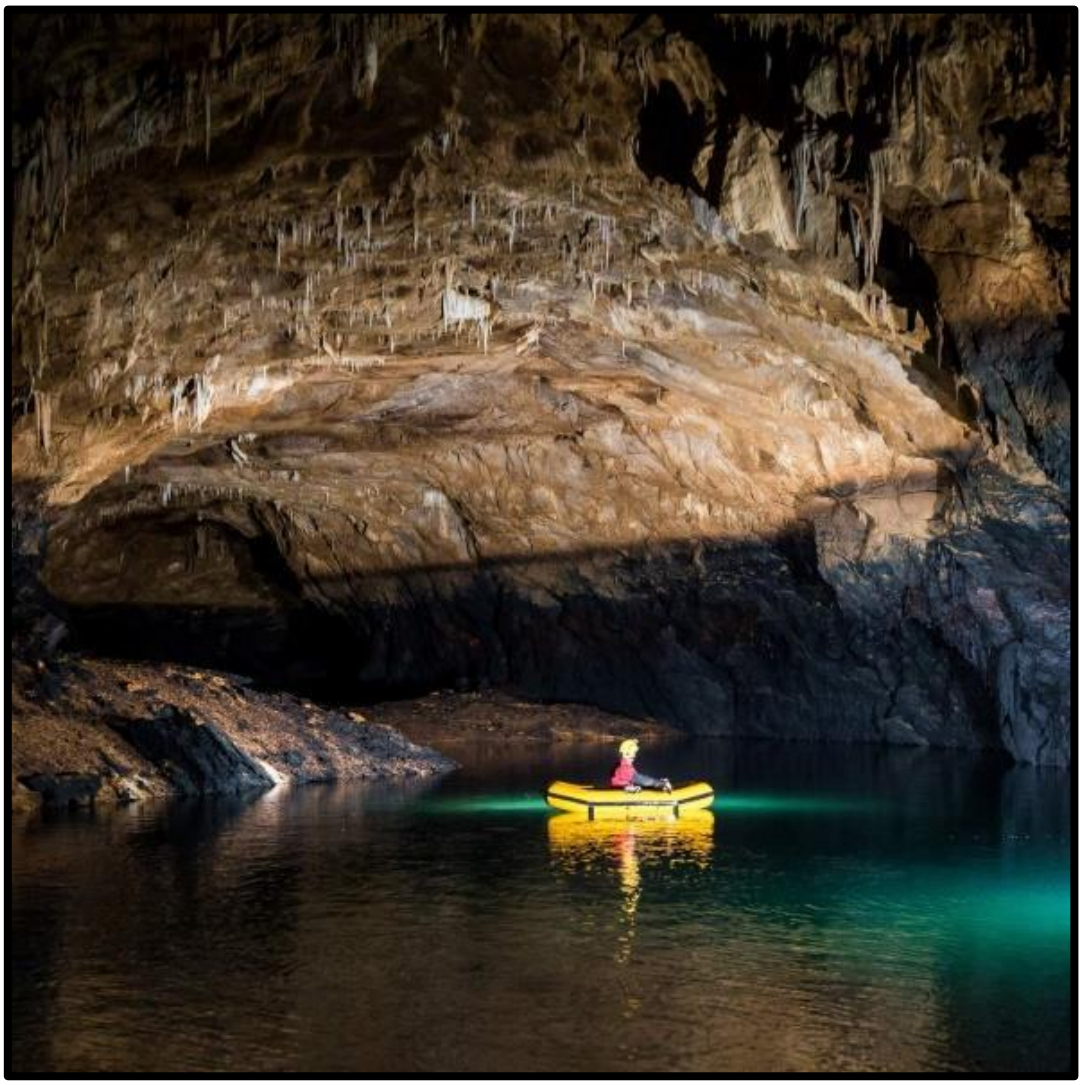
27th INTERNATIONAL KARSTOLOGICAL SCHOOL
"Classical Karst"

27. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

# KARST HYDROGEOLOGY – RESEARCH TRENDS AND APPLICATIONS

## KRAŠKA HIDROGEOLOGIJA – RAZISKOVALNI TRENDI IN UPORABA IZSLEDKOV



ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

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## KRAŠKA HIDROGEOLOGIJA – RAZISKOVALNI TRENDI IN UPORABA IZSLEDKOV

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POVZETKI & VODNIK

Postojna
2019

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Rak Branch in the cave of Planinska Jama (M. Blatnik)

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PROGRAM

| Monday, June 17th, 2019<br>Ponedeljek, 17. junij 2019 | |
|---|---|
| 8:00–13:00 | **REGISTRATION** / PRIJAVA UDELEŽENCEV |
| 9:00–9:20 | **OPENING CEREMONY** / OTVORITVENA SLOVESNOST |
| | **SESSION 1: KARST HYDROGEOLOGY – PAST, PRESENT, FUTURE**<br>SKLOP 1: KRAŠKA HIDROGEOLOGIJA – PRETEKLE, SEDANJE IN PRIHODNJE RAZISKAVE |
| 9:20–10:00 | *Keynote lecture* / *Plenarno predavanje*<br>I. Sasowsky: Karst hydrogeology: who, what, why, where, when, & how |
| 10:00–10:20 | A. Nannoni: Structural control on water circulation in the Bossea karst system (S Piedmont, Italy) |
| 10:20–10:40 | K. Csondor: Comprehensive hydraulic and hydrochemical interpretation of a karst area in South Hungary |
| 10:40–11:10 | *Coffee break* / *Odmor za kavo* |
| | **SESSION 2: MONITORING - INSTRUMENTATION AND DATA ANALYSIS**<br>SKLOP 2: MERITVE V KRASU – VZPOSTAVITEV MERITEV IN ANALIZA PODATKOV |
| 11:10–11:40 | *Invited lecture* / *Vabljeno predavanje*<br>R. Benischke: Monitoring of Karst Water – Methods and Techniques |
| 11:40–12:00 | V. Gajović: An attempt to characterize aquifer hydrodynamics with modern analytical tools using remote sensing data and on-site monitoring (example of Mt Miroč, Serbia) |
| 12:00–12:20 | M. Lipar: Water-rock interaction in Postojna Cave: can we use stable oxygen isotopes as palaeothermometer? |
| 12:20–12:40 | D. Paar: Interaction of air and water dynamics in deep caves of Mt. Velebit, Dinaric karst, Croatia |
| 12:40–13:00 | L. Kukuljan: Decreasing the unpredictability of karst aquifers – preliminary results of speleological and hydrological research in the Učka cave system, Croatia |
| 13:00–15:00 | *Lunch break* / *Odmor za kosilo* |
| | **MIXED SESSION: KARST HYDROGEOLOGY AND MONITORING**<br>MEŠANI SKLOP: KRAŠKA HIDROGEOLOGIJA IN MERITVE V KRASU |
| 15:00–15:20 | D. Ford: Mahony, Tunago and Neyadalin, three neighbouring but contrasted karst hydrogeologic systems in glaciated & permafrozen low plateaus, Northwest territories of Canada: an introduction |
| 15:20–15:40 | H. Benabderrahmane: Karstic conduits Connectivity, natural and disturbed hydraulic behaviours of the multi-layered aquifer system of Barrois limestone – IHLLW Cigéo Project (France) |
| 15:40–16:00 | T. Faulkner: Karst hydrogeology: The high-flow low-storage extreme in marble aquifers |
| 16:00–16:20 | K. Genuite: The Châtaigniers cave (Ardèche, France) : an indicator of Pleistocene variations and Combe d'Arc meander shortcut |
| 16:20–16:40 | A. Tóth: Basin-scale conceptual groundwater flow model for carbonate regions |
| 16:40–17:00 | *Coffee break* / *Odmor za kavo* |
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| 17:00–18:00 | Quick poster presentations / Hitra predstavitev posterjev |
| 18:00–20:00 | Poster display / Ogled posterjev |
| 20:00–22:00 | **ICE BREAKER** / UVODNO DRUŽENJE |

Cultural Centre Postojna
Kulturni dom Postojna

Karst Research Institute
Inštitut za raziskovanje krasa

| Tuesday, June 18th, 2019<br>Torek, 18. junij 2019 | | |
|---|---|---|
| 8:00–11:00 | **REGISTRATION** / **PRIJAVA UDELEŽENCEV** | Cultural Centre Postojna<br>Kulturni dom Postojna |
| | **SESSION 3: WATER RESOURCES QUALITY AND MANAGEMENT**<br>**SKLOP 3: KAKOVOST VODNIH VIROV IN UPRAVLJANJE Z NJIMI** | |
| 8:30–9:00 | *Invited lecture* / *Vabljeno predavanje*<br>M. Sinreich: From monitoring to management of karst groundwater resources | |
| 9:00–9:20 | A. Persoiu: Natural attenuation of pollution in karst – a geochemical, chemical and microbial investigation in the Carpathian Mts., Romania | |
| 9:20–9:40 | L. Valentić: Microplastic pollution in karst environment | |
| 9:40–10:00 | R. DiFilippo: Monitoring and methods to assess the groundwater quality degradation risk in karstic island aquifers (Bantayan Island, Cebu Province, Philippines) | |
| 10:00–10:20 | Z. Fekete: Karst hydrogeological investigations in the Bükk Mountains (NE Hungary) | |
| 10:20–10:40 | M. Temovski: Groundwater geochemistry of the hypogene karst systems in Mariovo, Macedonia | |
| 10:40–11:10 | *Coffee break* / *Odmor za kavo* | |
| | **SESSION 4: KARST WATER UTILIZATION**<br>**SKLOP 4: UPORABA VODNIH VIROV** | |
| 11:10–11:40 | *Invited lecture* / *Vabljeno predavanje*<br>I. Jemcov: Quantitative analysis of the hydrogeological research for engineering practice in karst environment | |
| 11:40–12:00 | T. Olarinoye: Applicability of automatic recession extraction methods to a large number of karst spring hydrographs | |
| 12:00–12:20 | D. Szieberth: Investigation of the flow system of the Molnár János cave | |
| 12:20–12:40 | D. Cailhol: Strategy to investigate and understanding complex aquifers: the karst systems of "Gorge de l'Ardèche, France" | |
| 12:40–13:00 | P. Žvab Rožič: Importance of methodological approach for karst aquifers evaluation: an example of study of Učja Valley aquifer, NW Slovenia | |
| 13:00–15:00 | *Lunch break* / *Odmor za kosilo* | |
| 15:00–20:00 | **Afternoon field trip (A)** / **Popoldansko terensko delo (A)**<br>Hydrogeological and speleological researches in the area of a new railway line Divača-Koper<br>Hidrogeološke in speleološke raziskave na območju nove železniške proge Divača-Koper | |
| 20:00–22:00 | **UNRESOLVED MYSTERIES OF KARST**<br>**NERAZREŠENE SKRIVNOSTI KRASA** | Karst Research Institute<br>Inštitut za raziskovanje krasa |

| Wednesday, June 19th, 2019<br>Sreda, 19. junij 2019 | | |
|---|---|---|
| 8:00–11:00 | **REGISTRATION / PRIJAVA UDELEŽENCEV** | Cultural Centre Postojna<br>Kulturni dom Postojina |
| | **SESSION 5: SOLUTE AND PARTICLE TRANSPORT** | |
| | **SKLOP 5: PRENOS TOPNIH SNOVI IN DELCEV** | |
| 8:30–9:00 | *Invited lecture / Vabljeno predavanje*<br>L. Gill: Modelling groundwater-surface water interactions in lowland karst (Ireland) | |
| 9:00–9:20 | P. Griffiths: A retrospective look at the first dye tracing study for karst-related forest management purposes in British Columbia (Canada) | |
| 9:20–9:40 | P. Frantar: National groundwater quantity assessment – karstic case studies for Slovenia | |
| 9:40–10:00 | P. Hauselmann: Impossible karstification: the Bärenschacht saga (continued) | |
| 10:00–10:20 | T. Stokes: A 'Field Lab' on the forested karst of Quadra Island, British Columbia, Canada | |
| 10:20–10:40 | A. Malard: Visual KARSYS – a web service for modelling karst aquifers | |
| 10:40–11:10 | *Coffee break / Odmor za kavo* | |
| | **SESSION 6: WATER FLOW AND MODELLING** | |
| | **SKLOP 6: TOK VODE IN MODELIRANJE** | |
| 11:10–11:40 | F. Ulloa-Cedamanos: Long-term trends for seasonal and interannual variations of stream water chemical composition, $pCO_2$, carbonate equilibrium and hydroclimatic parameters (discharge and temperature) in a mountainous karstic catchment (Pyrenees, France) | |
| 11:40–12:00 | J.-B. Charlier: Recent advances on the characterization of karst-river interactions during floods | |
| 12:00–12:20 | T. McCormack: Remote Sensing for Monitoring and Mapping Karst Groundwater Flooding in the Republic of Ireland | |
| 12:20–12:40 | M. Le Mesnil: Investigating the role of karst on the spatial variability of catchment water balance and its impact on flood processes | |
| 12:40–13:00 | E. Kaminsky: Hydrological monitoring in an Alpine vadose shaft to estimate the storage capacity of the epikarst, Hochschwab (Austria) | |
| 13:00–15:00 | *Lunch break / Odmor za kosilo* | |
| 15:00–20:00 | **Afternoon field trip (B) / Popoldansko terensko delo (B)**<br>Recent hydrogeological investigations in the Upper Pivka Valley<br>Zadnje hidrogeološke raziskave v Zgornji Pivki | |

| Thursday, June 20th, 2019<br>Četrtek, 20. junij 2019 | |
|---|---|
| 9:00–18:00 | **Whole-day field trip (C)** / **Celodnevno terensko delo (C)**<br>Groundwater flow in the Ljubljanica recharge area<br>Značilnosti podzemnega toka v zaledju Ljubljanice |
| 18:00–20:00 | *Break* / *Odmor* |
| 20:00– ? | **Reception at the Karst Research Institute**<br>**Sprejem na Inštitutu za raziskovanje krasa** |

| Friday, June 21st, 2019<br>Petek, 21. junij 2019 | |
|---|---|
| 9:00–18:00 | **Whole-day field trip (D)** / **Celodnevno terensko delo (D)**<br>Reka-Timava flow system in Kras/Carso<br>Sistem Reka-Timava in tok vode skozi planoto Kras |

