
Ključne besede*: Geomorfološka analiza, aridni kras, dayas, daljinsko zaznavanje*

Modeling the formation of low-karstified rock blocks in water divide areas and its influence on reservoir leakage

Modeliranje nastanka nizko zakraselih kamnitih blokov na območjih razvodja in njegov vpliv na puščanje iz rezervoarjev

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Reservoir leakage is a common concern in karst regions due to the presence of caves and conduits in the underlying aquifers, often necessitating significant anti-seepage measures. However, in karst water divide regions, the evolution of the aquifer may result in only minor leakage, which may not require additional control measures. The concept of low-karstified rock blocks (LKB) has long been used in leakage assessments of carbonate reservoirs in karst divide areas. Despite this, the quantification of leakage and its long-term evolution has seldom been explored. Modeling karstification and leakage in these regions is complex, yet essential for accurately determining project scale and investment needs. To address this, we developed a model that simulates the long-term evolution of an unconfined aquifer in water divide regions, incorporating a novel method to approximate the location of the water table under sustained rainfall recharge. The model simulates karstification processes and demonstrates that the resulting evolution leads to relatively low-karstified and low-permeable rock blocks in the middle and lower portions of the aquifer. In addition, we simulate leakage through these aquifers when a reservoir is constructed on one side. Our analysis investigates how the leakage rate varies with the height of water in the reservoir, offering valuable insights into the relationship between reservoir design and subsurface leakage behavior.

Keywords: *Karst modeling, fracture flow, water divide region, low-karstified rock blocks, reservoir leakage*
Ključne besede*: Modeliranje krasa, razponski tok, območje vodorazvodja, nizko zakrasele kamninske bloke, puščanje iz rezervoarja*

Hydrogeochemical monitoring of the Postojna–Planina caves system to study carbon transfer between air, water and rock

Hidrogeokemični monitoring v Postojnsko-Planinskem jamskem sistemu za študij prenosa ogljika med zrakom, vodo in kamnino

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Carbonate weathering is an important feature of the global carbon cycle, as such, it is critical to quantify the amount of CO_2 consumed in the weathering process and its potential storage underground. Karstification relies on the presence of water and CO_2, which control the dissolution and precipitation of carbonates. CO_2 exchange between groundwater and the vadose zone works in both directions. The vadose CO_2 can dissolve into the groundwater and promote calcite dissolution, and thus, the development of conduits. However, if the epiphreatic zone is well-ventilated and has a low CO_2 concentration in the air, the exchange reverses; the CO_2 degasses, which can lead to precipitation of calcite. Some of this CO_2 is then returned to the outside atmosphere through natural ventilation. As part of the CARDIKARST project, we are monitoring the CO_2 concentrations and hydrogeochemistry of air and water in various sites along the Pivka River flowpath to understand whether the river waters have the potential for calcite dissolution or precipitation and how this changes through the cave system. Our results show large differences between summer and winter conditions, and between low and high discharge scenarios. Comparing our hydrogeochemical data with the CO_2 measurements, discharge rates and climate conditions will provide a clear picture of the carbon transfer in the cave system between air, water and rock. These data will enable improvements and verifications of numerical models that are being developed within the CARDIKARST project.

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Keywords: *CO_2, water geochemistry, Postojna–Planina caves system, Pivka River, water–rock interactions.*
Ključne besede*: CO_2, geokemija vode, sistem Postojnsko-Planinske jame, reka Pivka, interakcije voda–kamnina*

The interactive role of groundwater and surface water within karst catchments during Mediterranean flash floods

Interaktivna vloga podzemne in površinske vode v kraških povodjih med sredozemskimi hudourniškimi poplavami

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Karst catchments frequently exhibit complex exchanges between groundwater and surface water. Whilst the swing between surface flood and underground flood is complex, a better understanding of this behavior would be of great interest for stakeholders in charge of flood forecasting and water recharge assessment. To address this issue, hydrometeorological and piezometric data have been collected for more than 20 years, and processed in order to identify flash flood events and their characteristics on the basis of measured signals previously identified as proxy of the karst-river exchanges. A special attention is dedicated to the number of flash floods and the occurrence of extreme rainfall events over the study period, in the context of climate change. Results show that an increase of extreme rainfall events is observed over the studied karst catchment, in agreement with the general trend over the Mediterranean basin. Changes in the dynamics of flash floods is discussed, though no clear trend in the number of floods is identified over the study area. The study focusses on a small Mediterranean catchment where karst/river interactions control the dynamic and genesis of surface floods but the proposed methodology is generic and might be applied to any catchment provided the availability of a sufficient database.

Keywords: *Flash floods, karst, groundwater/surface water interactions, extreme events, climate change*
Ključne besede: *Hudourniške poplave, kras, interakcije podtalnica/površinska voda, ekstremni dogodki, podnebne spremembe*

The role of the upper vadose karst zone during heavy precipitation events

Pomen zgornje vadozne cone v kraškem okolju ob intenzivnih padavinah

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Heavy rainfall events are occurring more frequently worldwide and often lead to a rapid response at the springs in karst areas. However, the parameters controlling flow and storage processes in karst systems are still open to debate and changes in the response due to different precipitation events has not yet been fully understood. The aim of this study is to investigate the groundwater recharge processes in the upper vadose zone, including the soil and epikarst, during different precipitation events at an Alpine case study cave (1895 m asl, Eastern Alps, Austria). We combine several methods: (1) high-resolution ERT measurements (electrical resistivity tomography, with 96 electrodes between the cave ceiling and the surface to generate 2D images); (2) measurements of cave drip water

(discharge, electrical conductivity and temperature); (3) high-resolution sampling of precipitation and cave drip water during events for stable water isotope analysis (δ^2H and $\delta^{18}O$); and (4) continuous monitoring of soil moisture with sensors at depths of 5 to 30 cm. Comparison of the results from the various sensors shows a good agreement for all the hydrological events investigated. The ERT images indicate that increased saturation is reached at depths of up to 10 m during heavy precipitation events. The signal from infiltrated water is clearly detectable in the cave drip water (discharge, electrical conductivity and temperature), while the water stable isotopes better resolving the flow and storage properties of events. Our results allowed us to determine that on average about one third of the cave drip water came directly from the rain event and about two thirds from older stored water, and that a large part of the rain event is stored in the epikarst and soil.

Keywords: *Hydrology, cave drip water, ERT, Alpine catchment*
Ključne besede*: Hidrologija, jamska kapnica, ERT (električna uporovna tomografija), alpsko zaledje*

The Great Pyramid of Giza exposed to Weathering
Zakrasevanje Keopsove Piramide

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The shape of the stone blocks making up the pyramid and their rock relief reveal characteristic weathering and the decisive factors and processes of karstification and wind erosion. There are several intertwining processes: the less intense dissolution of the rock, which is a result of the small amount of precipitation that directly reaches the rock and of the water trickling down it; the rapid evaporation and the consequent formation of crust on the surface of the rock; and the relatively intense wind erosion. Water dissolves the rock and as it evaporates it covers the rock surface with a crust, while wind is carving out the bare surfaces. Small cups are forming. They are a composite rock form, as their bare interiors, covered by a thin flaking crust at the most, are being carved out by the wind. The larger cups being notched into the bare rock are entirely aeolian. We can witness a similar shaping of the rock in the natural environment. This leads to the characteristic shape of the stone block. Most often the hard, crust-covered top is wider, with overhanging walls beneath it. The blocks made of a rock that mostly contains fossils are less dissected by rock relief and have preserved their original shape. The rapid weathering of stone blocks should be noted. Have they really only been bare for 700 years and already so eroded? The soft, mostly sandy rock certainly enables that. Only crust which covers parts of the rock partly protects it from disintegration and from wind erosion.

Keywords: *Carbonate rock, rock relief, complexometry, Great Pyramid of Giza, Egypt*
Ključne besede: *Karbonatna kamnina, skalni relief, kompleksometrija, Keopsova piramida, Egipt*

Speleothems tell tales about past permafrost dynamics
Sige kot pričevalci pretekle dinamike permafrosta

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Over the past decades, the cryosphere has shown a pronounced response to atmospheric warming, particularly in areas located at high latitudes or altitudes. In these areas, both warming and cooling trends are amplified. For instance, over the last century the European Alps was experienced a temperature increase at twice the rate of the mean for the Northern Hemisphere, while the Arctic warmed nearly four times faster than the global average. The amplified temperature change in these highly vulnerable areas may accelerate the rate of change in cryospheric systems such as the degradation of permafrost. To deepen our understanding of the potential future developments across mountain landscapes and polar regions, it is crucial to obtain paleoclimate archives with accurate chronology offering insights into the long-term changes of permafrost. In this talk I will introduce two types of speleothems—flowstones and cryogenic cave carbonates (hereafter CCC)—as excellent records of permafrost dynamics. Ancient flowstones from caves in eastern North Greenland, an area currently characterized by perennially frozen ground, provide evidence for the warmer and wetter conditions in the Arctic, and for the absence of permafrost during the Late Miocene. In contrast, the second type of speleothems, CCC form via freezing-induced supersaturation of small karst water bodies within cave ice when cave air temperature is slightly below 0°C. These minerals are currently present the best and sometimes single evidence for former cave glaciations. Their age can be accurately determined by the ^{230}Th dating method, and thus these unique speleothems can be used to reconstruct the time when perennial ice was present in a particular cave section. Recently CCC were discovered in a dozen of currently ice-free caves in the Eastern and Southern Alps, including Postojna Cave providing valuable insights into in permafrost changes during the Last Glacial.
Keywords: *Speleothem, cryogenic cave carbonates, cave glaciation, permafrost*
Ključne besede*: Siga, kriogeni jamski karbonati, poledenitev jam, permafrost*

Using tracer tests to characterize channel flow in different environments
Karakterizacija kanaliziranega toka v različnih okoljih z uporabo sledilnih poskusov

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Tracer tests are a crucial technique for determining preferential flow paths in karst. Tracer tests can among others determine the volume of mobile water between objects of interest. Tracer tests are commonly applied in karst conduits with flow rates of kilometers per day. In this project, we used

tracer tests to characterize flow paths in other environments—karst with extremely long residence time (6.4 m/day), sandstone pseudo-karst caves, and rifted granite in the thermal spring region. Tracer testing in the Chýnov karst identified flooded zones with a volume of 252,000 m³. Due to the extremely long mean transit time (434 days in 1200 m) these spaces were discovered. Also completely new proofs of the origin of the Chýnov karst have been found. The karst could only have been formed by extremely slow flow in phreatic loops without any sediment being transported for 20 million years. Another case was the fractured granite in the area around the thermal springs (Karlovy Vary). Six tracer tests were made there. The method consisted of injecting to various depths and monitoring remaining boreholes. One of the tracer tests in shallow zones of granite had a mean tracer time of over 7 days in 20 m. At this residence time the fluorescein had to be diluted in over 500 m^3 of water. This demonstrates the very high effective porosity of the fractured granite at shallow depths, which can hold hundreds of m^3 of water. Tracer tests were also used for characterization in the pseudo-karst sandstone caves in the Adršpach Rocks, where groundwater flow rates during different water conditions during the year. These examples show that tracer tests can be used in environments other than karst channels. Interpretation of tracer tests can provide valuable information on the hydrogeology and geology of interest areas.

Keywords: *Tracer tests, hydrogeology, flow paths, phreatic loops, Czechia*
Ključne besede*: Sledilni poskusi, hidrogeologija, tokovne poti, freatične zanke, Češka*

Deciphering karst chronology through ferricrete (U-Th)/He dating: Insights from the pinnacle karst, Western Australia

Odkrivanje razvoja krasa z datacijo ferikreta z metodo (U-Th)/He: vpogled v kras Zahodne Avstralije

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Dating karst landscapes presents a unique challenge, as the characteristic dissolution processes are by definition deleterious to the geological record. Given the removal of the primary carbonate material that could provide direct chronological constraints, traditional dating approaches have relied on the age constraints provided from karst-overlying or filling materials. Where possible, secondary by-products of karstification, such as ferricrete nodules, which accumulate as insoluble residues during the same intense weathering responsible for karst genesis, provide the most accurate means of dating karst. In Nambung National Park, approximately 200 km north of Perth, Western Australia, a remarkable pinnacle karst landscape has developed in Pleistocene aeolian calcarenite. Thousands of pinnacles, reaching up to 5 m in height, are exposed within a mobile quartz and carbonate sand cover. These features formed through solutional widening and coalescence of solution pipes, leaving behind a residual quartz-rich sand. Among the key by-products of this process are ferricrete nodules, which developed in the weathering profile as iron mobilized by water in residual sediment precipitated into hardened concretions. We applied (U-Th)/He dating to these ferricrete nodules to constrain the timing of the last major phase of dissolution. Although the (U-Th)/He method has been widely used for dating older ferricretes, it has never been tested on such geologically young material. Our results indicate

that pinnacle formation occurred at 102.8 +10.6/−11.4 ka, during Marine Isotope Stage (MIS) 5c, a period characterised by significantly wetter conditions than today. The (U-Th)/He ferricrete ages were validated with optically stimulated luminescence (OSL) and U-Th dating of the host rock and post-karst sediments, demonstrating that the technique can be extended to relatively recent weathering events, broadening its applicability in karst geomorphology. Our findings also provide an important palaeoclimatic signal, as pinnacle formation required substantially higher effective rainfall (the highest in at least the last 500 ka) than the present semi-arid climate of the region. This study shows the potential of (U-Th)/He dating of ferricretes to refine the chronology of dissolution events in karst landscapes and reconstruct past environmental events.

Keywords: Karst, geochronology, dating, geomorphology, pinnacles, ferricrete
***Ključne besede**: Kras, geokronologija, datiranje, geomorfologija, stolpiči, ferikret*

Volumetric storage parameters of karstified rocks derived from extreme and average hydrologic situations

Volumetrični skladiščni parametri zakraselih kamnin, določeni na podlagi ekstremnih in povprečnih hidroloških razmer

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Groundwater volume that can be effectively accumulated within a karst aquifer, or rather in the recharge area of a karst spring can be calculated from the amount of water drained within all outflow components (sub-regimes) of the spring's master recession curve assembled from the absolute maximal ever observed discharge. Usually exponential and linear equations with parameters α_i and β_i can relatively accurately describe master recession curve and define the individual flow components, and individual discharged volumes can then be easily calculated from the partial initial discharges Q_{0i} as Q_{0i}/α_i and $Q_{0i}/2\beta_i$, respectively. On the other hand, long-term spring's discharge averages can help us to determine the extent of its recharge area based on the knowledge of long-term value of effective precipitation. By comparing the evacuated volume VMRC and the area S_{basin} from which this volume was probably released, we obtain the size of the water column C_{basin} that has potential to be accumulated over a unit area in the springshed. The above procedure was applied to 111 springs in the Slovak Western Carpathians. C_{basin} values were found to range widely from 35 to 4395 mm, with a median Cbasin of 226 mm. The disproportion between fast and slow runoff components characterized by linear and exponential equations was interesting: in the case of fast-flow components, the size of the equivalent water column value emitted by them, C_{quick}, ranged from 3 to 559 mm with a median of 79 mm; for slow-flow components, C_{slow} ranged from 4 to 4395 mm with a median of 237 mm. However, the values and their ratios varied greatly and it is possible to single out several springs with an exceptionally high volume or a high proportion of the fast-flow component (interesting from the spring's water protection point of view, but also for its possible speleological attractiveness).

Keywords: *Master recession curves, flow components, water volumes, storage capacity*
***Ključne besede**: Glavne regresijske krivulje, komponente pretoka, količine vode, kapaciteta shranjevanja.*

Dye Tracing Analysis of Regional Flow Dynamics in Karstic Hydrological Basins in Jamaica using Dye Tracing Methods

Analiza regionalne dinamike toka v kraških vodonosnikih Jamajke z metodo sledenja z barvilom

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The Water Resources Authority of Jamaica (WRA) investigated the subsurface flow dynamics of various Karstic Basins in Jamaica from 2015 to the present, namely the Martha Brae Hydrologic Basin and the Dry Harbour Hydrologic Basin. For both basins, the WRA performed dye tracing exercises to verify the historical connectivity between various sinking and rising streams in both basins. Fluorescein, Rhodamine, Eosine and Sulfo-Rhodamine dyes were injected in various sinks (e.g., Tangle River, Lief's Sink, Quashie River, Cave River, and Lowe River) and charcoal receptors placed at multiple rising sources (e.g., Rio Bueno, Martha Brae, Laughlands Great River) for 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 similar basins via dye tracing and isotope hydrology studies.

Keywords: *Jamaica, dye tracing, karst, water*
Ključne besede*: Jamajka, sledilni poskus, kras, voda*

Thrombolitic texture of subaqueous calcite moonmilk from *Demänovská jaskyňa mieru, Slovakia*

Trombolitna tekstura podvodnega jamskega mleka iz Demänovske jame miru, Slovaška

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Subaqueous moonmilk is an uncommon variety of moonmilk that forms in smaller ponds and lakes developed in certain karstic caves. In *Demänovská jaskyňa mieru* (Demanovian Cave of Peace, Low Tatra Mountains, Central Western Carpathians, Slovakia) classic speleothems coexist with extensive calcite moonmilk deposits of diverse morphologies, which include an exceptional, 75 m^2 large, apparently active moonmilk lake, named Vatové jazero (Cotton Lake). The lake's subaqueous moonmilk deposits occur over brown allogenic clastic sediments on the floor of the chamber and laterally change into subaerial moonmilk covering stalactites, stalagmites, and flowstone on the adjacent cave wall. The lake is composed of sinuous moonmilk barriers, up to 20 cm high, that delimit rimstone pools, and is fully covered by white moonmilk deposits composed of delicate globular aggregates. The aggregates are locally coalesced into vertical structures resembling classic coralloid calcite speleothems, yet of highly porous and soft fabric. These aggregates consist of subspherical moonmilk clots, up to 5mm in diameter, arranged in irregular or arborescent thrombolite-like textures. SEM analysis has shown that the clotted moonmilk is mostly composed of needle fibre calcite crystals with overgrowths entrapped in an extremely porous 3D colloid-like fabric, made entirely of long calcite nanofibres. The calcite nanofibre fabric is a typical feature of subaqueous moonmilk forms known from other caves, such as, Snežna Jama na Raduhi (Slovenia) and Cataract Cave (Alaska, USA). Although the exact mechanism that produces such specific moonmilk texture is poorly understood, nanofibres seem to play a crucial role

in generation and preservation of highly porous textures that are morphologically and structurally similar to microbially-mediated textures known as thrombolites. Modern, actively-precipitating moonmilk settings, such as the lake of *Demänovská jaskyňa mieru*, offer a great opportunity to investigate the growth and diagenesis of this unique textural type of moonmilk.

Keywords: *Moonmilk speleothems, SEM, thrombolite, needle fibre calcite and calcite nanofibres*
Ključne besede: *Jamsko mleko, SEM, trombolit, igličasti vlaknati kalcit in kalcitna nanovlakna*

FloodWatch: a mobile application to monitor floods in karst areas
FloodWatch: mobilna aplikacija za spremljanje poplav na kraških območjih

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Floods are probably the most spectacular hazard happening in karst regions, covering large areas with water for periods that can be relatively long. Usually, floods are monitored by the monitoring network that is already installed in the area, which might considerably limit their characterization. Indeed, accurately monitoring every area prone to flood is not always possible, both due to budget restrictions and because the return period of the most extreme events might often be too long to justify the installation of a monitoring station. While satellite images of inundated areas proved to be useful to assess both flood duration and extension, they may not be available daily, have sometimes difficulties to differentiate water from vegetation, and do not always have the necessary resolution to characterize the flood properly. In many cases, the only available data relies solely on visual observation of the water level made by local citizens and environmental activists that witnessed the event. However, such valuable information remains often rather qualitative (i.e., without any measure of the flood level) and only known by the event direct observers, preventing its diffusion to a wider audience. To remedy this situation, a citizen-science mobile application aiming to monitor floods in karst areas was developed. FloodWatch is able to accurately record the flood level with the use of a simple smartphone. Along with water-level measurements, flooded surfaces and volumes can be computed. The measurements made with FloodWatch are registered in the user's personal database, who can then decide to share them with other application users. FloodWatch should be seen as an easy-to-use tool to monitor floods in karst areas in a pedagogic way. Its final aim is to foster science to the wider public by building a reactive community of citizen scientists ready to act when a flood occurs.

Keywords: *FloodWatch, mobile application, citizen science, floods, karst areas*
Ključne besede: *FloodWatch, mobilna aplikacija, občanske znanosti poplave, kraška območja*

High floods in Planinsko Polje: a 68 years data analysis
Velike poplave na Planinskem polju: analiza 68 letnega niza podatkov

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Planinsko Polje is the second largest Slovenian polje and is known for flooding regularly. The floods occur several times a year and may recover the polje for a surface up to 10 km^2. Usually, the maximum

water level registered at the polje main gauging station remains below 448 m a.s.l. Such elevation is considered as high but not problematic for the four villages surrounding the polje. However, floods surpassing 448 m a.s.l. for several meters may also occur. Those events can flood the polje for several months and have negative consequences for the local inhabitants. This work intends to understand Planinsko Polje most extreme events. To do so, an analysis covering the period 1954–2022 has been implemented. After computing some basic statistics on the floods, the daily water levels registered at the polje main gauging station were used to assess the polje surplus inflow. Then, the polje outflow was estimated with the help of the discharge data registered at the Ljubljanica Springs. This allowed reconstructing the polje water balance for 68 years. The data were used as input into a distributed pipe model that was able to reproduce successfully the water level in the polje during extreme floods. Finally, the same numerical model was tested on seven floods of different amplitude and duration that occurred in the period 2017–2020 where a complete dataset of the polje was available. The modelling results were in agreement with the previous ones, and confirmed that the outflow capacity of Planinsko Polje should be rather finite.

Keywords: *Planinsko Polje, flood, inflow reconstruction, ponor, numerical modelling*
Ključne besede: *Planinsko polje, poplava, rekonstrukcija pretokov, ponor, numerično modeliranje*

Semi-automatic detection of conical hills and uvlas based on the topographic openness index and shape delineation using the last closed contour method

Polavtomartsko zaznavanje kopastih vzpetin in uval na podlagi indeksa topografske odprtosti in zamejevanja oblik z metodo zadnje sklenjene plastnice

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Conical karst in temperate climates represents a type of karst landscape characterized by conical hills and intervening depressions known as uvalas. Existing methods for (semi) automatic detection of hills in karst terrain using geographic information systems (GIS) have primarily been developed for karst landscapes characterized by a strong dominance of hills in the relief, as is typical of tropical karst. The objective of this study was to develop a GIS-based method tailored for detecting conical hills and uvalas, where the surface is less rugged in comparison to tropical karst. The method is based on the identification of conical hills and uvalas using a digital elevation model (DEM) as input data, from which the topographic openness index is derived. Threshold values were established to represent numerical criteria for distinguishing between positive and negative surface areas. Within these areas, the last closed contour method is applied to delineate the shape of conical hills and uvalas. Conical hills were further classified into isolated hills and groups of hills sharing a common base. The detection results in Slovenia reveal spatial variations and similarities in the distribution and morphometric characteristics of the identified landforms in different areas. The highest density of detected conical karst landforms is observed on the elevated Dinaric plateaus (Banjšice, Trnovski gozd, Hrušica, Nanos, Javorniki, Snežnik), where the landscape is highly rugged. Lower densities are typical of less rugged karst terrains (e.g., Matarsko podolje, Kras, Suha Krajina). Morphometric analysis indicates that uvalas are, on average, more elongated than conical hills. The average height of hills and depth of uvalas fall within a comparable range, as do the elevations of hilltops and uvala rims. The majority of detected landforms exhibit a NW–SE (Dinaric) orientation. The developed method has proven to be effective in detecting conical karst features in conical karst landscapes typical for temperate climate regions and across karst terrains of varying ruggedness. It provides a valuable tool for further geomorphological investigations of conical karst.