**OPTIONAL/ IZBIRNO**

| Saturday, June 22nd, 2019<br>Sobota, 22. junij 2019 | |
|---|---|
| 9:00–17:00 | **Short course Visual KARSYS**<br>(organized by Swiss Institute for Speleology and Karstology)<br>**Kratek tečaj Visual KARSYS**<br>(organizira švicarski inštitut SISKA) |

Karst Research Institute
Inštitut za raziskovanje krasa

# LIST OF POSTER PRESENTATIONS

## SEZNAM PREDSTAVITEV PLAKATOV

| | CORRESPONDING AUTHOR | TITLE |
|---|---|---|
| **1** | Addesso Rosangela | Integrated approach for the geochemical characterization of vermiculations from Pertosa-Auletta Cave (Southern Italy) |
| **2** | Al-Akhras Khaled | The challenge of building infrastructures with the presence of karst formations |
| **3** | Berthelin Romane | Preliminary results of the characterization of the linkage between soil moisture dynamics and discharge at a karst region in Southwest Germany |
| **4** | Bočić Neven | Monitoring of environmental parameters in a tourist cave – case study of Upper Barać cave near Rakovica (Dinaric karst, Croatia) |
| **5** | Borges Quadros Franco | Numerical Geological Modeling of the Karst System from Lajedo Arapuá, Jandaíra Formation, Potiguar Basin |
| **6** | Breg Valjavec Mateja | Karst depressions: geoheritage hotspots on karst surface |
| **7** | Carey Anne | The geochemistry of the glacier ice and cave ice in the Triglav area, Slovenia |
| **8** | Corazzi Riccardo | Hydropower development in Nikaj-Merturi regional park (Albania): an attempt to over-exploitation carbonate aquifers and water caves |
| **9** | D'Angeli Ilenia | ESA CAVES program: astronaut training, testing and operations using speleology as an analogue to space exploration |
| **10** | D'Angeli Ilenia | Limestone and gypsum tablet weight loss in sulfuric acid speleogenetic caves of southern Italy |
| **11** | Delannoy Yago | Historiographic analysis and 3D light simulation of Hautecourt Cave (Ain, France) during the two last centuries |
| **12** | Dixit Satish | Interpretation and modelling of karst ground water quality |
| **13** | Faur Luchiana | Genesis of sediments in Muierilor Cave, Southern Carpathians, Romania; facies identification and hydrodynamics |
| **14** | Fekete Zsombor | Overview of the Bükk Karst Water Monitoring System (NE Hungary) |
| **15** | Ferk Mateja | New data about the flowstone age in the side entrance of Postojna Cave, Slovenia |
| **16** | Ferk Mateja | Karst processes and features in Slovenia and Tennessee; a comparison with the focus on karst depressions |
| **17** | Filipović Marina | Regional and hydrogeological relations in wider catchment area of South Dalmatia (Croatia) and West Herzegovina (Bosnia and Herzegovina) |
| **18** | Gadek Anna | Contemporary decantation karren in the Kraków Upland (Poland) – preliminary results of the hydrochemical analysis |
| **19** | Garašić Mladen | Contribution to Understanding Some Hydrogeological Relationships in Dinaric Karst |
| **20** | Garin Thibaut | Assessing the safe yield of a karst aquifer by rainfall-discharge modelling |
| **21** | Garin Thibaut | Improving pumping test interpretation in karst aquifer by diagnostic plot method |
| **22** | Goličnik Marušić Barbara | A potential of user related data in development of integral approach towards flood related spatial planning |
| **23** | Hez Gabriel | Geomorphologic presentation of Iraquara karstic basin - Municipio de Iraquara Bahia - Brasil |
| **24** | Hez Gabriel | Natural archives of the Iraquara karst : A wide variety of indicators for karstology |
| **25** | Jaillet Stéphane | Rock comets and karstic mushrooms, Patagonia archipelago, Chile |
| **26** | Kemper Jules | Environment evolutions and anthropic impact records in deposits and forms in the Hautecourt Cave (Ain, France) |
| **27** | Klasinc Matjaž | Hydraulic conductivity and effective porosity of karst, measurements along new railway line Divača-Koper |

| | | |
|---|---|---|
| **28** | Koret Kristina | Impact of soil hydrology on the hydrological recharge of karst regions – A model approach |
| **29** | Kovač Konrad Petra | Comprehensive educational programmes as a part of project "Center of excellence - Cerovac caves; sustainable management of natural heritage and karst underground" |
| **30** | Kunaver Jurij | The global warming and its impact on hydrology of Glijun, the main Kanin karst spring |
| **31** | Lipar Matej | Collapse dolines in Stockyard Gully National Park, Australia |
| **32** | Liso Isabela Serena | Geochemical and hydrogeological characteristics of the Santa Cesarea terme sulfuric acid cave systems (Apulia, southern Italy) |
| **33** | Martín Pérez Andrea | Microbiological characterization of moonmilk speleothems from Snežna jama na Raduhi and Košelevka Cave, Slovenia |
| **34** | McCormack Ted | Developing karst groundwater flood maps for Ireland |
| **35** | Menezes De Souza Eniuce | Karstic Features Analysis in Virtual Reality Environment |
| **36** | Mihevc Andrej | Distribution of dolines in Slovenia defined by LIDAR data sets and machine learning |
| **37** | Muhammad Ros Fatihah | Inland cockpit notch morphology in Kinta Valley, Malaysia and its significance to surface water behaviour |
| **38** | Nannoni Alessia | Hydrogeochemistry of a complex karst system: the Bossea cave example |
| **39** | Năpăruș-Aljančič Magdalena | Research Infrastructures and karst science |
| **40** | Oberender Pauline | Quantification of frost weathering and its influence on cave development |
| **41** | Pavić Mirja | Development of an IT platform for flood prevention and mitigation of harmful environmental impact - GDi ensemble FloodSmart |
| **42** | Penezić Lena | The pollution in Pazinčica stream and its effects on Pazinska jama Ponor (Croatia) |
| **43** | Prelovšek Mitja | Use of Arduino in speleology – development and application of ultrasonic level data logger |
| **44** | Reboleira Anna Sofia | HiddenRisk – a project to understand the impact of human activities on subterranean biodiversity |
| **45** | Reboleira Anna Sofia | Impacts of salinity and global warming on groundwater ecosystems: a case study in southwestern Australian aquifers |
| **46** | Shtober-Zisu Nurit | Tufa deposits sheltered by Inland notches as indicators of Quaternary denudation rates |
| **47** | Stroj Andrej | Dissolved oxygen as a tracer of flow characteristics in a karst hydrogeological system |
| **48** | Stroj Andrej | Typology of karst aquifers and recommendations for their management – GeoERA RESOURCE project, CHAKA work package |
| **49** | Szieberth Dénes | Anthropogenic pollution in the Molnár János Cave |
| **50** | Šarc Filip | Stratigrapic profile of the Slovačka pit (Northern Velebit, Croatia) |
| **51** | Tembe Mwela Valentin | Use of isotopes in the assessment of water resources in the city of Bandundu in Democratic republic of Congo |
| **52** | Temovski Marjan | Age determination of cave and glacial sediments in the Central Balkan Peninsula using in situ produced cosmogenic nuclides |
| **53** | Ulloa-Cedamanos Francesco | Long-term trends for seasonal and interannual variations of stream water chemical composition, $pCO_2$, carbonate equilibrium and hydroclimatic parameters (discharge and temperature) in a mountainous karstic catchment (Pyrenees, France) |
| **54** | Vargas Danny | Paleoclimate reconstruction based on speleothems from Ecuadorian caves |
| **55** | Virag Magdolna | Pleistocene paleohydrological changes reconstruction on the basis of speleothem studies in the Szemlő-hegy Cave (Buda Thermal Karst, Hungary) |
| **56** | Winkler Irene | Geomorphology, hydrology, and distribution of Gypsum karst in Lower Austria |
| **57** | Zajc Marjana | Improving groundwater vulnerability and risk assessments within karst aquifers using GPR |

**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 20 min (15 min for talk and 5 min for discussion). Invited lecturers have 30 min for the lecture.

**Posters**

- Poster size: suggested max. format is A0 – 841 x 1189 mm (portrait layout).
- Flash presentation session will be organised at the beginning of the poster session. For this, each author(s) is asked to prepare a 1 minute long "teaser" presentation with 1–2 slides to attract attention to the content of the poster. After 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 17$^{th}$, before the lunch break.
- Stand by your poster during the poster display.

**Lunch**

- 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.
- Lunch breaks are timetabled into the schedule during the session days (Monday, Tuesday and Wednesday).

**Field trips**

- Registration for each field trip will be possible only on Monday, 17th June 2019 at the registration desk. Since the places are limited, please, hurry up with the registration. Pre-announcement to the organizers is possible.
- 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.
- During Tuesday and Friday excursion we will cross Slovenian-Italian border. Despite of EU border system, take your documents (Identity cards / Passports). Each individual should take care about his/her formal requiremets (visa, etc.) when crossing the border.
- Insect repellents are recommended as we will be walking in the 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 organisers 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 organisers.

**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 20 minut (15 minut za govor in 5 minut za razpravo). Vabljena predavanja so omejena na 30 minut.

**Posterji**

- Velikost posterjev: največji format je A0 – 841 x 1189 mm (pokončna lega).
- V začetku predstavitve posterjev bo potekala hitra predstavitev v obliki diapozitivov. Pri tem vse avtorje vabimo k pripravi 1 minuto dolge predstavitve - napovednika (1–2 diapozitiva), 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, 17. junija, do odmora za kosilo.
- Med ogledom posterjev stojte poleg svojega posterja.

**Kosilo**

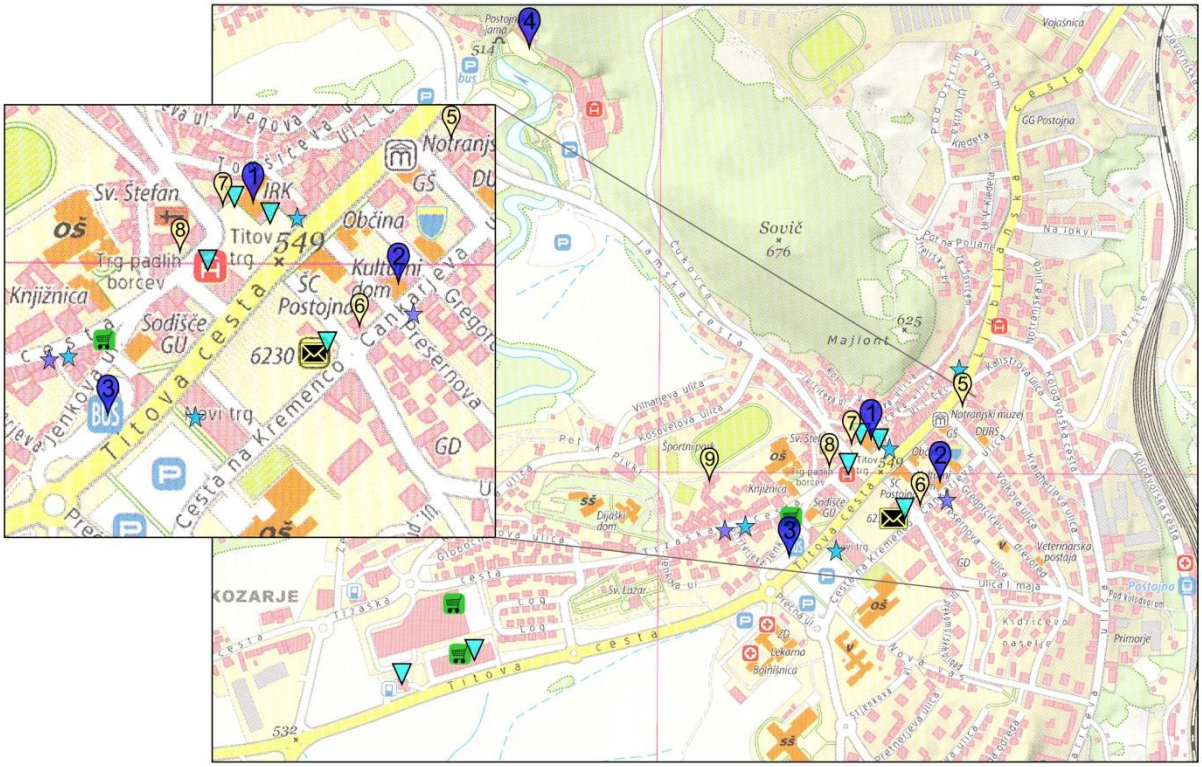
- Kosilo med predavanji in popoldanskim terenskim delom (torek in sreda) ni organizirano.
- Med celodnevnim terenskim delom (četrtek in petek) organiziramo enostavne obroke.
- Odmori za kosilo so v času predavanj (ponedeljek, torek in sreda) vključeni v program.