Keywords: *Conical karst, geographic information systems (GIS), digital elevation model (DEM), morphometry*
Ključne besede*: Kopasti kras, geografski informacijski sistemi (GIS), digitalni model nadmorskih višin (DMNV), morfometrija*

Resilience and decline: ecological responses of ancient fauna to climate extremes in karst regions
Odpornost in izumiranje: ekološki odzivi prafavne na podnebne ekstreme v kraškem okolju

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The Late Pleistocene was marked by repeated climatic oscillations that profoundly reshaped ecosystems across Eurasia. These environmental extremes, combined with the geographic expansion of early modern humans, contributed to the extinction of many large mammals and impacted the present-day distribution of extant species. Understanding how species responded to such pressures in ecological, genetic, and behavioural terms remains essential for evaluating extinction risk and resilience. Advances in ancient DNA and stable isotope analysis now allow for detailed reconstructions of past ecological responses. One emblematic example is the cave bear, which disappeared around 25,000 years ago. Abundant fossil material preserved in karst cave systems provides a unique window into its life history, especially during periods of climatic stress. Data from the Carpathian region reveal unexpected variability in cave bear dietary patterns, based on compound-specific isotope analysis. This variation does not correlate with sex, population structure, location, or time period, suggesting individual behavioural responses to local environmental conditions. These findings support the idea that the Carpathians served as a climatic refugium during the Last Glacial Maximum, a period marked by less extreme cooling and drying compared to other regions. This relatively buffered environment enabled localized ecological adaptations and dietary specialisation. Although such flexibility indicates a degree of resilience, it ultimately proved insufficient to prevent extinction. The integration of palaeogenomic, isotopic, and palaeo-environmental data from karst systems offers a powerful lens through which to explore the interplay between environmental extremes and species survival. It also underscores the importance of interdisciplinary approaches in uncovering hidden dimensions of past ecological dynamics, insights that remain critical as we face increasing climatic uncertainty in the present.

Keywords: *Ancient population genomics, Carpathians, palaeodiet, palaeoenvironment*
Ključne besede*: Genomika stare populacije, Karpati, paleoprehrana, paleookolje*

A few considerations on improving dye tracer detectability with activated carbon
Nekaj premislekov o izboljšanju zaznavnosti sledilnika barvila z aktivnim ogljem

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The activated carbon method was early suggested for tracer tests applied in karst studies by J. Dunn in 1957. Nowadays, it is always much appreciated for its simplicity of usage and it remains a standard for routine dye tracing with uranine. However, its performance and reliability still remain controversial, and sometimes leads to misinterpretations, especially when applied as the unique method of detection. This can be attributed to a lack of scientific knowledge of the processes and kinetics of adsorption (in the field)/extraction (in the laboratory). That is the reason why, besides accumulating an

empirical understanding through practice, we conducted various tests since several years, a part of which being presented here. In these tests, we shared laboratory and field testings with the aim of identifying which factors are the most relevant. The results presented here are mainly based on batch tests in a laboratory tank and field tests on a known karst system in various conditions (among which the design and position, as well as immersion time, of the charcoal detectors). These tests confirmed the importance of the kinetics but mainly showed the utmost importance of the microscopic/interfacic conditions of flow around the detectors. These results easily explain why the accumulation factor (ratio between the concentration in the eluent and that in the water) may range between more than 1000 and less than 1, thus giving or not a chance to undoubtedly detect uranine. Other considerations like the competition with organic background, robustness of the method, optimization of extractions, or applicability to other tracers than uranine are also discussed.

Keywords: *Tracer test, uranine, charcoal, accumulation factor, adsorption*
Ključne besede*: Sledilni test, uranin, oglje, factor, akumulacijski faktor, adsorpcija*

Preliminary results of mapping Croatian dolines
Preliminarni rezultati kartiranja hrvaških vrtač

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Dolines are small to intermediate enclosed depressions that are one of the most numerous surface karst features in Croatia. They tend to be circular in plan form and vary in diameter from a few metres to over a kilometer. They can develop in limestone, dolomite, carbonate breccia and conglomerate and occupy different geomorphic settings. They were formed by various processes like dissolution, collapse, suffosion and transformation of caves to surface features by denudation. Publicly accessible digital elevation model (DEM) derived from the recent nationwide lidar survey of Croatia as used for this study. To catalogue dolines, we manually label a fraction of the DEM of Slovenia with a binary mask indicating if the area is a doline or not. We then train a slightly modified u-net, a type of machine learning algorithm, on the labelled territory. Using the trained algorithm, we infer the binary mask on the entire Croatian DEM. We convert the resulting mask into an ESRI Shapefile and do a preliminary study of the acquired map. This basic dataset for dolines enables further study and comparison of dolines with the geology and topography of kars. However we intend to further verify the current map and publish more comprehensive findings in an upcoming paper. Dolines in Croatia are found in most of the karst areas, except on floors of poljes and steeper slopes, and are less abundant on sloping surfaces. We find that typical Croatian doline areas are defined by geological and morphological conditions.

Keywords: *Dolines, Croatia, DEM, machine learning*
Ključne besede*: Doline, Hrvaska, DMR, strojno učenje*

Karst geomorphology along the complex fault systems: Timok fault system, east Serbian Carpatho–Balkanides

Kraška geomorfologija vzdolž kompleksnih prelomnih sistemov: prelomni sistem Timoka, vzhodnosrbski Karpato-Balkanidi

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The connectivity of the surface and subsurface processes and forms in karst terrains has been extensively studied, especially because of the related practical water supply problems in areas dominated by carbonates. It is widely accepted that geological structures are the best water conduits in karst areas, but the improvement of this general statement may be obtained through the detailed insight. Focusing to the particular structures in karst caves may lead to better understanding of speleogenesis and functioning of the karst system, in terms of their relationship with dimensions and orientation of cave passages, as well as with the locations and types of speleothems and clastic sediments.

One of the ideal areas for such kind of research is located along the Timok fault system within the Carpatho–Balkan orogenic system, situated in eastern Serbia. The Timok fault system represents a very complex fault zone consisting of large-scale strike-slip faults that had been active since the Oligocene–Miocene period. The activity of these faults brought tectonic units from different structural levels into direct contact, in some cases exposing narrow areas of carbonate rocks into the direct contact with non-karstic rocks, while in other places it formed regional-scale zones of fault rocks (fault breccias, fault gauge, etc.). In this paper, we show geomorphological evidence of the influence of these regionally significant faults onto the karst process, both on surface and underground, through the study within six selected areas along the Timok fault system. Results indicate differences in the development of karst landforms and underground features depending on the position within this fault system.

Keywords: *Timok fault, Carpatho-Balkan, orogen, karst process*
Ključne besede: *Timoški prelom, Karpato-Balkan, orogen, kraški proces*

Artificial intelligence-based model for flood prediction in Škocjan caves

Model za napovedovanje poplav v Škocjanskih jamah na osnovi umetne inteligence

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We present a robust methodology for constructing a flood prediction model using Multi-Layer Perceptron Artificial Neural Networks (MLPANN) tailored to complex terrains, exemplified by the Škocjan Caves area in Slovenia. The primary objective is to predict water flow at the Cerkvenikov Mlin surface measurement station six hours in advance, utilizing historical flow and rainfall data. The MLPANN model successfully predicts high flow events with acceptable accuracy, crucial for operational use in emergency scenarios. It minimizes false alarms during low flow periods and accurately forecasts peak values and flow recession. The model incorporates both temporal flow data and aggregated rainfall data from multiple meteorological stations, ensuring a comprehensive understanding of factors influencing flood events. This approach balances the need for historical data consistency and the

inclusion of newer, more localized rainfall measurements. Implementing this model significantly enhances the flood preparedness of Škocjan Caves, enabling timely evacuations and infrastructure protection. The model's real-time predictions and integration into existing alert systems ensure practical utility in safeguarding tourists and staff. The success of the model in the challenging karst terrain of Škocjan Caves demonstrates its potential applicability to other regions with complex topographies. The methodology's adaptability and effectiveness suggest that similar models could be developed for various flood-prone areas worldwide. The use of MLPANN provides a cost-effective and accessible solution for flood prediction, requiring no specialized knowledge of neural networks. The model's construction and training processes are feasible with modern computational resources, making it a practical choice for real-world applications. In conclusion, the presented methodology offers a valuable tool for predicting flash floods, enhancing emergency response capabilities, and potentially saving lives and property in flood-prone regions. The successful application in Škocjan Caves underscores the model's reliability and broader relevance.

Keywords: *Artificial neural networks, artificial intelligence, flood, Škocjan cave*
Ključne besede*: Umetne nevronske mreže, umetna inteligenca, poplave, Škocjanska jama*

An up-to-date karst landforms and landscape map of Abruzzo region (Italy, Central Apennines)

Posodobljen zemljevid kraških reliefnih oblik in kraške pokrajine v regiji Abruzzo (Italija, osrednji Apenini)

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The Central Apennines are a key area for karst studies in Italy, yet the Abruzzo region remains largely unexplored in terms of recent analyses of epigean karst features. Despite long-history and extensive documentation on hypogene karst and karst springs studies, a small-scale systematic mapping of surface karst landforms using high-resolution data and GIS-based methods is lacking. This study aims to fill that gap by developing the first region-wide, up-to-date map of karst landforms and landscapes in Abruzzo. Carbonate karst terrains cover approximately 40% of the Abruzzo region (Jurassic-Cretaceous limestone ridges separated by flysch-filled valleys or tectonic basins). These units are bounded by normal faults active since the late Pliocene–early Pleistocene that dislocated several karst paleosurfaces and influenced the development of fluvio-karst drainage patterns and many endoreic basins. Karst landforms were extracted using a combination of 10- and 5-meter resolution custom-processed DEMs and, where available, 1-meter resolution LiDAR. The employment of semi-automated techniques such as fill sinks method and DEM elaborations (e.g., Sky View Factor, Topographic Position Index, curvature, openness) have allowed to identify and classify +100,000 karst landforms. The extracted features were filtered using morphometric parameters (mainly circularity, elongation, depth and area), allowing the classification of dolines, karstic plains, poljes, open depressions and fluvio-karst valleys. This process was supported with field check in selected areas, manual remote validation (with topographic maps and multiband satellite imagery) and comparison with geomorphological datasets, that helped to clean the dataset from several artifacts. The main outcome is a new karst features map, containing +4,000 dolines, +60 karstic plains, 14 poljes—and their endoreic catchments—, and +100,000 between open depressions and karst dry valleys. The entire dataset and the up-to-date karst landforms map represent a significant step forward in understanding the spatial distribution and evolution of karst landscape in the Abruzzo region.

Keywords: *Central Italy, Abruzzi, epigean karst landforms, geomorphological mapping*
Ključne besede*: Osrednja Italija, Abruco, epigene kraške oblike, geomorfološko kartiranje*

Quantification of solid and dissolved load from the mass balance of a major karst spring
Ocena trdnih in raztopljenih snovi na podlagi masne bilance pomembnega kraškega izvira

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A major karst spring (average flow rate of around 5 m^3/s) on the northern edge of Hochschwab mountain range plays a crucial role in Vienna's water supply but is prone to turbidity during flood events due to mobilization of suspended sediment. While the dissolved load was already quantified 20 years ago, the suspended sediment load has remained uncertain. This study aims to establish a correlation between turbidity (NTU) and total suspended solids (TSS) to quantify the solid load discharged from the karst system. Water samples were collected at different discharge conditions, including the highest turbidity event (48 NTU) in the last 5 years. Suspended sediments were separated by settling and were dried before weighing. To establish source areas of the TSS, grain size distribution was analysed and mineralogical composition was determined by XRD. This was compared to cave sediments, fault gouges and soils. Hydrological parameters such as turbidity, electrical conductivity, temperature, and discharge were recorded at 10-minute intervals. The dissolved load was determined using a regression between calcium and magnesium hardness and electrical conductivity ($R^2 = 0.99$). Preliminary results suggest a linear TSS-NTU relationship, with suspended sediment discharge estimated at 180 t per year, significantly lower than the dissolved load (22.000 t per year). Further sampling will be necessary to refine this correlation.