**Terensko delo**

- Prijave za terensko delo bodo mogoče le v ponedeljek, 17. 6. 2019 pri mizi za prijavo udeležencev. Pohitite s prijavo, saj so mesta omejena. Možna je predhodna najava organizatorjem.
- 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.
- Tekom terenskega dela v torek in petek prečkamo mejo z Italijo. Kljub olajšanemu načinu prehajanja državnih meja znotraj Evropske Unije, imejte pripravljene osebne dokumente (osebna izkaznica / potni list). Vsak posameznik je ob prečkanju meje dolžan poskrbeti za svoje formalnosti (vizum itd.)
- 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

Places to eat: / Možnost prehrane:

5. Pizzeria and restaurant „Minutka“ / Picerija in restavracija „Minutka“
6. Bistro „Štorja pod stopnicami“ / Bistro „Štorja pod stopnicami“
7. Restaurant „Proteus“ / Restavracija „Proteus“
8. Bistro „Bar Bor“ / Bistro „Bar Bor“
9. Pizzeria and restaurant „Čuk“ / Picerija in restavracija „Čuk“

- Fast Food / hitra prehrana
- Bakery / pekarna
- Market / trgovina
- ATM / bankomat
- Post Office / pošta

## INVITATION TO A SPECIAL SESSION: UNRESOLVED MYSTERIES OF KARST

(Tuesday, 18th June, 2019)

This year's school will be as always a great opportunity as a meeting point between experienced and new researchers from different parts of the globe.
The last years, a Special Session on Mysteries in Karst science was held, and it was quite successful, in that some answers could be found, and others are actively investigated at the moment.
Usually talks in schools and congresses deal with progress of ongoing research and with their results. This session, however, has the aim to present the still-unresolved problems and to promote and stimulate research! In opposition to many other scientific branches, karstologists most often try to collaborate in order to resolve problems. This session should therefore promote further the world-wide collaboration.
Because there are no results, talks usually are short, but because questions are formulated, discussion should be longer. Therefore, talks are limited to max. 5 minutes, while discussions may last 10–15 minutes.

You are all invited to contribute to the session. Please send a brief problem outline and description to praezis@speleo.ch.

With best regards,
Philipp Häuselmann (moderator)

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## POVABILO NA POSEBNO SEKCIJO: NERAZREŠENE SKRIVNOSTI KRASA

(torek, 18. junij 2019)

Kot je že v navadi, tudi letošnja MKŠ predstavlja odlično priložnost za srečanje tako uveljavljenih kot tistih manj uveljavljenih raziskovalcev krasa iz različnih predelov sveta.
V zadnjih letih, ko prirejamo posebno sekcijo, t.i. "Nerazrešene skrivnosti krasa", se je izkazalo, da je tovrsten način sodelovanja med raziskovalci zelo učinkovit, saj je bila tekom let razrešena marsikatera raziskovalna dilema, z mnogimi izmed njih pa se raziskovalci trenutno še aktivno ukvarjajo.
Običajno predstavitve na izobraževanjih, delavnicah in kongresih podajajo informacije o poteku raziskovanja ter končne rezultate raziskav. Pristop te sekcije pa je drugačen, saj je njen namen predstavitev še nerešenih raziskovalnih problemov ter spodbujanje raziskovalnega dela. V nasprotju z mnogimi drugimi panogami je pri reševanju krasoslovnih raziskovalnih vprašanj pogosto vzpostavljeno sodelovanje strokovnjakov z različnih področij, kar v širšem mednarodnem okviru spodbuja tudi ta sekcija.
Predstavitve naj bodo kratke, največ 5 minut; predstavljeni naj ne bodo rezultati raziskav, temveč raziskovalna vprašanja. Diskusija pa je lahko daljša, od 10 do 15 minut.

Vabim vas, da se aktivno udeležite sekcije. Prosim vas, da krajši povzetek raziskovalnega problema in njegov opis pošljete na e-naslov *praezis@speleo.ch*.

S spoštovanjem,
Philipp Häuselmann (moderator)

## INVITATION TO SHORT COURSE: VISUAL KARSYS

(Saturday, 22nd June, 2019)

## VABILO NA TEČAJ: VISUAL KARSYS

(sobota, 22. 6. 2019)

# Short Course
# Visual KARSYS

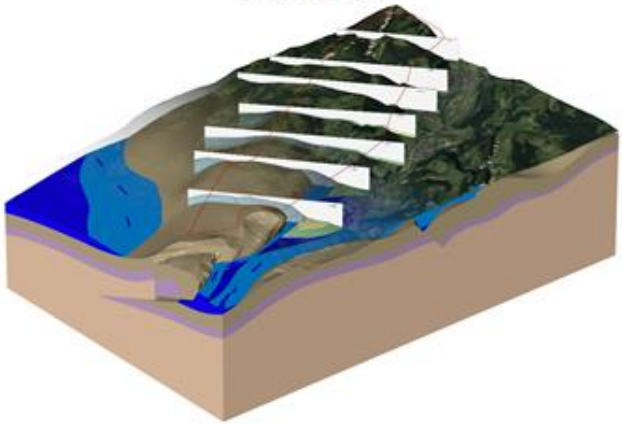
**Applied and innovative methods for the management of karst environment!**

## Saturday 22nd June, 2019 | Postojna (Slovenia)

SISKA organizes a short course dedicated to the learning of the KARSYS approach through the use of the visual KARSYS web-service.

The course will be held in the frame of the 27th Karstological School Classical Karst

The course is designed for geologists and hydrogeologists (engineers, academic, students) working in karst environments for applied issues (groundwater management, geothermy, construction, etc.). It intends to provide steps and tools to participants who will apply KARSYS by themselves.



Course price: 60 €/pers (including lunch)
Contact for registration / questions: arnauld.malard@isska.ch
Link to the conference web page
**Link to Visual KARSYS**

ISSKA • SISKA

# FIELD TRIPS

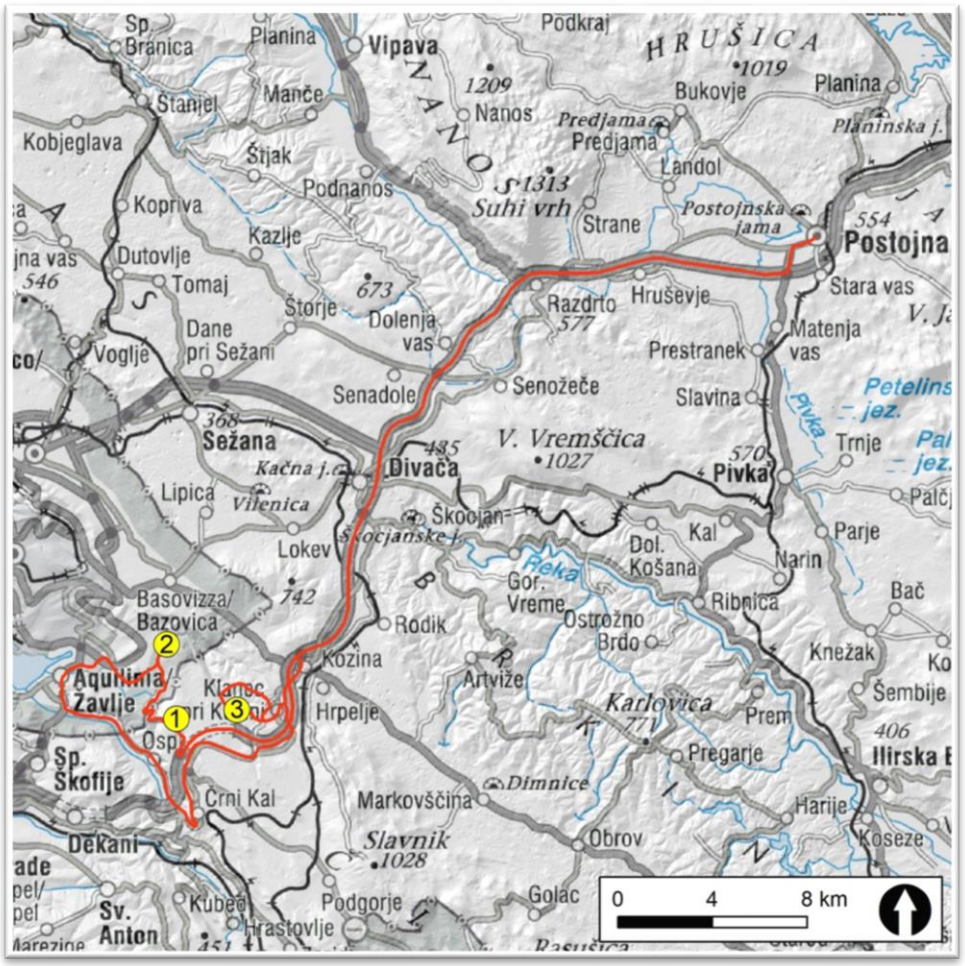
## TERENSKO DELO

**Afternoon field trip (A):**

# HYDROGEOLOGICAL AND SPELEOLOGICAL RESEARCHES IN THE AREA OF A NEW RAILWAY LINE DIVAČA-KOPER

Tuesday, 18. 6. 2019, 15:00–20:00

*Stops:*
**1** – The Socerb hill viewpoint
**2** – The Boljunec karst spring
**3** – The Beka-Ocizla cave system




**Hidrogeološke in speleološke raziskave na območju nove železniške proge Divača-Koper**
*Popoldansko terensko delo (A)*
Na ekskurziji bomo podrobneje predstavili najnovejše hidrogeološke in speleološke raziskave, izvedene v procesu načrtovanja nove železniške proge Divača-Koper, ki bo izboljšala prometne povezave med Slovensko obalo in celino. Njen odsek med Črnim Kalom in Divačo bo precejšen del potekal skozi predore (severni T1 in južni T2) v visoko občutljivem čezmejnem kraškem vodonosniku z več pomembnimi vodnimi viri v Sloveniji in Italiji. Zato je potrebno ugotoviti, kam vode z območja načrtovane trase odtekajo, saj je mogoče le na območjih, na katerih so bile določene smeri in značilnosti toka podzemne vode, z zadostno zanesljivostjo napovedati morebitne težave povezane z gradnjo ali obratovanjem proge. Pridobljeno znanje nam bo tudi omogočilo, da opredelimo, kateri kraški viri so ogroženi zaradi gradnje in delovanja nove železniške proge in da načrtujemo ustrezne zaščitne ukrepe.

## INTRODUCTION

During the field work, hydrogeological and speleological studies carried out in the process of planning of a new railway line Divača-Koper will be presented in more details. This new railway line will significantly improve the traffic connections between the Slovene coast and the inland. Its section between Črni Kal and Divača (Fig. 1.01), of which a considerable part will run through tunnels (northern tunnel T1 and southern tunnel T2), transects the highly vulnerable Slovene-Italian transboundary karst aquifer with several important water sources on both sides of the border. An inspection for groundwater drainage patterns along the proposed route is therefore necessary, as only in areas, in which the courses and characteristics of the groundwater flow have already been determined it is possible to predict the possible problems with groundwater during construction with sufficient reliability. This will also enable us to define, which karst sources are due to building and operation of a new railway under threat and to plan proper protection measures.

## HYDROGEOLOGICAL CHARACTERISTICS OF THE AREA

The wider area of the planned railway line between Črni Kal and Divača (Fig. 1.01) is characterized by an imbricate thrust structure, where stripes of Eocene flysch alternate carbonate rocks – predominantly limestone of Upper Cretaceous and Palaeocene age. In hydrogeological terms, carbonate rock represents highly permeable karst aquifers, where underground water flow prevails (Cucchi *et al.* 2015; Turpaud *et al.* 2018). Flysch on the surface enables surface flows to sink underground on contact with karst. On the other hand, flysch also acts as a hydrological barrier, which causes underground karst waters to emerge onto the surface in karst springs.

The main paths of the groundwater flow from the area of the planned route are directed towards the springs of Timava/Timavo (Slovene/Italian name of the spring), Rižana, Osapska Reka and Boljunec/Bagnoli della Rosandra. The Timava/Timavo spring in the Gulf of Trieste of the Adriatic Sea has three main outlets with the total discharge between 9.1 $m^3$/s and 127 $m^3$/s; the mean discharge is 29.3 $m^3$/s. The Rižana spring emerges at the contact of the karst aquifer with the poorly permeable flysch rocks across which the Rižana River flows into the Adriatic Sea (Janža 2010; Zupan Hajna et al. 2015; Ravbar et al. 2018). The discharges of the Rižana spring range from 30 L/s to 91 $m^3$/s; the mean discharge is 4.3 $m^3$/s. An intermittent spring of Osapska Reka flows from a karst cave. The entrance to the 1,200 m long and 49 m deep cave is located 105 m a.s.l. The spring is only active after heavier rain; during a high water level, the discharges can amount to several m3/s. Even before the water flows out of the cave, numerous springs become active in the riverbed below the entrance. The Boljunec/Bagnoli spring is described in more details in one of the following chapters. Numerous other springs, which emerge at the contact of the karst aquifer with the impermeable flysch or represent a direct outflow into the sea, are smaller and of a more local character.

The Rižana karst spring was already in use in the early 19$^{th}$ century, while in 1935 a regional water supply system was constructed to supply Slovenia's Primorska region with drinking water. Today a majority of the inhabitants of this area (86,000 permanent inhabitants, rising to 120,000 during the tourist season) are connected to this water supply network. The Boljunec/Bagnoli spring is much smaller and is only used in a nearby fish farm. However, it is important to focus our studies also to this spring, to assess possible transboundary impacts of the planned railway line.

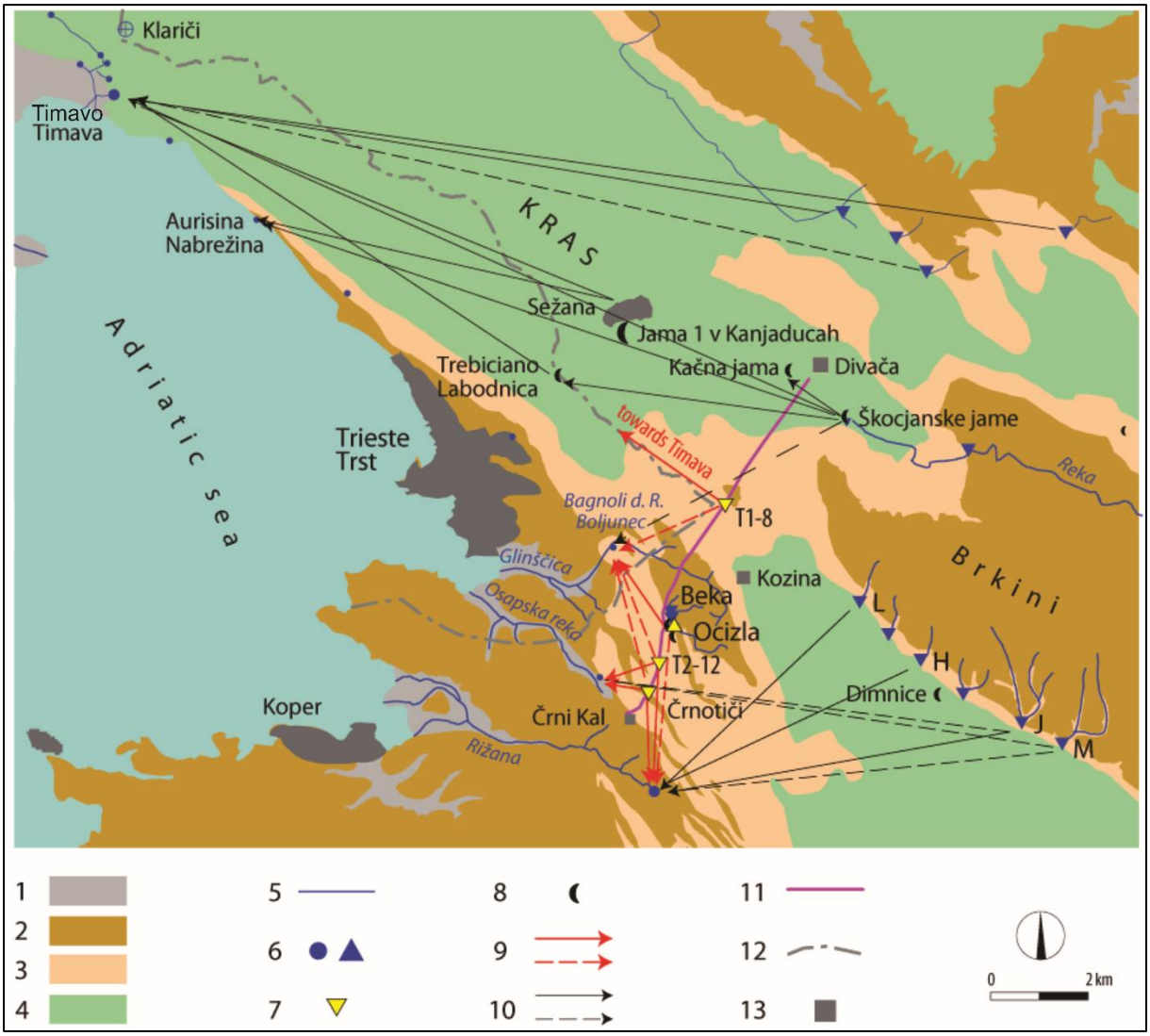



***Figure 1.01:*** *Hydrogeological map of the broader area of the planned route (Legend: 1. well permeable rocks with intergranular porosity, 2. very low permeable Eocene flysch, 3. well permeable Tertiary limestone and dolomite, 4. well permeable Cretaceous limestone and dolomite, 5. surface stream, 6. spring, ponor, 7. injection point in tracer tests on the route of the railway, 8. cave, 9. main and secondary direction of groundwater flow proved by tracer tests on the route of the railway, 10. main and secondary direction of groundwater flow proved by previous tracer tests, 11. planned railway route, 12. state border, 13. settlement).*

Related to the alternation of differently permeable rocks is the phenomenon of ponors, in which the surface waters from the flysch sink at the contact with karstified carbonate rocks and then flow through the underground towards the karst springs. The closest to the railway route are the ponors of the Beka-Ocizla cave system (Fig. 1.01), which are described in more details in one of the following chapters. The surface Reka River sinks into the cave Škocjanske Jame approximately 3.5 km east of the railway route. Its minimum discharge is 0.18 m3/s, while its mean discharge is 8.26 $m^3$/s. During very high water levels, its discharge can increase to over 300 $m^3$/s.

In order to provide a general presentation of the characteristics of the fluctuation of the water table in the karst aquifers in question, some basic data on the levels of water in karst caves and in karst springs are presented. In the caves of Škocjanske Jame the lowest water level is around 210 m a.s.l., whereas in the cave of Kačna Jama near Divača it is 156 m a.sl. (Fig. 1.01). Towards the west the water table drops towards the cave Labodnica/Trebiciano in Italy to a height of 12 m a.s.l. During

high waters the level in Škocjanske Jame reaches 345 m a.s.l., in Kačna Jama 260 m a.s.l. and in Labodnica/Trebiciano 112 m a.s.l. The underground flow in this segment of the karst aquifer is directed towards the Timava/Timavo spring, which is situated merely some 0.5 m a.s.l.

In the ponor caves at the foothills of the Brkini the permanent water flow can be observed only in the Dimnice cave at a height of 474 m a.s.l. The Rižana spring is situated at around 70 m a.s.l.; during a low water level the water in the spring cave of Osapska Reka drops below 50 m a.s.l., whereas during high water levels it springs out of the cave at an altitude of 105 m a.s.l. Based on the data it can be concluded that the level of karst water in this area slopes steeply towards the southwest and, due to the imbricate structure of alternating flysch barriers in karstified limestones, also in grades. In Boljunec/Bagnoli the water springs at around 50 m a.s.l.

## TRACER TESTS IN THE AREA

Important additional information on the courses and characteristics of underground discharge in karst can be obtained by applying a tracer test method. Additional to several previous tests, four new tracings have been carried out since 2001 in the area of the planned railway. The results of the last one have not been published yet, and only some preliminary results will be presented during the field work. The three previous tracer tests are briefly described below; more details can be found in cited references (Kogovšek & Petrič 2004; Petrič & Kogovšek 2011, 2016; Gabrovšek *et al.* 2015; Petrič 2019).

On 29 March 2001, a solution of 3 kg of uranine was injected in a stream that sinks into the Beka–Ocizla cave system, which is intersected by the planned route of the railway (Fig. 1.01). During a high water level on 1 December 2009, a solution of 3 kg of uranine was injected into a well permeable fissure near the village of Črnotiče and flushed with 2.5 $m^3$ of water from a fire cistern. On 18 November 2010, a solution of 4 kg of uranine was injected into the T2-12 borehole and a solution of 305 g of amidorhodamine G into the T1-8 borehole. In both cases, the boreholes and their surrounding were flushed with 6 $m^3$ of water from the fire cistern, before and after injection. Samples were regularly taken at the Rižana, Osapska Reka and Boljunec/Bagnoli springs with the ISCO 6700 automatic samplers, and the fluorescence of uranine and amidorhodamine G was measured by a Luminescence Spectrometer (LS 45, Perkin Elmer). During the tests in 2009 and 2010, parallel measurement of the fluorescence in 30-minute intervals was conducted directly at the Rižana spring by a field fluorometer (LLF-M, Gotschy Optotechnik).

The results of the tracer tests are reviewed according to the position of the injection points (Figs. 1.01 & 1.02, Tab. 1.01). From the borehole T1-8 in the area of the northern tunnel T1, a secondary connection with the Boljunec/Bagnoli spring was defined (linear dominant flow velocity 61 m/h, recovery 7 %), and the main direction toward north-west is supposed based on the results of previous tracer tests (Gabrovšek *et al.* 2015). Approximately 5 km to the south, the Beka–Ocizla cave system is located on the contact flysch–limestone; it has been proved by the tracer test in 2001 that the water from this system flows mainly towards the Boljunec/Bagnoli spring where uranine appeared in very high concentrations with declining spring discharges. Although the test was carried out at relatively low waters, a concentrated and fast flow through the karst aquifer with a linear dominant flow velocity of 33 m/h and recovery over 90 % was defined. With a longer time lag, and to a smaller degree (a few percent), the tracer was also detected in the Rižana spring; therefore, the possibility of a connection with this water source during higher water levels cannot be overlooked.