This project is supported by Wiener Hochschuljubiläumsfonds (H-523246/2024).

Keywords: *Turbidity, karst spring, water resources, karst hydrodynamics*
Ključne besede*: Motnost, kraški izvir, vodni viri, kraška hidrodinamika*

Investigation of the water balance of Lake Hévíz
Raziskava vodne bilance jezera Hévíz

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Lake Hévíz is fed by the water of high-discharge cold and hot springs, which are in a spring cave located at a depth of approximately 40 meters, making it one of the most significant drains of the main karst water reservoir of the Transdanubian Mountains. As an emblematic place of Hungarian bathing culture, its natural and economic value is unquestionable. In order to optimally manage the lake, which is fed by underground water resources, it is necessary to quantify the elements of the water balance. By supplementing the monitoring system and with a campaign-type measurement series, we measure the discharge through the two gates, the water evaporating from the lake, the water entering it as precipitation, and the water seeping in and out of the soil. The latter (i.e., the connection with groundwater) is monitored with Dataqua water level recorders placed in groundwater wells and with a pair of soil moisture and temperature measuring instruments installed at two depths in the soil. Lake evaporation was estimated using the eddy covariance method. Surface inflow and outflow are negligible. The aim of the research is to contribute to the optimal operation of the Spa and sustainable water management.

Keywords: *Water balance, monitoring sytem, thermal water, Lake Hévíz*
Ključne besede*: Vodna bilanca, opazovalni sistem, termalna voda, jezero Hévíz*

Prototype for the Slovenian Karst Database – advancing to cataloguing multidisciplinary karst data
Prototip slovenske krasoslovne baze podatkov – napredovanje v katalogizacijo multidisciplinarnih kraških podatkov

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Since 2024, the Karst Research Institute ZRC SAZU has been developing the Karst Database (KarstDB)—a multidisciplinary platform designed to support the comprehensive study of karst systems. KarstDB aims to enhance the measurement of the complexity of karst systems while promoting data interoperability and collaboration across scientific disciplines. The platform enables the structured collection, storage and dissemination of raw and processed research data. These datasets are made accessible through a customized interface that integrates visualizations (e.g., maps, graphics) and is linked to the institute's metadata portal (https://metadata.izrk.zrc-sazu.si). The development is guided by the FAIR data principles: Findability, Accessibility, Interoperability and Reusability. As a prototype, KarstDB (https://karstdb.zrc-sazu.si) is not designed solely as a stand-alone system, but also as an interoperable bridge connecting different tools and platforms. It is integrated with GeoNetwork (for metadata management), QGIS Server (for raster layers), ArcGIS Online (for vector data), a dedicated environment for interactive data visualization and a Handle PID system for persistent identifiers. This architecture ensures flexibility and technological neutrality and promotes seamless connectivity between different data types and research workflows. KarstDB thus represents a significant advance in the digitization, standardization and accessibility of karstological research. The current prototype will be further developed and refined over the next two years with the aim of creating a robust and collaborative research infrastructure for the karst research community from Slovenia and abroad.

KarstDB project (SRI-2402 RSF Krasoslovna baza) was funded by the Slovenian Research and Innovation Agency.

Keywords: *Karst, database, FAIR, metadata, multidisciplinarity*
Ključne besede*: Kras, baza podtakov, FAIR, metapodatki, multidisciplinarosti*

Laboratory-scale investigations of flow in synthetic conduits with high roughness
Laboratorijske raziskave toka v sintetičnih kanalih z visoko hrapavostjo

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The inherent heterogeneity of karstified fractured-porous systems poses a major challenge for the characterization of these systems and for the process-based simulation of flow and transport. Conduit networks that are embedded in the fractured-porous matrix offer a domain for fast drainage towards

karst springs. Hence, laminar and turbulent flow within conduits are controlling processes whose understanding is vital for the development of sound conceptual models with respect to flow and transport. Past experimental investigations of laminar and turbulent flow in smooth and rough pipes provide the foundations for modeling karst network scale flow processes by offering estimates of friction factors for a range of Reynolds numbers. However, the roughness of karst conduits can be significantly larger than for the types of rough pipes that form the experimental basis for the friction factors used to compose the Nikuradse diagram or Moody chart. We present a review of experimental investigations of flow in rough conduits and highlight the deviations from the correlations based on the Nikuradse diagram and Moody chart. Furthermore, we present a novel experimental approach that employs 3D-printed synthetic karst conduits based on field data to study flow and transport on the laboratory scale. Such a setup enables to systematically study the friction factor over a range of Reynolds numbers for different (realistic) conduit roughness, and to investigate the onset of the laminar-turbulence transition and range of Reynolds numbers over which it occurs.

Keywords: *Karst, conduits, experiments, friction factor*
Ključne besede*: Kras, kanali, eksperimenti, faktor trenja*

Decoding a 60,000-year tectonic history: Speleoseismicity from a fault in Postojna Cave

Razkrivanje 60.000-letne tektonske zgodovine: speleoseizmičnost preloma v Postojnski jami

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This study applies speleoseismology to investigate the long-term tectonic activity within the Postojna Cave system (SW Slovenia), offering new insights into paleoearthquake occurrences along the NW–SE striking Dinaric Fault System. Located in the tectonically active Northwestern Dinarides, an area lacking Quaternary surface sediments, Postojna Cave provides an ideal natural archive for reconstructing seismic history through speleothem deformation. Nine speleothems exhibiting breakage or healed fracturing were sampled along a fault zone associated with documented micro-displacements and seismic transients recorded by a TM extensometer since 2000. Absolute U-Th dating using MC-ICP-MS was performed to constrain the timing of speleothem deformation. The results span from <0.5 ky BP to ~55 ky BP, forming three significant age clusters: 1,375–4,312 years BP, 6,000–8,000 years BP, and 20,000–23,000 years BP. These deformation episodes align well with paleoseismic data from nearby faults (Selce, Idrija, and Predjama), and with sedimentary earthquake records from Lake Bohinj. The oldest sample, VG-9 (~55,864 BP), may indicate even earlier tectonic activity or gravitational influence, pending further analysis. The spatial association of sampled speleothems with fault structures, the nature of healed fractures, and correlation with instrumental displacement data collectively suggest tectonic, likely seismic (paleoearthquake), origins for most deformations. Non-seismic processes (e.g., sediment subsidence, anthropogenic effects, cryoturbation) were systematically excluded through site selection and micro-context analysis. This research highlights the utility of speleothems as paleoseismic archives and reinforces the value of integrating speleoseismology with instrumental and regional paleoseismic data. The findings contribute to a broader understanding of Holocene and Late Pleistocene seismicity in the NW Dinarides and demonstrate the long-term tectonic imprint preserved within karst systems.

Keywords: *Speleoseismology, Paleoearthquakes, Karst, Caves, SW Slovenia*
Ključne besede*: Speleoseizmologija, paleopotresi, kras, jame, JZ Slovenija*

Climate change and extreme environmental events require more knowledge about protection and rescue in the education system and among the public

Podnebne spremembe in izjemni okoljski dogodki zahtevajo več znanja o zaščiti in reševanju v izobraževalniem sistemu in v javnosti

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Global climate patterns are changing, leading to more frequent extreme weather events and natural disasters. In order to effectively meet the challenges of natural disasters, we need to implement strategies for effective management of these crises. Interdisciplinarity, global and local characteristics, disaster management and governance approaches, ethical issues, social commitment, political and legal frameworks, and technologies, must all be taken into consideration. The need for experts with interdisciplinary knowledge and skills in the fields of civil protection, disaster management and rescue is greater today than ever before. The importance of proactive management and protection of ecosystems and natural resources in disaster management emphasises the need for universities to play an important role in crisis management and disaster mitigation. Some universities have already responded to this challenge and recognised the importance of including topics related to disaster management and governance in their curricula. The increasing complexity of extreme events and environmental disasters requires a comprehensive, interdisciplinary approach in education, especially in the field of environmental sciences. As part of the Environmental Management course (School of Environmental Sciences, University of Nova Gorica), students took part in a practical simulation of regional disaster response operations, focussing on disaster risk factors, activation procedures and inter-agency coordination. Examples included a tourist accident in a karst cave and a wildfire in a karst area near a watercourse, illustrating the environmental risks of firewater runoff and the complexity of emergency response planning.

Keywords: *disaster management, crisis governance, environmental risks, simulation training, environmental science*
Ključne besede: *upravljanje nesreč, upravljanje kriz, okoljska tveganja, simulacijsko usposabljanje, znanosi o okoju*

Dynamics of Permanent Ice in the Deep Caves of Velebit Mountain, Croatia: Implications of Extreme Weather Events and Climate Change

Dinamika trajnega ledu v globokih jamah Velebita (Hrvaška): vpliv skrajnih vremenskih dogodkov in podnebnih sprememb

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Within the CARDIKARST project, we are developing methodologies for monitoring and interpreting cave microclimates, aiming to apply these approaches to various locations. Over the past thirty years, research on the northern part of Velebit mountain has identified permanent ice deposits in numerous deep pits, reaching depths of several hundred meters. The shift of ice boundaries toward deeper, colder, and more climatically stable cave zones, along with observed ice loss, indicates that these formations are strongly affected by extreme weather events and broader climatic variability within the

karst system. To investigate these interactions, we are systematically monitoring permanent ice at ten sites across Northern Velebit, integrating continuous microclimatic measurements. Perșoiu et al. (2019) demonstrated that record summer rainfall in 2019 led to substantial loss of both surface and cave ice across Southeastern Europe, emphasizing the vulnerability of subterranean ice to short-term climatic extremes. Monitoring ice caves is crucial, as these deposits act as natural archives, preserving valuable records of past climatic conditions. Changes in the volume, structure, or spatial distribution of cave ice offer insights into wider environmental shifts. In addition, these caves host unique ecosystems adapted to stable and specific microclimatic conditions, making them especially sensitive indicators of environmental change. Ice caves also function as critical aquifers supplying freshwater to surrounding regions. Deeper understanding of cave microclimates can improve predictions and management of water resources, particularly in areas vulnerable to drought or contamination. Understanding ice dynamics and related climatic factors is crucial for ensuring the safety of cavers and researchers, while studying interactions between ice and karst processes contributes to broader geological knowledge, including erosion, sediment transport, and speleogenesis.

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Keywords: *Permanent ice, deep pits, Velebit, climate change*
Ključne besede*: Trajni led, globoka brezn, Velebit, podnebne spremembe*

Late Holocene climate anomalies are recorded in annually laminated speleothem from Croatia
Poznoholocenske podnebne anomalije, zabeležene v letnih laminah sige iz Hrvaške

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The Late Holocene is characterized by several short-term climate anomalies, such as the Little Ice Age (LIA) and the Medieval Climate Anomaly (MCA), although their precise timing and spatial extent remain subjects of an ongoing scientific debate. Addressing these uncertainties requires high-resolution, precisely dated palaeoclimate archives. Here, we present evidence for regional climate responses to these anomalies over the past ~1500 years, based on annually laminated speleothem record from the Nova Grgosova Cave in continental Croatia. The age-depth model for the NG-2 stalagmite was developed using a floating lamina-based chronology, anchored by 17 U-Th radiometric dates. The model reveals two phases of condensed growth: one coinciding with the LIA (ca. 1625–1830 CE), and another spanning the MCA and the Dark Ages Cold Period (DACP, ca. 710–1050 CE), during which the growth rate declined to approximately 0.01 mm/yr. In contrast, the fastest growth rate (approximately 0.2 mm/yr) occurred during the past 185 years. Stable isotope analyses of in-situ farmed calcite at the NG-2 growth site confirm that calcite was deposited under near-equilibrium conditions, thus reliably recording climatic signals. We combined stable isotope data with trace element and petrographic analyses to reconstruct climate conditions during the studied period. All proxies consistently indicate drier and cooler conditions during the LIA and DACP, and wetter, warmer conditions during the MCA.