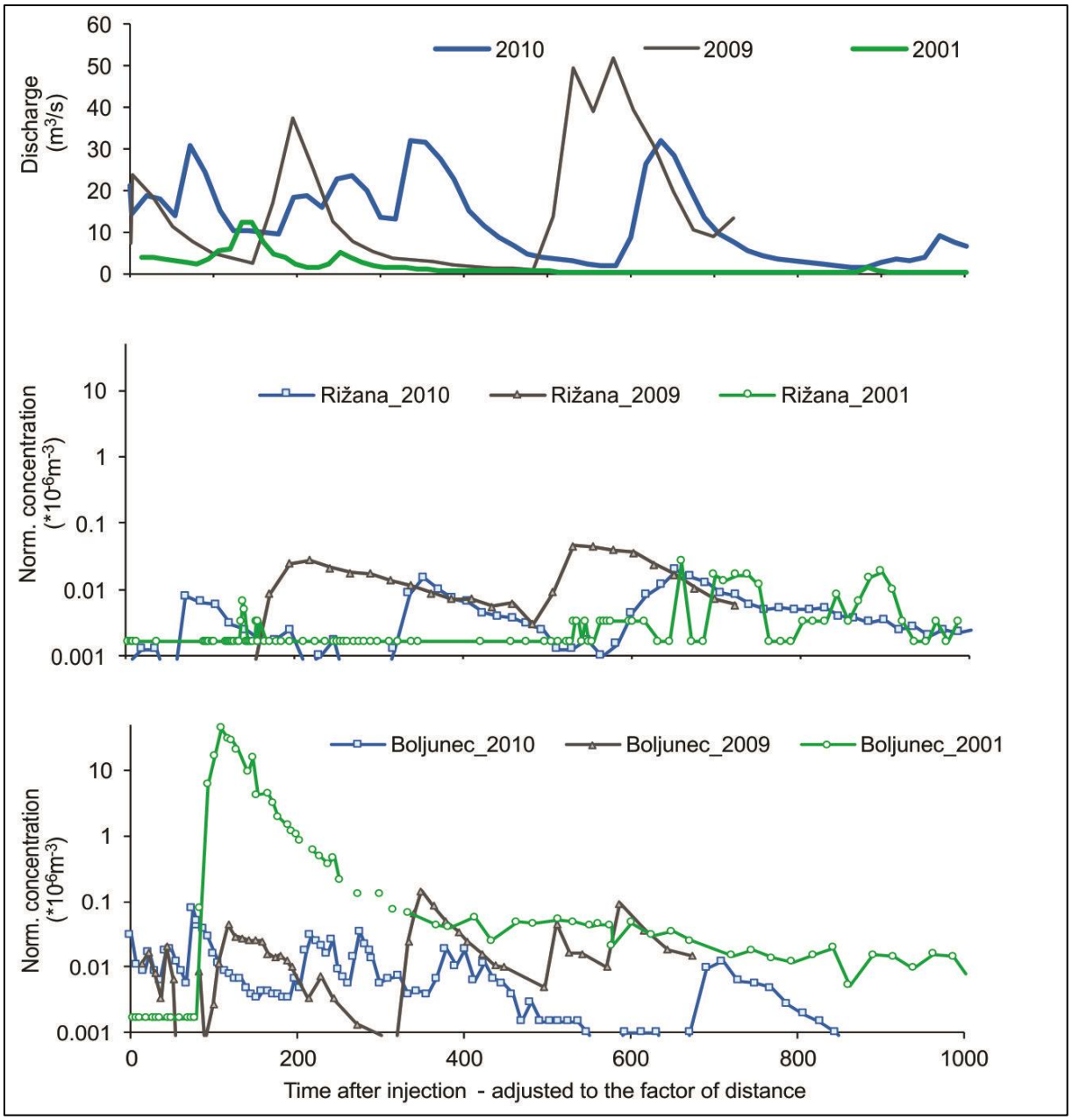



***Figure 1.02**: Discharge of the Rižana spring, and tracer breakthrough curves of the Rižana and Boljunec/Bagnoli springs for the tracer tests in the area of the planned railway route (normalized concentration: values of measured tracer concentrations divided by the tracer mass injected; the times after injection are divided by the factor of distance, which was determined for each individual test and the two springs by dividing the distance between the injection point and the sampling point by the shortest such distance in the tracer tests considered).*

***Table 1.01**: Results of the three tracer tests in the area of the planned railway route ($v_{dom}$: linear dominant flow velocity in m/h, R: tracer recovery in %).*

| ***Year*** | **2001** | | **2009** | | **2010** | | | |
|---|---|---|---|---|---|---|---|---|
| ***Injection site*** | **Beka-Ocizla** | | **Črnotiče** | | **T2-12** | | **T1-8** | |
| ***Spring*** | **$v_{dom}$** | **R** | **$v_{dom}$** | **R** | **$v_{dom}$** | **R** | **$v_{dom}$** | **R** |
| **Rižana** | 6 | 2 | 22 | 87 | 62 | 41 | | |
| **Boljunec/Bagnoli** | 33 | 91 | 10 | <1 | 48 | 1.6 | 61 | 7.3 |
| **Osapska Reka** | | | 33 | 11 | 23 | 33 | | |

From the borehole T2-12 in the area of the southern tunnel T2, water drains in the directions of all observed springs. The linear flow velocities were 62 m/h for the Rižana spring, and 48 m/h for the Boljunec spring. After two and a half months, over 76 % of the injected tracer had recovered through the springs, namely 41 % through the Rižana, 33 % through the Osapska Reka, and 1.6 % through the Boljunec/Bagnoli spring.

Very similar results were obtained by the tracer test in 2009, when the tracer was injected into a well permeable fissure at the surface near Črnotiče. A shift in the tracer breakthrough curve and lower flow velocities (22 m/h to Rižana, 33 m/h to Osapska Reka, and 10 m/h to Boljunec/Bagnoli) are a consequence of different hydrological conditions with a delay in the flood pulse during the tracer test in 2009. Higher recovery rates are due to a longer period of very high discharge in the second flood pulse of the Rižana spring, which efficiently pushed out of the karst system the majority of injected tracer.

## RISK OF CONTAMINATION OF KARST WATER IN THE IMPACT AREA OF THE PLANNED RAILWAY LINE

A review of the results of the conducted tracer tests has shown good permeability of the karst and a concentrated and fast flow through the karst aquifer. From the northern part of the planned route the substances dissolved in the water would appear in the Timava spring during a low water level about a month later; but during a high water level they could appear within one week. From the area of the T1-8 borehole also the possibility of a smaller portion (10 %) flowing out towards the Boljunec/Bagnoli spring was proven. During a high water level, the potential contamination in this spring would appear after approximately four days.

Waters flow from the flysch area in the northern part of the T2 tunnel towards the contact with karst rocks in the area of the Beka-Ocizla cave system; from there a direct connection to the Boljunec/Bagnoli spring has been proved; the substances dissolved in the water from the area of the railway route could appear there within approximately four days during a low water level or even earlier during a high water level. The possibility of a slower flow towards the Rižana spring was also confirmed. The portion of the tracer recovered in the Rižana spring was small, but because it is an important water source, this underground water connection must be taken into account when planning protective measures.

In the southern part of the T2 tunnel, the waters flow out mainly towards the Rižana and Osapska Reka springs. During a high water level, the tracer appeared in the Osapska Reka spring after three days, and about a day later in the Rižana spring. Under such conditions we could predict the risk of the contamination of the Rižana by observing Osapska Reka. When the water level drops, the portion of the flow towards the Rižana spring probably increases. Potential contamination from this section of the route might also appear in the Boljunec/Bagnoli spring to a small degree (a few percent) and later.

## THE BOLJUNEC KARST SPRING

Three karst springs are located at the altitude around 50 m a.s.l. in the village of Boljunec/Bagnoli della Rosandra in Italy. In the previous text we used for them a common name Boljunec/Bagnoli springs. However, they are called individually Na placu/Abbeveratoio, Pri pralnici/Lavatoio and Jama/Antro di Bagnoli (Fig. 1.03). The first two are permanent; the latter is intermittent, emerges from a karst cave and acts as an overflow of the spring Pri pralnici/Lavatoio. During a low water level, the total discharge of the springs amounts to merely a few litres per second; during high waters it can exceed 2 $m^3/s$.

During the above described tracer tests the samples were taken in all three springs. In all tests the tracer appeared distinctly in the Pri pralnici/Lavatoio and Jama/Antro di Bagnoli springs, but not in the nearby Na placu/Abbeveratoio spring. Parallel chemical analysis also showed significant differences, therefore it can be concluded that despite the distance of only a few tens of meters, this spring has a different recharge area and is not directly connected with the groundwater flow from the area of the planned railway line.

***Figure 1.03**: The permanent spring Pri pralnici/Lavatoio (right) and the intermittent spring Jama/Antro di Bagnoli (left) in the village of Boljunec/Bagnoli della Rosandra in Italy.*

The Pri pralnici/Lavatoio spring is being used for fish farming. The established good connection with the Beka-Ocizla ponor system points to the high endangerment level of this spring and the possibility of a direct impact of the planned railway construction. Similarly, from the other parts of the planned railway line, also the Rižana and Osapska Reka springs are potentially endangered. Therefore, a comprehensive analysis of the quality of the springs should be performed prior to commencing construction, and consequently the so-called zero state should be determined (monitoring the quantity and quality under various hydrological conditions). More detailed monitoring during construction and afterwards, during operation, will be necessary to show the actual impact of the planned activity.

***Figure 1.04**: Placement of water level, temperature and conductivity data loggers in the Jama/Antro di Bagnoli spring.*

**SPRINGS' MONITORING**

Some analyses of the quantity and quality of the above mentioned springs were performed in the last years. The monitoring of discharges, temperature and electrical conductivity in 30-minute intervals has been carried out in Rižana, Osapska Reka and Jama/Antro di Bagnoli springs (Fig. 1.04) since October 2012 (with intermediate interruptions of various duration).

On Figure 1.05 the measured values for the period October 2017 – March 2019 for the Rižana and Boljunec/Bagnoli springs are presented. For the latter the total discharge of all three springs, and temperature and conductivity measured in the Jama/Antro di Bagnoli spring are shown. The Rižana and Boljunec/Bagnoli springs have similar hydrological characteristics with fast increase of discharges following precipitation events. However, changes in temperature and conductivity values indicate significant differences in the characteristics of water flow and solute transport in their recharge areas. More pronounced changes in the Boljunec/Bagnoli spring are due to a smaller extent of the recharge area (~ 6 $km^2$), larger influence of allogenic recharge and fast groundwater flow through karst conduits. In more extensive recharge area of the Rižana spring (~ 250 $km^2$) the influence of allogenic recharge is less evident, and increase of conductivity after precipitation events reflects the outflow of water stored in the karst aquifer for longer time.

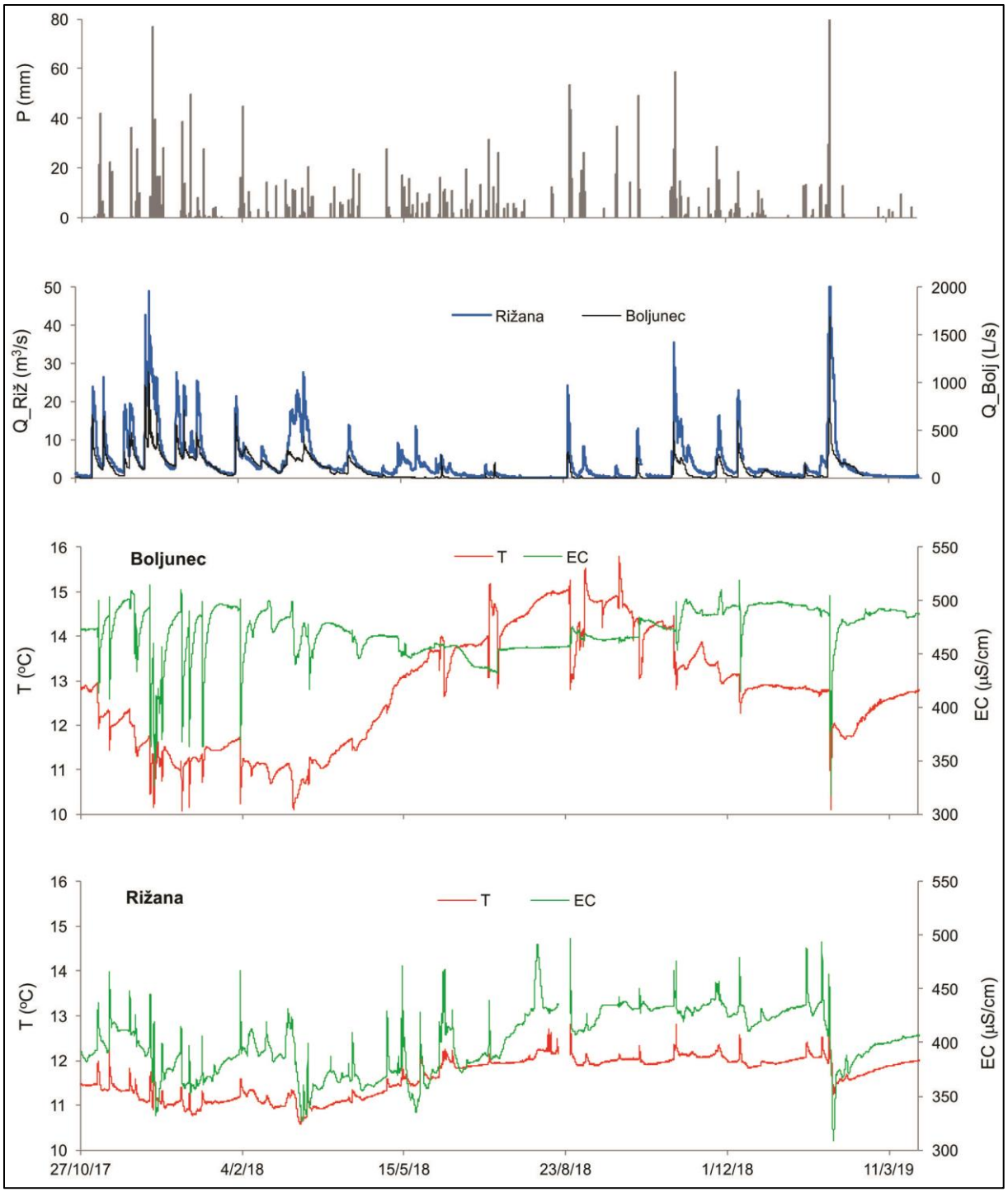



***Figure 1.05**: Precipitation (P) in the recharge area, discharges (Q), temperature (T) and electrical conductivity (EC) of the Boljunec/Bagnoli and Rižana springs.*

## THE BEKA-OCIZLA CAVE SYSTEM

***A brief overview of the system***

The Beka-Ocizla cave system developed at the contact between Palaeocene limestone and Eocene flysch in a shallow depression. Approximately 4 km$^2$ large flysch recharge area is drained by two (almost) perennial and two intermittent streams, active only at intense rain events. Their total maximal discharge is estimated to about 10 m$^3$/s. The streams sink along the flysch-limestone contact line and at several distinct ponors. Active and fossil ponors are connected by a complex conduit network with the total length and depth of 2780 m and 150 m, respectively. The maximal distance between the entrances is about 500 m. Six known caves are now connected into the Beka-Ocizla cave system: Ocizeljska jama (*Ocizla cave*), Blažev spodmol (*Blaž's rock shelt*er), Maletova jama s slapom (*Maletova jama cave with waterfall*), Jama z naravnim mostom (*Cave with the natural bridge*), Jurjeva jama v Lokah (*Jurjeva cave in Loke*) and S-4/Socerb. The caves were mostly explored in 1980s and 90s, however new passages have been found recently and are being explored.