These findings contribute new insights into the extent, timing and persistence of regional climate variability in South Central Europe over the last two millennia.

Keywords: Late Holocene, speleothems, lamina counting, U-Th dating, multi-proxy approach, Nova Grgosova Cave
***Ključne besede**: Pozni holocen, siga, štetje lamel, U-Th datiranje, večkazalni pristop, jama Nova Grgosova*

Mismanagement of karst environments: the increase in vulnerability to flash floods in Apulia
Neustrezno upravljanje kraških pokrajin in povečana ranljivost za hudourniške poplave v Apuliji

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In karst, floods are frequent and damaging geological hazards, due to hydraulic and hydrogeological peculiarities of this very fragile environment. They often result in severe damage to human activities and infrastructures, threatening lives as well. These problems have been significantly exacerbated in the last century because of a variety of anthropogenic actions, starting from the increasing expansion of urban areas. The territory of Apulia, mostly consisting of soluble rocks, is affected at many locations by frequent flash floods, which numbers have definitely increased in the last decades, sometimes also locally claiming casualties. In the Gargano Promontory, severe rainstorms in the first week of September 2014 caused many geohazards, from flash floods to landslides and sinkholes. Further south, in the Murge area, several towns have been hit by floods, as Bisceglie and Molfetta, where the system of temporary water courses work as the main water flow way during floods, invading wide sectors in the industrial areas and at the outskirts of the inhabited zone. Bari itself, the most populated and important city in Apulia, suffered many times during the years by floods. In Low Murge, between Putignano and Castellana-Grotte, closure of a high number of swallow holes had been at the origin of repeated inundations. The coastal area, too is involved in such phenomena: on the Adriatic side, downhill from Ostuni, several tourist resorts have been hit, in many cases due to the wrong location of these structures. Toward the Ionian Sea, the town of Ginosa was hit by two severe flood events in 2013, sadly resulting in four victims. The southernmost portion of Apulia, the Salento peninsula, shows many urban centers interested by floods and inundations, even in consequence of not significant rainfall events.

Keywords: *Karst, floods, geohazards, Apulia*
***Ključne besede**: Kras, poplave, geohazard, Apulija*

Microplastic Contamination in Karst Waters: Evidence from Greek Cave Systems

Onesnaženost kraških voda z mikroplastiko: dokazi iz grških jamskih sistemov

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Here we present the first systematic assessment of microplastic occurrence in karst waters from selected cave systems across Greece, highlighting a growing environmental pressure on already scarce groundwater resources. Water samples from drip water and cave streams, along with sediment samples from clastic deposits, were collected from caves spatially covering the total extent of the country. Laboratory analysis, including filtration and spectroscopic identification, show the consistent presence of microplastics, mainly fibers and fragments, at all sites. Concentrations varied with proximity to surface inputs and levels of anthropogenic activity. Our findings confirm the strong connectivity between surface and subsurface in karst systems and indicate that microplastic pollution, compounded by climate change, poses an escalating pressure to Greek karst aquifers. Our findings add to the growing evidence of microplastic infiltration into groundwater and highlight the need for monitoring and mitigation efforts in vulnerable karst settings.

Keywords: *Microplastics, karst waters, cave sediments, Greece*
Ključne besede*: Mikroplastika, kraške vode, jamski sedimenti, Grčija*

Estimating parameters of calcite photoluminescence from video recordings

Določanje parametrov fotoluminiscence kalcitnih kristalov iz videoposnetkov

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Due to the presence of different kinds of luminescence centres, certain natural calcite crystals luminesce after being excited with a powerful but short (<1000 ms) pulse of light. It has been proposed to use the colour and duration of luminescence for deducing the temperature at which a crystal formed. However, using, or even validating, the method while performing the video analysis with standard graphical processing software has proven itself challenging and time-consuming. We therefore develop and test a software package for analysing video-recordings of calcite crystal photoluminescence. It requires less manual work than the preceding methods. Furthermore, it quantifies the luminescence through estimating parameters of a first-principle model of luminescence in an attempt to make the method more repeatable than the use of ad-hoc measures. We demonstrate that we can reliably identify different types of luminescence within a single crystal and estimate the ratio between them. We ensure that only a consumer camera, a tripod, and a photographic flash are required as measurement hardware, and our next goal is making the software package user-friendly and freely available. It can then be tested whether this method can be applied to deduct information on formation temperature and put to practical use.

Keywords: *Luminescence, formation temperature, digital video processing, inverse modelling*
Ključne besede*: Luminiscenca, temperatura nastanka, digitalna obdelava videoposnetkov, inverzno modeliranje*

Recharge of karst aquifers by extreme rain events (and their long-term drying)
Napajanje kraških vodonosnikov z ekstremnimi nalivi (in njihovo dolgotrajno sušenje)

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In this talk, we discuss the recharge of karst aquifers during extreme rain events (i.e., tropical storms) and combine these data with information on water recharge, storage and flow through different karst zones to build a (bleak) view of future water storage and supply from karst aquifers in the context of climate change.

Karst aquifers provide drinking water for about 25% of the population worldwide and are also important sources of water for irrigation, animal husbandry and industry. While groundwater reserves are to a certain extent buffered against short-term weather and climate variability, karst aquifers, due to the specific nature of the host rock, behave close to a “gray box” (partial knowledge of the systems) in terms of residence times, source and recharge patterns of the water they store. In this context, understanding how and when karst aquifers are recharged and what is the precise source of the water they store is of paramount importance.

We present here a study of shallow and deep karst aquifers responding to the passage of a tropical storm in the Caribbean and combine this data with karst aquifer behavior in Central Europe to raise questions and hypothesis that could be used to further advance knowledge of karst hydrology and water resources availability.

In August 2021, Tropical Storm Grace (TS Grace) made landfall in Jamaica with very heavy rainfall (~250 mm) and wind speeds up to 85 km/h. A program of sampling water for stable isotope analyses was in place in Jamaica since March 2021, with monthly sampling of precipitation (three stations), and groundwater from deep (up to 228 m) and shallow karstic aquifers, ponors and associated springs. Additionally, during the passage of TS Grace (August 17–18, 2021), precipitation samples were collected hourly, from the beginning to the end of the rain (13 samples). The results of the stable isotope analyses show that TS Grace had very low values of $\delta^{18}O$ and $\delta^{2}H$ so even the monthly composite sample of August 2021 dropped markedly (by up to 8 ‰ at the station nearest to the center of TS Grace). Except for the deep aquifers, all types of waters were impacted by the strongly depleted δ values of TS Grace, with small surface rivers showing the highest impact and springs discharging shallow aquifers, the lowest. Large rivers feeding the underground karst flows through ponors experienced intermediate impacts. In contrary, the water of the deep wells showed no sign of change in their $\delta^{18}O$ and $\delta^{2}H$ during or after the passage of TS Grace. The $\delta^{18}O$ and $\delta^{2}H$ of all water compartments recovered quickly to pre-storm values in the coming weeks. The data indicates that

surface waters quickly moved through the karst system, the high volumes of water delivered by TS Grace not having a lasting impact on the recharge of shallow aquifers. Crucially, water delivered by TS Grace did not reach the deep aquifers. These observations complement stable isotope data from the year before TS Grace, which shows that the shallow karst aquifers are mainly recharged by slowly infiltrating water delivered during periods of sustained rain, with summer intense rains contributing only marginally to recharge. The combined results of stable isotope analysis of water in Jamaica thus indicate that intense rains are not contributing significantly to the recharge of both shallow and deep karstic aquifers, the large amounts of water delivered during such events quickly flowing through a possibly very well developed karst.

Similar observations were also made in several karst regions in Romania and Bulgaria. Data spanning several years of monitoring karst systems (ponor-to-spring) in northwestern and southeastern Romania and in northeastern Bulgaria, as well as drip waters in six caves in Romania, all with monthly resolution, showed that: 1) limestone porosity exerts the strongest control on the recharge pattern of karst aquifers by drip water, the flow paths being markedly different even within the same cave; 2) all karstic aquifers in Romania are predominantly recharged by slowly infiltrating snowmelt (as drip water), whereas warm season heavy rainfalls are quickly moving through the karst systems, 3) base flow from shallow karstic aquifers in Romania and Bulgaria is dominated by water infiltrated during the winter months, while deep aquifers discharge old water (>50 yrs and up to 14,000 yrs old), with no indications of being connected to present-day precipitation.

Our data suggests that in both tropical and temperate karst environments, short and intense precipitation events do not significantly contribute to the effective recharge of shallow aquifers, while secondary (and tertiary) porosity controlling flow through the unsaturated zone, are rapidly removing water from the rock. As virtually all climate models predict the intensification of the global hydrologic cycle, leading to more extreme rain events, as well as the increase in the frequency and intensity of tropical storms, it results that karstic aquifers are prone to continuous depletion, leading to water shortages that could prove catastrophic for communities relying on them for their water needs.

Keywords: *Karst, aquifer, extrem events, stable isotopes, long-term drying*
Ključne besede*: Kras, vodonosnik, ekstremni dogodki, stabilni izotopi, dolgoročno sušenje*

Systematics of geometric and hydraulic properties of karst conduits revealed by LiDAR-derived 3D models of cave walls

Sistematična analiza geometrijskih in hidravličnih značilnosti kraških kanalov na podlagi LiDAR-skih 3D modelov jamskih sten

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In karst landscapes, the formation of voids through the dissolution of limestone occurs across many scales. Over time, these voids coalesce into conduit networks focussing the majority of water flow and solute transport. Estimating head losses along a given part of the network conduit requires two main parameters: hydraulic diameter and roughness. The first can be computed from the topometric data of traditional cave surveys, while the second is usually sampled from a range of plausible values, corresponding to the expected size of obstacles to flow relative to the conduit opening. Therefore, flow and transport models need a realistic representation of the conduits. However, a fundamental challenge in modelling flow in karst is the representation of the complex three-dimensional geometry of conduits, and specifically how to substitute a section of cave by its equivalent conduit. To address this challenge, we surveyed cave passages and analysed their geometry and spatial organisation, and

carried out detailed geomorphological mapping. Underpinning the survey method are LiDAR technologies which we used to construct precise and accurate maps of real cave passages wherever they are known and accessible. We built a catalogue of real cave geometries by selecting various hydrologically active cave passages from the Jura and European Alps: the KarstConduitCatalogue (available at: https://doi.org/10.60544/sbjr-z851). We computed high-resolution meshes of key passages to perform the calculation of geometric indicators from mesh at regular section intervals. Using a variety of shape descriptors, we present the systematics of meso-scale geometric attributes of this karst conduit catalogue. We highlight the value of generating new morphometric indicators adapted to the complexity of cave datasets to calculate equivalent hydraulic radii, or along passage roughness, both of which can be used to inform cave-network scale models of flow and transport, and better constrain their behaviour with regards to extreme flow events.