Almost all the mentioned cave entrances function as permanent/intermittent stream sinks, except for the S4/Socerb and the entrance to Blažev spodmol, which are relict. The most permanent inflow of water is the one to Maletova jama s slapom and Jama z naravnim mostom; the inflow to Jama z naravnim mostom is the last to dry up. The streams sinking into Ocizeljska jama and Jurjeva jama are intermittent, active only during intensive precipitation.

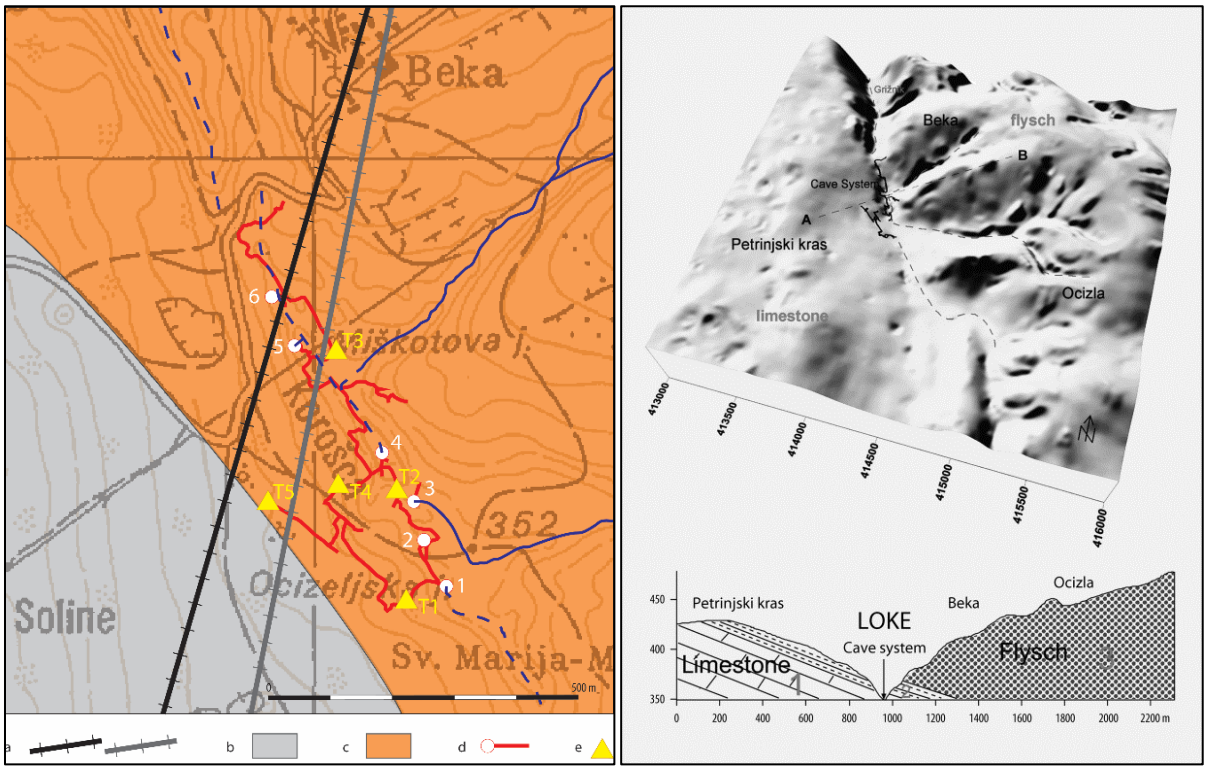



***Figure 1.06**: **Left**: Location of the caves **1.** Ocizeljska jama, **2.** Blažev spodmol, **3.** Maletova jama s slapom, **4.** Jama z naravnim mostom, **5.** Jurjeva jama and **6.** S-4/Socerb; **a.** route of the tunnel (grey – proposed, black – accepted), **b.** limestone, **c.** flysch and transitional beds, **d.** cave entrance and underground passages, **e.** hydrological observation stations. **Right:** Morphology of the contact between limestone and flysch and the geological cross-section of the lithological contact. The contact between **1.** Lower Eocene Alveolina-Nummulites limestones and **3.** Eocene flysch (alternation of marls, silicate sandstones and breccias) is gradual over so-called **2.** transitional beds permeable layers (salty marls and marly limestone).*

***The tunnel and an engineering importance of the system***

The interest in the speleology and hydrology of the system rose, when planning for the new railway connection between the town of Divača and port of Koper started in late 1990s. The route includes a set of tunnels, up to almost 7 km long. The second, 6 km long tunnel passes immediate vicinity of Beka-Ocizla system. The construction works started in 2019. The level of the tunnel when the location closest to the system will be 260 m a.s.l., which corresponds to the position of some of the main active channels. Initial planned line of the tunnel even intersected the known passages. For this reason, new survey of the cave and continuous observations of groundwater within was established.

***Broader structural and speleogenetic framework***

The area belongs to the morphostructural unit of Podgorski kras, which has typical narrow stripes of flysch between limestone, as the territory structurally belongs to the imbricate structure of Čičarija. There is no evidence of younger marine deposition than Eocene in the south-western part of Slovenia. Younger sediments occur only in caves and very rarely on karst surface (different soils and few remains of terrigenous sediments). Calibrated data from paleomagnetic research of cave sediments of the area indicate that evolution of caves in south-western Slovenia took part within one post-Eocene karstification period.

***Hydrological characteristics***

In 2001 the uranine dye was injected directly into the sinking stream of Maletova jama s slapom (No. 3 in Fig. 1.06). The majority (91 %) of tracer appeared at springs in Boljunec with first appearance 84 h after the injection and maximum at 108 h (Fig 1.01). The apparent $v_{max}$ = 42 m/h, and $v_{dom}$ =33 m/h. About 2 % of tracer appeared at Rižana springs. There, first short appearance of the tracer was detected 10 days after injection, while longer period of slightly increased concentration (up to 0.1 mg/m$^3$) was recorded between 40 and 70 days after injection (Fig. 1.07).

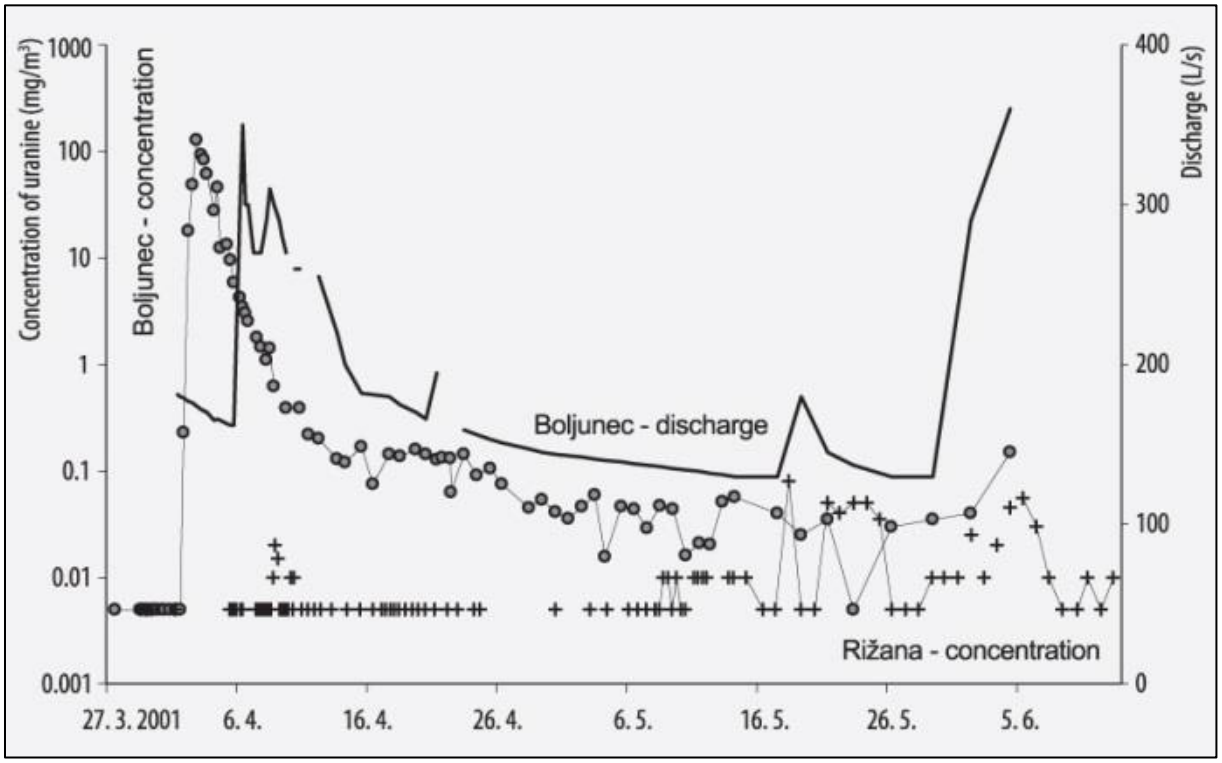



***Figure 1.07****: Tracer concentration curves at the Boljunec and Rižana springs following the injection of uranine into a sinking stream of Beka-Ocizla system.*

***Hydraulics of the cave system***

During flood events, the flow in the Beka-Ocizla cave system is very complex; water enters the system through several ponors, the caves are hydraulically connected, directions of the flows are not unambiguous, the numerous constrictions present hydraulic bottlenecks that cause back-flooding. A detailed study of the water conditions in the cave would require the setup of a large number of observation points and measurements of the flow rates of all inflowing allogenic water. Still, one would probably not be able to avoid a deficient characterization, as the cave system most likely extends far beyond what has been explored so far.

A set of autonomous loggers (Ejkelkamp Diver and HOBO U24) was placed into the cave system, starting in 2008. The network has been maintained with varying number of observation points and with some interruptions since then. Observations in the terminal sump in Jama z naravnim mostom, have been established only in 2018 and no data have been retrieved from there yet.

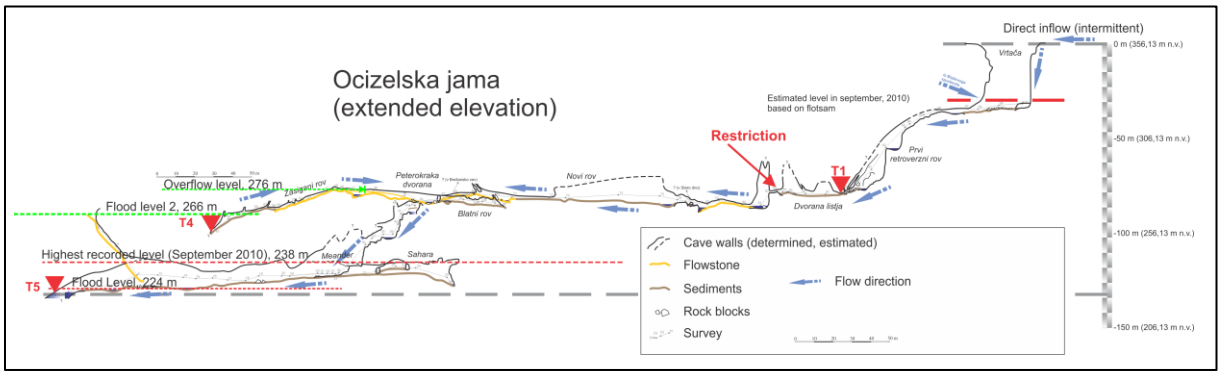



***Figure 1.08:*** *Cross-section of Ocizeljska jama with the position of observation points and some important water levels*

Here we describe few interesting features observed in Ocizeljska jama, where three observation points were set up (see Fig. 1.08).