Keywords: *Cave survey, LiDAR scanning, surface reconstruction, shape analysis*
Ključne besede*: Jamska izmera, LiDAR skeniranje, rekonstrukcija površja, analiza oblike*

Taking into account recharge by snow for accurate karstic discharge modelling: implications for water resource management in the Dévoluy Massif (France)

Vključevanje snežnega napajanja v natančno modeliranje kraškega odtoka: implikacije za upravljanje vodnih virov v masivu Dévoluy (Francija)

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Rainfall-discharge modelling is an essential tool for understanding the behaviour of mountain karst systems, particularly in regions affected by precipitation with a significant snow component. The Dévoluy karst, located in France's Southern Alps, is a perfect example of this problem, given the high contribution of snow to the recharge of the hydrogeological system. To assess the impact of snow recharge on karst reservoir discharge, we used KarstMod, a reservoir rainfall-discharge model adapted to karstic systems. Our simulations show that the absence of snow recharge during modeling leads to a significant underestimation of spring discharge, resulting in an inability to accurately reproduce the system's behavior during the snowmelt period. By integrating KarstMod's snow routine, we were able to parameterize the accumulation and progressive release of water in the system, reproducing the effect of snow accumulation and melting. This enabled us to significantly improve the modeled discharge, both in spring during melting period and in winter, when the water is stored in the snow and does not contribute directly to discharge. This approach also enabled us to assess the sensitivity of the karst system to climate variations by modifying the snow routine parameters to simulate temperature changes associated with global warming. We show that higher temperatures lead to a reduction in the snowpack, causing faster recharge and lower water storage in winter. Discharge is lower in spring and low-water periods are longer in summer. This study highlights the importance of taking account of snow processes in hydrological modelling of mountain karst systems. The use of KarstMod, coupled with fine calibration of its snow routine, not only improves the representation of reservoir discharge, but also enables us to explore the potential impacts of climate change on these vulnerable systems. This approach opens up prospects for improved water resource management in mountainous karst environments.

Keywords: *Rainfall discharge modelling, snow recharge, mountainous karst environnment*
Ključne besede*: Modeliranje odtoka padavin, snežno napajanje, gorsko kraško okolje*

Distribution and complexity of karst depressions in the Rovte area (Central Slovenia): a geomorphometric and lithological perspective

Razporeditev in morfološka kompleksnost kraških depresij na območju Rovt v osrednji Sloveniji: geomorfometrična in litološka analiza

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This study presents geomorphological characteristics of karst depressions in the Rovte area in Central Slovenia. The region is part of the prealpine (isolated) karst and lies within the transitional zone between the Dinaric and Alpine karst. The karst landscape has developed in nearly latitudinal belts of Lower and Middle Triassic dolomites, limestones, and marly limestones, which are interbedded with siliciclastic rock sequences. Closed depressions of various sizes and shapes are a common landform in both dolomites and limestones, with a moderate to high doline density (40 dolines/km² in average). The main objective of this study was to investigate the relationship between the morphometric parameters of identified closed depressions, their complexity, and the lithostratigraphic units of the area. Special attention was given to the analysis of complex karst depressions occurring in clusters across different units. The analysis was based on a 1 × 1 m DEM obtained from the ARSO Geoportal (https://gis.arso.gov.si), along with a digital version of the geological map of the region at a scale of 1:25,000. The results were then validated through field observations. The Minimum Eroded Volume method was used to determine the denudation rate and its spatial variations across different lithostratigraphic units. The most complex and largest karst depressions are found in the Lower Triassic dolomites, forming the highest and best-preserved fragment of the karst plateau in the study area.

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Keywords: *karst depressions, geomorphometric indices, denudation rate, Rovte, Central Slovenia*
Ključne besede: *Kraške kotanje, geomorfometrični kazalniki, stopnja denudacije, Rovte, osrednja Slovenija*

CO_2-controlled processes in speleogenesis and climate geoengineering

Procesi, nadzorovani z ogljikovim dioksidom, v speleogenezi in geo-inženirstvu za uravnavanje podnebja

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In August 2024, the Damokes Bridge Cave was discovered in the Totes Gebirge in Austria. Special attention was paid to a small chamber with a corrosional notch. The cave and chamber are presented. What is new is that this notch is not interpreted as recent evidence of a cave lake, as in Boegli 1978, but as an early speleogenesis form from times of previously soil-covered karst. This interpretation follows the Nerochytic Speleogenesis (NERO for short). This theory assumes, that in summer CO_2 passes from the soil into the cave air and from the cave air into old, calcium-saturated karst water. This then gives it additional dissolving power. NERO karstification could be considered one of the most important processes in overall karstification in the future. Understanding CO_2-controlled karstification processes, such as NERO, could have great potential in climate geoengineering. Carbon capture and storage (CCS) from exhaust gases is mature. There are some analogies to natural karstification processes. These analogies help to make CCS acceptable for humans. Carbon capture from karst springs is more economical than carbon capture from the atmosphere. Lime tuff from farming (inspired

by peat moss from farming) could be a great building material compared to cement building materials. Details are presented.

Keywords: *Speleogenesis, climate geoengineering, mobile CO_2*
Ključne besede*: speleogeneza, podnebno geoinženirstvo, mobilni CO_2*

A comparative study of time-series data from high-latitude karst springs
Primerjalna študija časovnih nizov podatkov iz kraških izvirov na visokih geografskih širinah

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Small karst springs provide accessible drinking water sources in rural areas and may sustain a low water flow even during dry or cold periods. Time-series data from springs give information on the hydrodynamic function and the physical-chemical response of the aquifers to recharge events. Here, we present multi-parameter data sets from four small karst springs used for water supply. The springs are in marble stripe karst in North Norway, which experiences a west coast climate. Despite similarities in precipitation pattern, catchment size and karstification, the springs display contrasting temperature and electrical conductivity (EC) patterns. In addition to event-based responses, seasonal to diurnal fluctuations are detected. A stable temperature pattern and high EC reflect diffuse recharge conditions and high water–rock contact, though extensive cave systems and cave streams imply that preferential flow paths exist within the aquifers. In contrast, a seasonal temperature pattern combined with high-magnitude short-term temperature and EC oscillations are associated with ephemeral point recharge and stream sink. In general, there is a strong correlation between EC and Ca-concentration, which are negatively correlated with flow rate, and thus reflects variability marble dissolution. However, some (short-term) fluctuations in EC suggest that other mechanisms also play a role. Comparison of data from springs in similar settings allows for a better understanding of the influence of subsurface karstic systems versus external recharge conditions. Continuous monitoring data provides a context for interpreting discontinuous water sample data, essential for designing a proper sampling strategy to assess water quality (and quantity) for springs utilized as drinking water. Furthermore, long-term monitoring is vital to evaluate the influence of climate change, extreme events, and human intervention on catchments, aquifers and water resources.

Keywords: *Karst hydrology, time-series, marble karst, spring*
Ključne besede*: Kraška hidrologija, časovne vrste, kras v marmorju, izvir*

Microbial diversity on cave walls in Slovenian karst caves
Raznolikost mikrobnih združb na stenah Slovenskih kraških jam

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Caves are generally characterized as habitats with constant darkness, high humidity, low and stable temperatures and limited nutrient availability. Despite these seemingly uniform conditions, micro-locations within caves can differ and influence microbial communities. The aim of the study was to

characterize the microbial communities on cave walls in six Slovenian caves and to investigate their diversity. Two samples were taken from each selected wall at a distance of 0.5 to 1 m using sterile brushes. DNA was extracted and bacterial 16S rRNA genes were analysed by Illumina sequencing. The results show that the community structure varies between caves and even between individual micro-locations on the same cave wall. Actinomycetota (38.8% to 69.8%) and Pseudomonadota (49.3% to 67.3%) dominated in most samples, except at one micro-location in Škocjanske jame, where Bacillota (50.2%) predominated. Besides bacteria, archaeal taxa were also identified, with a notable presence of Thermoproteota in Županova jama (Velika dvorana chamber; 10.0% to 15.2%) compared to other caves. Based on the identified genera, chemoorganotrophic bacteria dominated on all surfaces, except one micro-location in Kostanjeviška jama, where *Nitrospira* showed the highest abundance (47.6%). The identified genera and their abundance varied between the micro-locations on the individual walls, except in Predjama and Županova jama, where the community structures were similar. Among the genera that constituted at least 1% of the community, *Gaiella* and *Pseudonocardia* were found in all caves. Interestingly, *Kribella*, appeared only at one site in Jama pri Svetih Treh Kraljih. The methylotroph *Hyphomicrobium* was found in all caves, except Predjama. The methanotroph *wb1-P19* dominated in Predjama (51.4% to 53.3%) and Županova jama (Velika dvorana; 44.7% to 49.3%). In Županova jama, the abundance of *Methylocapsa* (15.1% to 16.9%) was higher compared to other caves, as was the abundance of *Nitrosarchaeum* (6.9%) at one micro-location in Postojnska jama. These results highlight the spatial heterogeneity of microbial communities among close and distant sites in cave ecosystems.

Key words: *Microbiome, extreme environment, micro-location, 16S rRNA gene sequencing*
Ključne besede: *Mikrobiom, ekstremno okolje, mikrolokacija, 16S rRNA amplikonsko sekvenciranje*

The Overlooked Threat: Impacts of Wildfire and Mitigation on Karst
Spregledana grožnja: vplivi gozdnih požarov in omilitvenih ukrepov na kraško okolje

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The worsening global impact of wildfires, fueled by more pronounced drought due to climate change, and expanding development into forested areas, is causing escalating natural, social and economic damage. A 2023 report from the U.S. Congress Joint Economic Committee, estimates the annual cost of wildfires in the USA at $394–$893 × 109. Consequently, protecting lives and infrastructure necessitates a greater dependence on aerial fire retardants (i.e., Phos-Check), which include chemicals like ammonium polyphosphate. Due to climate change, wild fires are more frequent and devastating and present global threat (i.e., in Mediterranean karst). Wildfires in karst, alter forest ecosystems, decrease carbonate dissolution and speleothem growth, change groundwater recharge, as well as increase pollutant transport and sedimentation. Maps for aerial applications identify sensitive species, cultural resources, and waterways, but fail to account for vulnerable karst areas. The use of fire retardants can increase concentration of nutrients (N, P) and eutrophication as well as toxic metals (e.g., cadmium, chromium, and vanadium) in water sources, impacting water quality and aquatic ecosystems. However, the impact on karst aquifers—combination of highly permeable systems prone to rapid contaminant transport and poor permeability in less karstified rock mass—has received little attention. Tobin et al. (2014) documented fire-retardant contamination of karst groundwater in Sequoia National Park, California, potentially affecting sensitive aquatic ecosystems. Good-scenario wildfire management must balance protecting life, infrastructure, and ecosystems while minimizing environmental damage. In karst, the rapid movement of fire retardants into groundwater raises concerns about long-term contamination. Given the increasing frequency of wildfires, action is needed

to designate sensitive karst areas as fire avoidance zones and to study the movement and ecological consequences of fire retardants. Future research should assess the persistence of fire-retardant contaminants in karst systems, impact on groundwater-dependent ecosystems, and strategies for mitigating contamination.

Keywords: *Wildfires, fire retardants, wildfire suppression, environmental impact, karst fire avoidance zones, karst ecosystems*
Ključne besede*: Gozdni požari, zaviralci gorenja, zatiranje gozdnih požarov, vpliv na okolje, območja za preprečevanje požarov na krasu, kraški ekosistemi*

Preliminary results of isotope studies in the Late Holocene speleothem from Gigant cave in the Prokletije mountains, Montenegro

Preliminarni rezultati izotopskih raziskav poznoholocenske sige iz jame Gigant v pogorju Prokletije, Črna gora

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The Prokletije Mountains represent the highest part of the Dinaric Alps, where intensive and systematic speleological exploration has been carried out since 2006. However, scientific research in this region began only recently. The presented results come from the Kolata Massif area, which hosts what are likely the oldest cave systems in the region. The studied speleothem was collected from Gigant Cave, one of the highest-elevation caves in the area (entrance at 2116 m a.s.l.). Gigant Cave is one of the deepest caves in the Kolata Massif. Notably, only the upper level of the cave features rich speleothem formations, including stalagmites and flowstones (Kicińska et al., 2023). A narrow entrance corridor leads into three chambers, two of which contain relatively well-developed secondary carbonates deposits. The sampled speleothem was dated to a time span between 14.5 ka and 2.9 ka. A more detailed age-depth model revealed a significant hiatus, likely encompassing part of the Early and the entire Middle Holocene. The onset of crystallization in the younger section of the speleothem, around ~4.5 ka, potentially linked to increased influence of Atlantic air masses on the regional climate (Perșoiu et al. 2017; Hercman et al. 2020). This presentation focuses on the Late Holocene, captured in a relatively continuous part of the speleothem. Preliminary stable isotope data show elevated $\delta^{18}O$ and $\delta^{13}C$ values around 4.2 ka, suggesting a period of cooling and drying—consistent with the "4.2 ka event" recorded in other paleoclimate archives from northern Italy (Zanchetta et al. 2016) and the Balkans (Zanchetta et al., 2012). After this event, a gradual warming and increase in humidity is recorded, reflected in declining $\delta^{18}O$ and $\delta^{13}C$ values until ~3.5 ka. This is followed by a renewed gradual decrease in temperature and humidity until the end of the record.