**T1** - Dvorana listja (Hall of Leaves). Its location is below the entrance shaft series.

**T4** - Zasigani rov (Flowstone Channel). The main junction in Ocizeljska jama is Peterokraka dvorana (Pentagon Hall). The water continues along the meander with a series of drops towards the terminal sump at the end of the passage Rov velike razpoke with T5. Another channel, parallel to the Rov velike razpoke, initially ascends from the Peterokraka dvorana, then bends towards the southeast and descends down from the level 277 m a.s.l. to 254 m a.s.l., where sediment deposits prevent its further exploration. The sediment (flysch sand and pebbles with organic debris and pieces of garbage) clearly indicates the vicinity of the surface sinking stream. The logger is fixed two metres above the bottom to prevent it from being buried by the sediments which are redistributed due to the upwelling water during the flood event.

**T5** - s sump lake at the end of the passage Rov velike razpoke. The deepest point of the system is a lake at the end of the passage Rov velike razpoke in Ocizeljska jama. The lake is located at the altitude of 222 m a.s.l. The divers explored it in 1990 and found a chamber with open water surface on the other side of the sump but no clear continuation. The lake is up to 24 m deep. Figure 1.08 shows the cross-section and ground plan of the lake.

Figure 1.09 shows characteristic level hydrographs from T4 and T5 from December 2017, where several precipitation events occurred within two weeks. The level at T4 rises quickly for 10 m, reaching a stable flood level at 266 m a.s.l. Further peaks, reaching 10 m higher follow the intense rain periods. This level (276 m a.s.l.), is the maximal at T4 and presents the channel's apex, where water flows over towards T5. The level and temperature hydrographs at T5 show clear responses following an overflow of water from T4. The overflow periods last rarely for more than a day. Water

at T4 returns to the level 266 m a.s.l., which presents a relatively stable level and few days after the rain, starts to recede slowly (-4.5 m/day) until the logger becomes dry. This last stage probably presents leakage from a perched reservoir.

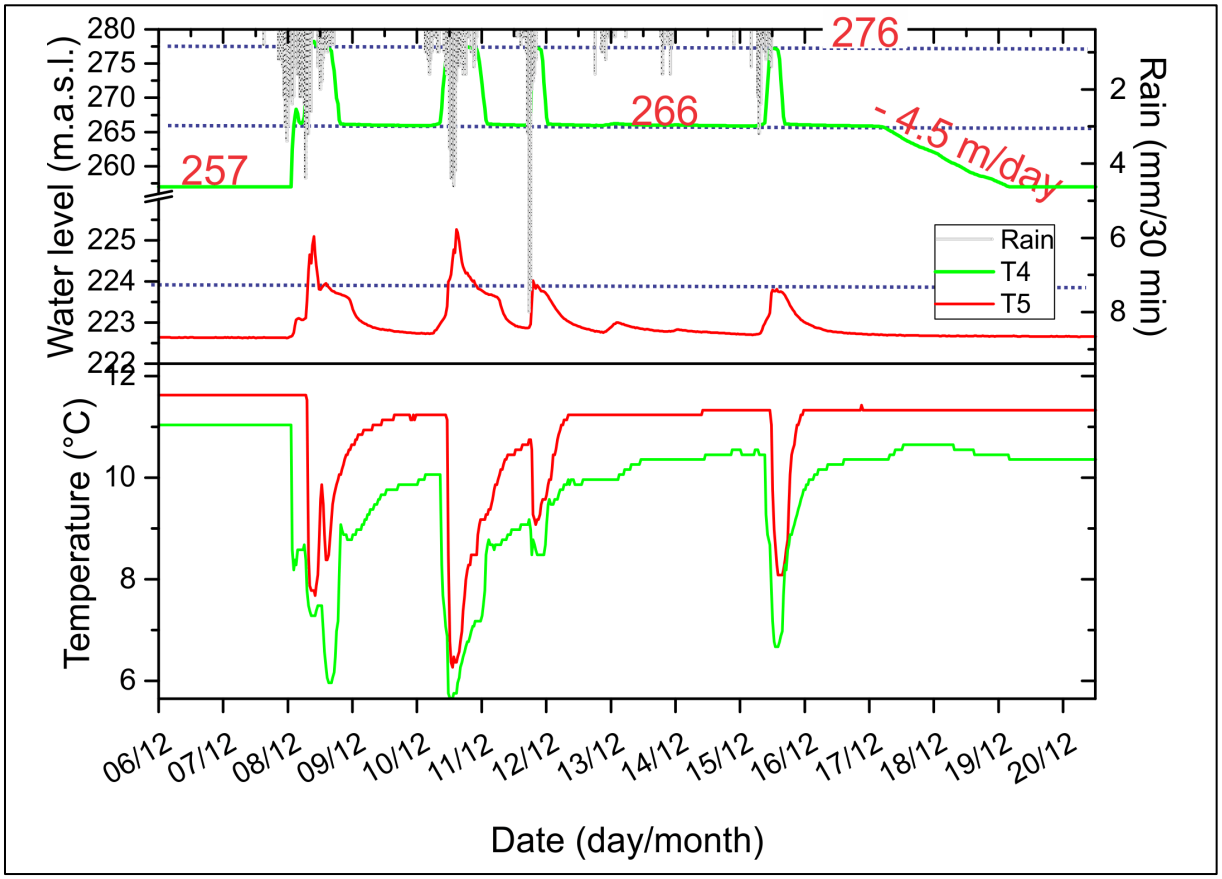



***Figure 1.09**: Level and temperature hydrographs of stations T4 and T5 in Ocizeljska jama.*

The conceptual model used to interpret the observed response is shown in Figure 1.10. We assume that the water to T4 comes from Jama z naravnim mostom. As there is no overflow channel above T4 at 266 m a.s.l., the position must be maintained by an overflow channel in Jama z naravnim mostom. An increasing input back-floods this channel and causes further rise above T4 until the overflow position at 276 m a.s.l. is reached. Blue arrows indicate flow direction.

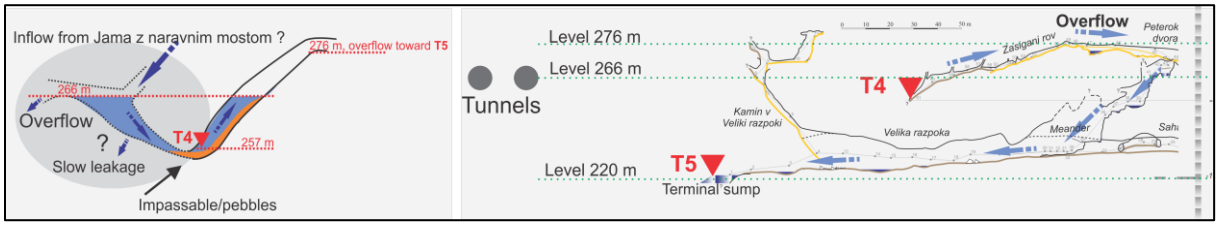



***Figure 1.10**: Left: Interpretation of unknown geometry (shaded elipse) leading to response at T4. Right: Back-flooding and overflowing in the lower part of Ocizeljska jama with distinct levels and position of tunnels.*

However, the level at T5 only rarely rises above 2.5 m, which indicates a highly transmissive drainage channel about two meters above the level of the sump. Although such channel has not been found during diving explorations, the measurements suggest it. The concept is shown on Figure 1.11a, where unexplored but inferred section is shaded by an ellipse.

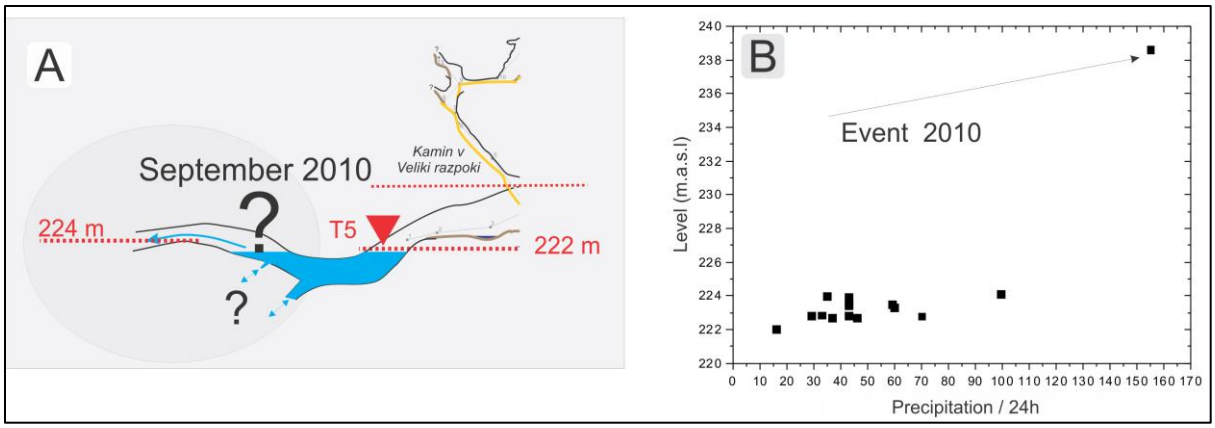



***Figure 1.11:*** *a) Situation at terminal sump (T5). The ellipse indicates inferred channels providing efficient drainage. b) Maximal levels at T5 during flood events. Note the event from September 2010, when over 16 m rise was recorded.*

Between September 17th and 19th 2010, over 200 mm of rain fell in a series of intense events with rain intensity reaching over 50 mm/h. At that time, T5 was the only observation point in the cave system. Based on the occurrence of flood deposits before and after the event, it was evident that the entrance collapse doline of Ocizeljska jama was flooded over 5 m high. The entrance series of shafts was surely completely flooded. At the bottom of the cave (T5), however, the water level rose up for 16 m, to about 240 m a.s.l., therefore, much of the deeper part of the cave was not completely flooded. The water from the surface was probably back-flooded, due to the restrictions at the altitudes of 270–280 m.

Currently the observations are still ongoing. Instrument in the terminal sump in Jama z naravnim mostom has not been downloaded yet as there is another perched sum on the way to it. These data, together with new exploration might resolve some open questions.

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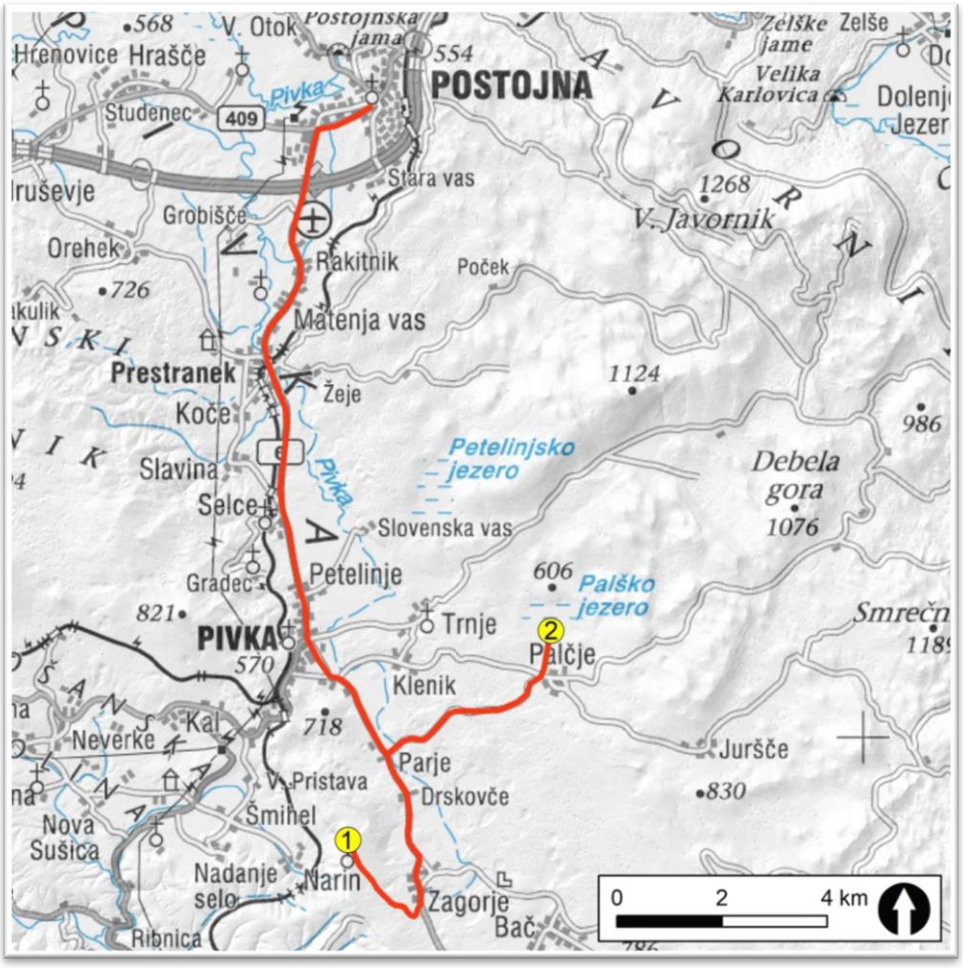
**Afternoon field trip (B):**