Keywords: *Prokletije mountains, Holocene, U-Th dating, stable isotopes*
Ključne besede: Prokletije, Holocen, U-Th datacija, stabilni izotopi

Integration of Karst Spring Hydrological Data and Land Use Disturbance Information: Towards Development of a Karst Catchment Management Plan, Quadra Island, British Columbia

Povezovanje hidroloških podatkov kraških izvirov z vplivi rabe prostora: k razvoju načrta upravljanja kraškega zaledja na otoku Quadra (Britanska Kolumbija)

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Considerable data has been collected over the last ten years for the Stramberg karst springs on Quadra Island which are used as a domestic water resource and have a catchment in an area of active land use and forestry operations. A key part of this research has been to investigate the karst springs' water quality and quantity over time and assess any changes due to land disturbance activities and/or climate change and extreme weather events. Continuous monitoring of this karst spring has collected measurements of flow rate (water level), conductivity, water temperature, turbidity, ambient air temperature and rainfall. Field mapping along with LiDAR and dye tracing (in the past) have delineated the extent of the karst catchment and the likely subsurface flow paths, suggesting a relatively shallow karst with both autogenic and allogenic recharge components. Details on the locations and ages of forestry activities (e.g., new cut blocks) in the karst catchment have also been determined along with other land use activities. Recent research from the nearby Port Alberni karst spring using an R software routine has resulted in the development of a framework for data analysis allowing for the systematic evaluation of annual surface temperature and precipitation records (on and off site), as well as comparisons between spring water temperature, water level, water conductivity and turbidity data. This R software routine has been modified and applied to the Stramberg karst springs. It is anticipated that on completion of the analysis the hydrological findings will be incorporated into a karst spring and catchment management plan that will take into consideration the water users, forest tenure holders, and the local First Nations. The local First Nations community has indicated their support and interest in the project, fostering mutual learning, collaboration, and a shared respect for the land and water.

Keywords: *Karst springs, Vancouver Island, hydrological monitoring, land disturbance, climate change, First Nations*
Ključne besede*: kraški izviri, otok Vancouver, hidrološko spremljanje, motnje rabe zemljišč, podnebne spremembe, staroselska ljudstva*

The SLO KARST Near-Fault Observatory: monitoring tectonic dynamics in southwestern Slovenia

SLO KARST obprelomni observatorij: spremljanje tektonske dinamike v JZ Sloveniji

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The area of the Slovenian Karst Near-Fault Observatory (SLO KARST NFO, https://slo-karst-nfo.si/) is located in southwestern Slovenia between Postojna, Jelšane and the Snežnik Castle area and covers an area of approximately 2,000 km^2. The first Slovenian NFO site was established in 2020 with the aim of becoming part of the EPOS Thematic Core Service (TCS) Near-Fault Observatories (NFO). It consists of a new seismic network with seven stations (https://www.fdsn.org/networks/detail/S5/) and is jointly operated by the ZRC SAZU Karst Research Institute and the Slovenian Environment Agency (ARSO). The seismic data is collected by both operators in real-time and shared with the EIDA node NIEP. In addition to its seismic network, the SLO KARST Near-Fault Observatory (NFO) serves as a multidisciplinary research infrastructure located in a tectonically active karst region. It integrates

studies in seismology, geology, geodesy, and karstology. The observatory features multi-parametric monitoring, including measurements of fault deformation using extensometers within the Postojna Cave. It also supports continuous observation of chemical processes (radon, methane, carbon dioxide), the cave atmosphere (air temperature, humidity, air pressure, and ventilation), and hydrological parameters in the nearby Pivka Valley. From 2024 to 2027, the ZRC SAZU Karst Research Institute is a partner in two EU Horizon projects: EPOS ON (The European Plate Observing System Optimization and EvolutioN) and TRANSFORM2 (TowaRds AdvaNced multidiSciplinary Fault ObseRvatory systeMs²). Both projects include solid Earth science data from the SLO KARST Near-Fault Observatory (NFO), which will be made accessible through EPOS data portals (EPOS Central Portal, FRIDGE Portal). The establishment of a new NFO network south of Postojna is a key development for generating new scientific data and products in the field of solid Earth sciences, as well as for the continuous monitoring of the chemical and physical processes that govern active crustal deformations in southwestern Slovenia
(https://www.youtube.com/watch?v=NM1so88QNgc&t=6s&ab_channel=EPOSSlovenia).

Keywords: *External Dinarides, active tectonics, karst, earthquakes, EPOS*
Ključne besede*: Zunanji Dinaridi, aktivna tektonika, kras, potresi, EPOS*

A study of silver-copper coin weathering in cave sediments

Raziskava preperevanja srebrno-bakrenih kovancev v sedimentih jamskega okolja

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An archaeological dig in a small cave from the southern part of Preluca Mountains, N Romania has uncovered various pre-modern ceramic shards as well as 12 silver - copper coins, dating from 1446 to max. 1599. The coins were dug out of a disturbed detrital sediment pile in a floor pocket of the cave passage, which accumulated silt, clays, speleothem and bone fragments, and charcoal. Two Hungarian denars minted at Kremnicz in 1557 give a minimum age for the hoard burial. The weathered coins were identified using high resolution photos and binocular microscope observations, using catalogues and internet databases. They were minted in the kingdoms of Bohemia (3), Hungary (2), Poland (6), and the free city of Schweidnitz (1), all of them by the hammering technique. Both their obverse and reverse were analysed by means of surface X-ray diffraction, Raman spectroscopy, and scanning electron microscopy. Once the initial analyses on the coin surfaces were completed, weathering crusts were sampled from the coin surface and re-analysed by the same methods. Mineralogical analyses of the weathering crusts have shown that cuprite and malachite are the main secondary minerals formed on the coins, while rouaite, a copper nitrate, though ubiquitous, generally occurs as a minor component with a better defined XRD pattern in one of the coins. We have also noticed neo-formation silver in the forms of cubic crystals (rare) and "whiskers" (?) on the surface of several coins. The formation of cuprite and malachite is due to the exposure of the coins to the humidity of the cave sediments, the latter in the presence of CO_2 enriched dripwater seeping in the cave sediments. The nitrogen required for rouaite precipitation has probably derived from bird and mammal droppings in the sediments near the cave entrance.

Keywords: *Archaeological excavation, cave sediments, coin weathering*
Ključne besede*: Arheološka izkopavanja, jamski sedimenti, korozija kovancev*

U-Th dating of internal speleothem reference materials – laboratory comparison of LSCE and ATOMKI

Datiranje sige z metodo U-Th na notranjih referenčnih materialih: primerjava laboratorijev LSCE in ATOMKI

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U-Th dating is a frequently applied geochronological method in karst studies to constrain the age of speleothems for various purposes (e.g., reconstruction of cave evolution, speleothem-based paleoclimate studies, constraining the age of archeological findings etc.). Various analytical approaches are applied by different laboratories, both in terms of the chemical preparation of the samples and subsequent isotopic measurements. To assure the quality of the obtained geochronological data, beyond the requirement of the quality of the analyzed material (e.g., U-series closed system evolution, free of detrital Th), reference materials can be analyzed independently at different laboratories. For this purpose, two internal speleothem reference materials have been prepared and their U-Th age determined independently at two laboratories: at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) in France, with long-term experience in U-Th dating, and at the HUN-REN Institute for Nuclear Research (ATOMKI) in Hungary, where the method was recently established. The speleothem reference materials were prepared from stalagmites obtained from Dino Cave in Ecuador (D1std) and Salamandre Cave in France (SalamExt). Subsections of the stalagmites were cut, cleaned, crushed to powder and sieved to <500 µm size, with powder aliquots subsequently shared between the laboratories. At both laboratories chemical separation of U and Th fractions followed similar procedures with the isotopic measurements carried out on Thermo Scientific Neptune Plus MC-ICP-MS, connected to Aridus 3 desolvating system. Detailed descriptions of the analytical procedures for LSCE are given in Pons-Branchu et al. (2014, 2022) and for ATOMKI in Temovski et al. (2024). Comparison of the obtained results will be presented.

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Keywords: *U-Th dating, speleothems, reference materials, laboratory comparison*
Ključne besede*: U-Th datiranje, siga, referenčni materiali, laboratorijska primerjava*

Geomorphology of the Egyptian Travertine Alabaster Caves, the Eastern Desert of Egypt

Geomorfologija egipčanskih travertinskih alabastrnih jam, vzhodna puščava Egipta

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Egyptian alabaster is a unique mineral formed when calcium carbonate crystallizes from spring water rich in dissolved calcium bicarbonate. Most commonly, it is seen as small bowls, vases, and other small artifacts in most ancient Egyptian archaeological sites; although a few locations provided cave-like veins of stone, it probably provides the origin of the term "alabaster cave." The common term for this specific form of alabaster is "travertine." There are only a few sources for this form of gypsum. The major source is the Eastern Desert, from some caves and open-pit quarries at Hatnab, near Tell El Amarna. There is still a lesser-known third source in the environs of Helwan, well to the south of Cairo City. This research considers the geomorphological work. The research employs Lidar scanning for 3D mapping, laser total station surveying, and profiling, and also uses carbon 14 to date a sample of stalactites from one of the caves in Tell El Amarna. The author found two alabaster caves in the Tell El Amarna area, south of Minia Governorate, in 2023 and 2024. Neither of these two caves had been explored before, and they were found in addition to the famous Sannur Cave SE of Bani Sweif City in Egypt's Eastern Desert. Some geomorphological maps were made to show how the karst geomorphological features found in the caves were spread out geographically. These features included stalactites, stalagmites, columns, curtains, and other formations in the Sannur Cave's horizontal chambers and the Tell El Amarna area's vertical dual levels. Their presence shows how vulnerable these caves are to climate change.

Keywords: *Egyptian alabaster, travertine alabaster caves, Sannur Cave, Tell El Amarna, Eastern desert of Egypt*

Ključne besede*: Egipčanski alabaster, jame v travertinu, jama Sannur, Tell El Amarna, vzhodna puščava Egipta*

Microfacies and mineralogical investigations of an Upper Eocene detrital sequence from Tăușoare Cave, Romania

Mikrofaciesna in mineralna analiza zgornjeeocenske detritičnega zaporedja iz jame Tăușoare (Romunija)

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We present an investigation of a 4-m sedimentary sequence from Tăușoare Cave, Rodnei Mountains (Northern Romania) by means of optical microscopy, X-ray diffraction, scanning and transmission electron microscopy and energy dispersive X-ray spectroscopy. Four main lithofacies types characterize the studied sedimentary sequence from the Tăușoare Cave. They are represented by carbonate beds, carbonate micro-breccia levels, sandstone layers and clays. The bottom and top carbonate beds of the studied sequence present two main microfacies types, bio-extraclastic grainstone/packstone and bioclastic wackestone with Chapmanina. The main mineral constituents of the studied sequence are quartz, calcite, muscovite, chlorite and occasionally pyrite, plagioclase feldspars and kaolinite. The clay fraction is dominated by muscovite and chlorite, with palygorskite and rectorite occurring in several samples. The secondary minerals formed through the exposure of the

deposits to the cave environment are aragonite, iron hydroxides, gypsum and natrojarosite. The abundance of quartz extraclasts and of other silicates, the poor sorting of the main mineralogical components, as well as the dominance of the granular sparitic facies prove the proximity of the deposits to the source area. The structural-textural features of the dominant microfacies types of the carbonate units reflect an internal, shallow-water paleoenvironment characterized by different grades of hydrodynamic regimes, in a ramp-type depositional system during the late Eocene. The vertical architecture of the studied lithofacies reflects progressive changes in the sedimentation rates, and a rhythmically developed appearance with a shallowing-up tendency for the whole succession.

Keywords: *Carbonates, mineralogical association, rectorite, natrojarosite*
Ključne besede*: Karbonati, mineralna asociacija, rektorit, natrojarozit*

Ecohydrological Impacts of Large-Scale Forest Disturbances on Karst Aquifers
Ekohidrološki vplivi velikopovršinskih motenj gozdov na kraške vodonosnike

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Large-scale forest disturbances play a crucial role in the dynamics of forest ecosystems and have a significant impact on hydrological processes such as evapotranspiration, soil infiltration and recharge processes. Karst aquifers, known for their biodiversity and groundwater resources, are particularly vulnerable to environmental changes due to their unique hydrological characteristics. In this study, the effects of large-scale forest disturbance on karst hydrology are analysed. First, a global and regional assessment of forests on carbonate rocks was conducted using publicly available geodatabases of forests and karst aquifers. Of the 45.6 million km² of forested area worldwide, 6.3 million km² (13.9%) are located on carbonate rock, which corresponds to 31.3% of the world's karst aquifers. Secondly, 117 full-text articles and 160 case studies on forest disturbances and hydrological processes from 2001 to 2020 were analysed as part of a systematic literature review according to the PRISMA checklist. Most studies (2011–2017) were conducted at the plot or catchment scale, with 29% focussing on karst areas—more than expected given their global distribution. Research primarily addressed the effects of fire, pests and disease, but no study examined the effects of ice storms on hydrology or the effects of pests and disease in karst areas. To better understand the effetcs of large-scale forest disturbance on the ecohydrology of karst aquifers, a Karst Critical Zone Observatory was established in the Postojna–Planina karst area in southwestern Slovenia, using an innovative, multi-level ecohydrogeological monitoring approach. This framework improves the monitoring of ecohydrogeological interactions at the interface between the atmosphere, geosphere, hydrosphere and biosphere and promotes interdisciplinary cooperation in environmental management. Considering the sensitivity of karst aquifers to changing environmental conditions and large-scale forest disturbances, we highlight important knowledge gaps and outline future research priorities.

Keywords: *Evapotranspiration, soil infiltration, recharge processes, carbonate rocks, Karst Critical Zone Observatory*
Ključne besede*: Evapotranspiracija, infiltracija tal, procesi napajanja, karbonatne kamnine, kraška kritična opazovalna cona*

Fluorescent calcites in the Molnár János Cave

Pojav fluorescenčnih kalcitov v jami Molnár János

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Calcite in its pure form is not fluorescent, however common impurities can cause vivid fluorescence for UV excitation. The presence and type of fluorescence carries information on water chemistry and conditions during the formation of the mineral. Observations of fluorescent calcites in submerged environments are relatively rare, since waterproof UV lights emitting the necessary excitation frequencies are not widespread. The Molnár János Cave is a submerged hypogenic cave located under the Hungarian capital. The walls of its passages are rich in calcite and baryte crystals, that were deposited in several layers from thermal water filling the fissures pre-forming the present cave. Upon irradiation by UV light some calcite crystal layers show vivid pink fluorescence. By mapping the position and orientation of the fluorescent and non-fluorescent layers, and by determining the impurities in calcite that are promoting or inhibiting fluorescence (e.g., manganese and iron) we plan to extract information about the prevailing conditions at the time of the different phases of crystal formation.

Keywords: *Calcite, fluorescence, underwater cave, crystal formation*
Ključne besede*: Kalcit, fluorescenca, podvodna jama, tvorba kristalov*

Poljes, a pre-structuration of the hydrosystems in plateau karsts, the example of the Jura mountain (France)

Polja kot predstrukturni elementi hidroloških sistemov v planotastih krasih: primer gorovja Jura (Francija)

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The aim of this work is to analyze—through the prism of poljes—the development of karst networks and the organization of underground drainage in the case of plateau karsts. The methodology combines various approaches: i) surface morphology, ii) speleogenesis and iii) hydrogeology. The study site is the Loue basin, located in the french Jura Mountains. It is a typical plateau karsts, with its high karstification degree (around a hundred karst networks over 100 m, several karst springs with an average flow superior to 1 m^3/s), and its extensive hydrogeological knowledge of karst hydrosystems (several hundred dye tracer tests available). First, a detailed surface morphological mapping has shown that the current plateaus correspond to ancient depressions with relatively flat, elliptical bottoms, and large extension (~400 km^2). These plateaus are enclosed between the raised hydrological barriers of anticlines (fold systems). We interpreted these depressions as paleo-poljes. Currently perched 150 m above the base level, they only have a residual hydrological functioning; that is the lowest of them are subject to occasional flooding by exceeding the infiltration capacity of the ponors. Second, the analysis of numerous dye tracer tests within the largest karst hydrosystems has enabled us to determine their current recharge area. A strong spatial correlation between the geometry of the recharge area and the paleo-poljes suggests that the poljes plays a pre-structuring role in the organisation of the underground drainage. Third, the analysis of the horizontal galleries (relative altitude and endokarst forms) shows several significant levels and different speleogenetic processes (paragenesis, alteration) that can be linked to ancient local base levels contemporary of the hydrological functioning of the

paleo-poljes (regular and long periods of flooding). Finally, our results enable us to propose a new conceptual model of plateau karsts in the Jura Massif, highlighting the role of poljes in karstogenesis and in the hydrogeological compartmentation of current hydrosystems.

Keywords: *Plateau karst, polje, speleogenesis, hydrologeology, Jura mountains*
Ključne besede*: Planotasti kras, polje, speleogeneza, hidrogeologija, gorovje Jura.*

Sub-BioMon project - Addressing the challenges of monitoring subterranean biodiversity in karst

Projekt Sub-BioMon: reševanje izzivov spremljanja podzemne biotske raznovrstnosti v kraških okoljih

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Monitoring the status of biodiversity in time is especially challenging in subterranean habitats. Subterranean species are rare, difficult to find and typically having small distribution ranges. The subterranean biodiversity is unevenly distributed, with only a few very rich regions, and big community changes already at short distances. Caves are the points of direct human access to subterranean realm, while species inhabit also small fissures around the large voids. Currently, there is no standardized sampling method to monitor the subterranean biodiversity via caves, which would enable assessment of its conservation status, and detection of any negative trends. The development of monitoring approaches is the central challenge of the three-year international project Sub-BioMon, funded by the EU Biodiversa+ mechanism (https://www.sub-biomon.net/). The aim is to establish standardized methods that will allow a comparison of the state of the subterranean biota in different geographical regions and over time. We will test field-sampling methods at a set of caves in each country, and define subterranean bioregions based on selected taxa. We will explore the efficiency of DNA-based molecular approaches (DNA barcoding, eDNA) in routine species identification and detection. The project includes the stakeholders, from national authorities to general public. To identify specific needs, we conducted a survey addressing different stakeholders, on acquaintance with needs of subterranean biodiversity monitoring. Partners come from six European countries, where there are different proportions of karst, richness of subterranean species as well as levels of national monitoring of these habitats. Caves are protected as a habitat type under the EU Habitats Directive (8310 “Caves not open to the public”), and need to be biologically monitored. The project will provide the scientific baseline for subterranean biodiversity monitoring and aims to facilitate its implementation also in the wider international community.

Keywords: *Monitoring, caves, springs, biodiversity*
Ključne besede*: Spremljanje, jame, izviri, biotska raznovrstnost*

Investigations of Microplastics in the Poole's Cavern karst System

Preučevanje prisotnosti mikroplastike v kraškem sistemu Poole's Cavern

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Microplastic pollution (particle size <5 mm) has become a significant environmental concern, with widespread presence in oceans, rivers, soils, and groundwater systems. However, its occurrence in karst groundwater systems, which are highly vulnerable, remains underexplored. The aim of this study is to investigate the movement and accumulation of microplastics in the Poole's Cavern tourist cave in the UK Carboniferous limestone karst, by examining water samples collected from sinking streams, cave stream points, and springs. The study also assessed whether sediment samples from the cave stream bed accumulate microplastics. Microplastic analysis was performed using FTIR (Fourier Transform Infrared Spectroscopy), capable of detecting particles as small as 25 µm. Preliminary findings showed that microplastics were present in all water samples, with concentrations increasing downstream through the system (stream sinks → Poole's Cavern → springs). Comparison of springs, one fed by the cave stream and one without, indicated an increase in microplastic concentrations downstream, but the study found no clear influence of cave tourism. Silicon-based polymers were the most frequently detected with the range of below detection limit (BDL to 1.5 MPs/L), followed by polyester (BDL-2.55 MPs/l) and polypropylene (BDL to 2.32 MPs/L). Sediment samples will be analysed to assess microplastic accumulation. This research represents the first investigation of microplastics in a UK cave system, providing valuable insights into their distribution and movement within karst groundwater systems.

Keywords: *Microplastics, karst groundwater, Poole's Cavern, FTIR Analysis*
Ključne besede*: Mikroplastika, kraška podzemna voda, Poole's Cavern, FTIR analiza*

Geochemical behaviour and health risks of trace elements in karst water systems: role of allogenic water in mitigating contamination

Geokemijske značilnosti in zdravstvena tveganja elementov v sledovih v kraških vodnih sistemih: pomen alogenih voda pri zmanjševanju onesnaženja

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Karst water systems, critical for global freshwater supply, are prone to trace element contamination, particularly in regions with high geological metal backgrounds and dynamic recharge. Yet the influence of allogenic water is poorly understood. This study examines the geochemical behaviour and health risks of trace elements in karst water sources—allogenic water (Aw), surface water recharged by Aw (ASw), groundwater recharged by Aw (AGw), and karst groundwater (Kw)—in Guangxi, southern China. Using multivariate statistics and Monte Carlo simulations, we found that while heavy metal concentrations complied with Chinese drinking water standards, iron exceeded 0.3 mg/L in 34.5% of

samples (max: 1.80 mg/L in ASw), and 13.8% of samples exceeded Al and Mn limits, predominantly in Aw and ASw, due to weathering and redox dynamics. The Crystal Ball simulation indicates that Mn is the leading non-carcinogenic risk factor via dermal exposure, while As and Cd contribute significantly to ingestion risks. Allogenic water interactions modulated contamination through dilution, adsorption, and redox transformations, reducing risks in AGw. These findings highlight Mn, As, and Cd as priority contaminants in karst systems and underscore allogenic water's role in natural attenuation. By linking geochemical processes to health outcomes, this study offers insights for mitigating chronic exposure risks in karst regions, emphasizing pH and redox management as practical strategies for sustainable water safety.

Keywords: *Karst, trace elements, health risk assessments, allogenic water, Monte Carlo simulation*
Ključne besede*: Kras, sledni elementi, ocene zdravstvenega tveganja, alogena voda, Monte Carlo simulacija*

Cave sediments as archives of extreme climatic and hydrological events
Jamski sedimenti kot arhivi ekstremnih podnebnih in hidroloških dogodkov

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Cave sediments represent valuable archives of past environmental dynamics, particularly extreme hydrological and climatic events such as floods, droughts, and episodes of intense precipitation. Through detailed stratigraphic, sedimentological, and geochemical analyses, it is possible to reconstruct the frequency, magnitude, and environmental context of such events over various timescales. Cave sites offer unique insights into how karst systems have responded to both long-term climate variability and sudden, high-energy disturbances. A combination of preliminary, newly obtained, and previously published results from caves of the Classical Karst region illustrates the potential of cave sediments to capture and preserve evidence of extreme events across diverse karst settings. These findings enhance our understanding of the mechanisms behind such events and their lasting imprints within the subsurface, thereby supporting efforts to anticipate and mitigate their future impacts.

Keywords: *Cave sediments, karst, extreme events, paleoclimate, hydrological variability*
Ključne besede*: Jamski sedimenti, kras, ekstremni dogodki, paleoklima, hidrološka spremenljivost*