## RECENT HYDROGEOLOGICAL INVESTIGATIONS IN THE UPPER PIVKA VALLEY

Wednesday, 19. 6. 2019, 15:00–20:00

*Stops:*
**1** – Šilentabor viewpoint
**2** – Palško Jezero and Matijeva Jama




**Zadnje hidrogeološke raziskave v Zgornji Pivki**
*Popoldansko terensko delo (B)*
Poseben hidrološki pojav zahodnega dela kraškega masiva Javornikov so presihajoča Pivška jezera. Za celotno območje je značilna interakcija podzemnih in površinskih voda. V kraškem vodonosniku se vode pretakajo večinoma podzemno, ob močnejših in dolgotrajnejših padavinah pa se nivo podzemne vode dvigne in voda se na številnih mestih preliva na površje. Tako postanejo aktivni občasni kraški izviri ob reki Pivki, z vodo pa se napolnijo tudi kraške globeli in nastane lahko do 17 presihajočih kraških jezer. Nekatera se pojavljajo dokaj pogosto in imajo vodo tudi do pol leta, večinoma pa nastanejo bolj poredko, z vodo pa so zalite le kratek čas ob močnejših poplavah.
Vodne jame so na tem območju redke, a dragoceni vir informacij o podzemni vodi. Iz nekaterih so v preteklosti črpali vodo za oskrbo. Ena takšnih je tudi Matijeva jama, ki leži na vzhodnem robu Palškega jezera. V okviru ekskurzije bomo predstavili hidrogeološke značilnosti Palškega jezera in estavel ob robu jezera ter možnosti za rabo vode na tem območju.

## INTRODUCTION

The Pivka Valley is a large depression laying between the high karst plateaus of the Slovene Dinaric Karst (Nanos, Hrušica, Javorniki; all ~1250 m a.s.l.), the low plateau of Slavenski Ravnik (600 – 700 m a.s.l.) and the Snežnik Mountain (1796 m a.s.l.). The northern part of the valley, i.e. the Lower Pivka Valley consists of noncarbonate flysch rocks, where superficial drainage prevails. The southern part, i.e. the Upper Pivka Valley is constituted of carbonate Cretaceous layers belonging to the Snežnik thrust sheet that lies over the Palaeocene and Eocene layers of the Komen thrust sheet. The displacement of the Snežnik thrust sheet over the Komen one is estimated to be of about seven kilometres. However, the intensity of the thrusting is less distinctive towards the northwest (Placer 1981).

From the hydrological point of view, the most significant unit is the Javorniki-Snežnik plateau, which is a deep diffuse karst. It is characterised by an immediate infiltration of rainwater underground and fast vertical drainage in different directions towards the springs located on the border of the plateau, where the groundwater generally flows rapidly through karst conduits. Consequently, the Javorniki-Snežnik massif drains towards both Adriatic and Black Seas. The southeastern part of the massif drains in the direction of Croatia and the Riječina River, whereas its northeastern part belongs to the recharge area of the Ljubljanica River. The northern part of the massif also partly drains towards the Vipava springs via several swallow holes. Finally, the southwestern part of the massif belongs to the catchment of the Reka River (Habič 1989; Kogovšek 1999; Ravbar & Goldscheider 2007).

In the west of the Upper Pivka Valley, the flysch layer acts as an impermeable barrier for the groundwater that runs from the Javorniki-Snežnik massif (Figs. 2.01 & 2.02). This partly prevents its draining towards the west, i.e. towards the Reka River. Therefore, the major part of the water coming from under the Snežnik Mountain rebounds against the flysch barrier and flows northwards towards the Pivka spring, and further to the springs recharging Planinsko Polje (Petrič & Kogovšek 2005). The underground water level strongly oscillates depending from precipitation and snowmelt: at low water conditions, the hydraulic gradient is inclined solely towards Cerkniško and Planinsko poljes, whereas it is also inclined towards the Pivka Valley at high water levels (Gospodarič 1989).

## HYDROGEOLOGICAL CHARACTERISTICS OF THE UPPER PIVKA VALLEY

Because of the underlying flysch rocks, a shallow karst aquifer is formed in the Upper Pivka Valley (Fig. 2.02). Due to the important groundwater fluctuations and weak connections between different karst conduits, several intermittent lakes of different size appear under high water conditions. When the groundwater level is rising, the water reaches the surface and activates several intermittent karst springs in the valley recharging the Pivka River as well as the intermittent lakes (Kovačič & Habič 2005). The water also pours out of the aquifer through innumerable fissures and voids at the bottoms or edges of depressions. These features are often small and not very distinctive. During recession periods, the water sinks underground through the same fissures and voids, which consequently act as small estavelles. Additionally, numerous swallow holes are activated. Finally, the Pivka River also seeps and sinks underground at different locations in its riverbed. In dry periods, the swallow holes and estavelles remain dry.

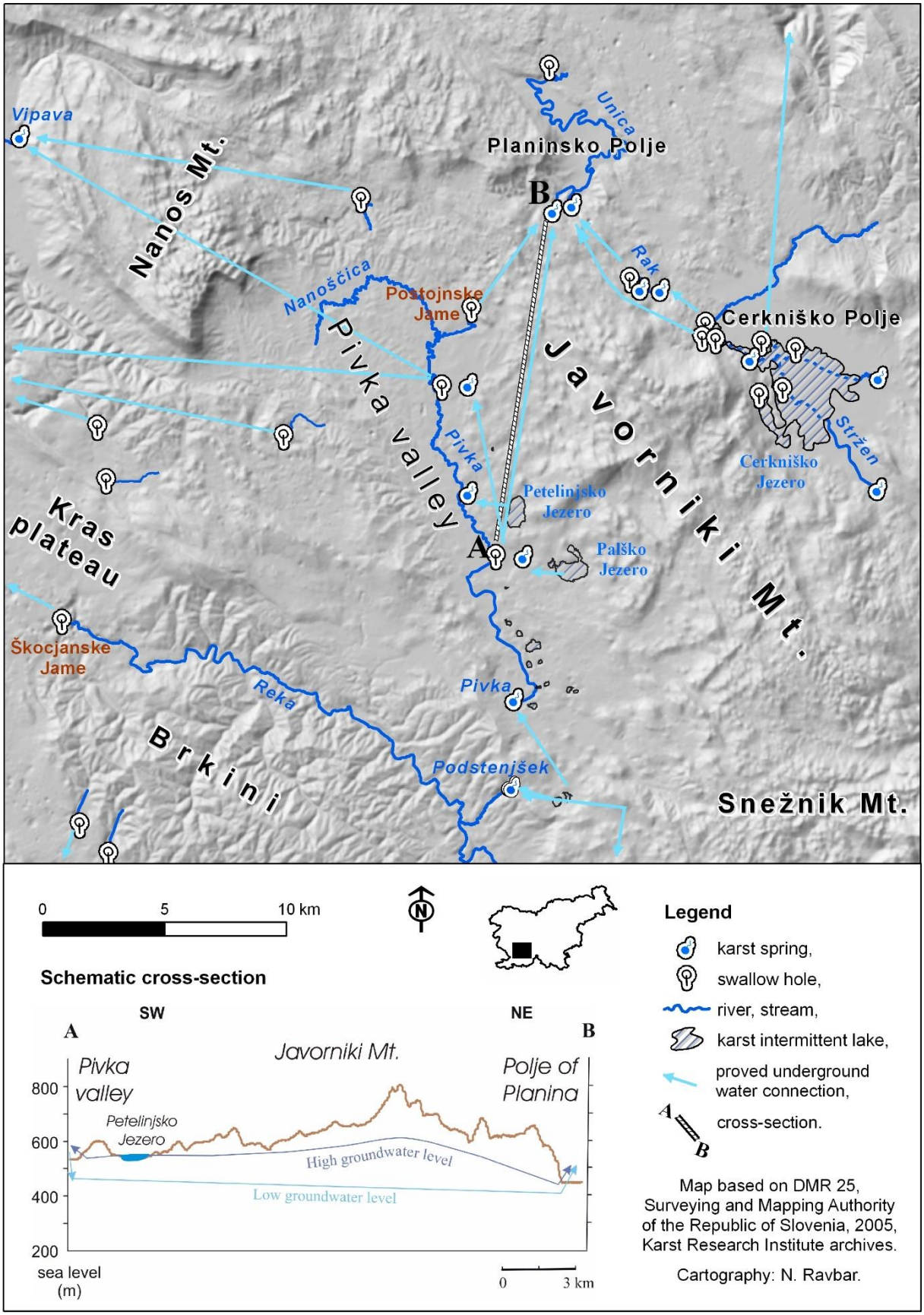



***Fig. 2.01:*** *Hydrological map of the Javorniki Mountains, Cerkniško Polje and Pivka Valley with the underground connections proved by tracer tests, and a schematic cross-section of the area during low- and high-water conditions (Ravbar 2013).*

The intermittent lakes appear in doline-like depressions with flat bottoms (Fig. 2.02). The two largest are the Palško Jezero (~1 $km^2$) and the Petelinjsko Jezero (~0.7 $km^2$). In addition, numerous smaller lakes extend over a few hectares (Ravbar & Šebela 2004). The flood duration and frequency is specific for each lake. Some of the lakes appear once or several times per year, while others occur only during exceptionally wet periods, maybe a few times in a century (Kovačič & Habič 2005). Similarly, some of the lakes contain water up to six months per year (e.g., Petelinjsko Jezero; Fig. 2.03), while the majority of them are flooded only for some days during and after very high precipitation events.

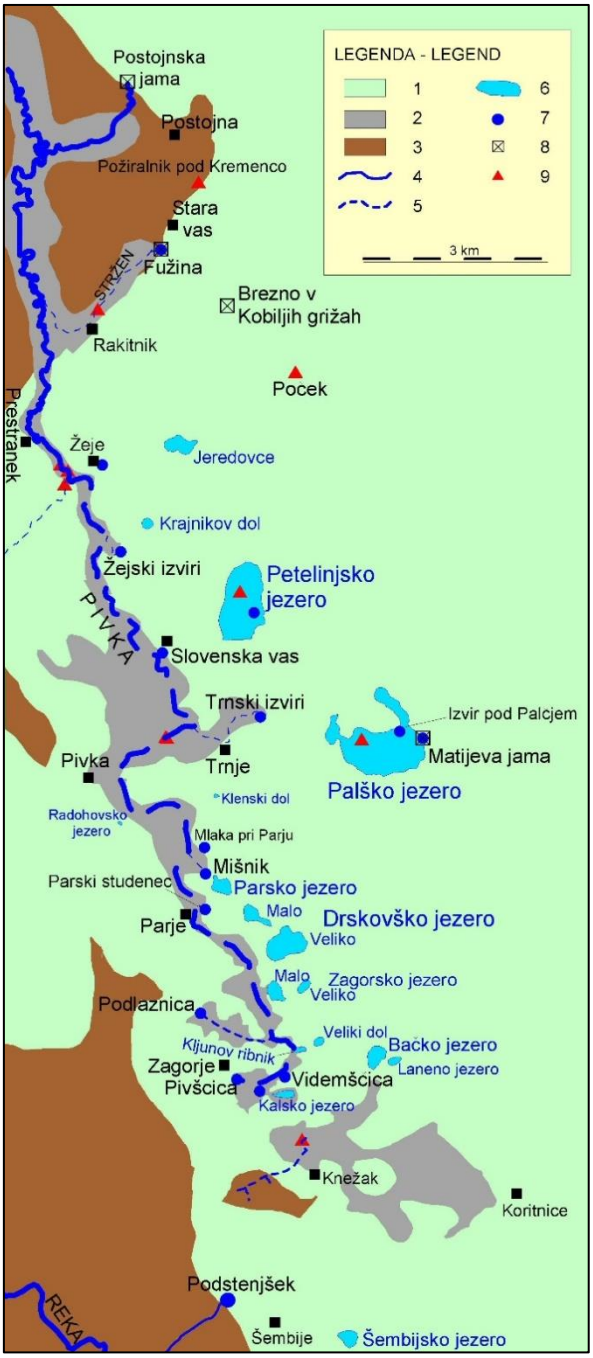



***Fig. 2.02:*** *Hydrogeological map of the Pivka Valley (Petrič & Kogovšek 2005). Legend: 1. Karst aquifer, 2. Porous aquifer, 3. Very low permeable rocks, 4. Surface flow, 5. Intermittent surface flow, 6. Intermittent lake, 7. Major spring, 8. Water cave, 9. Injection point.*

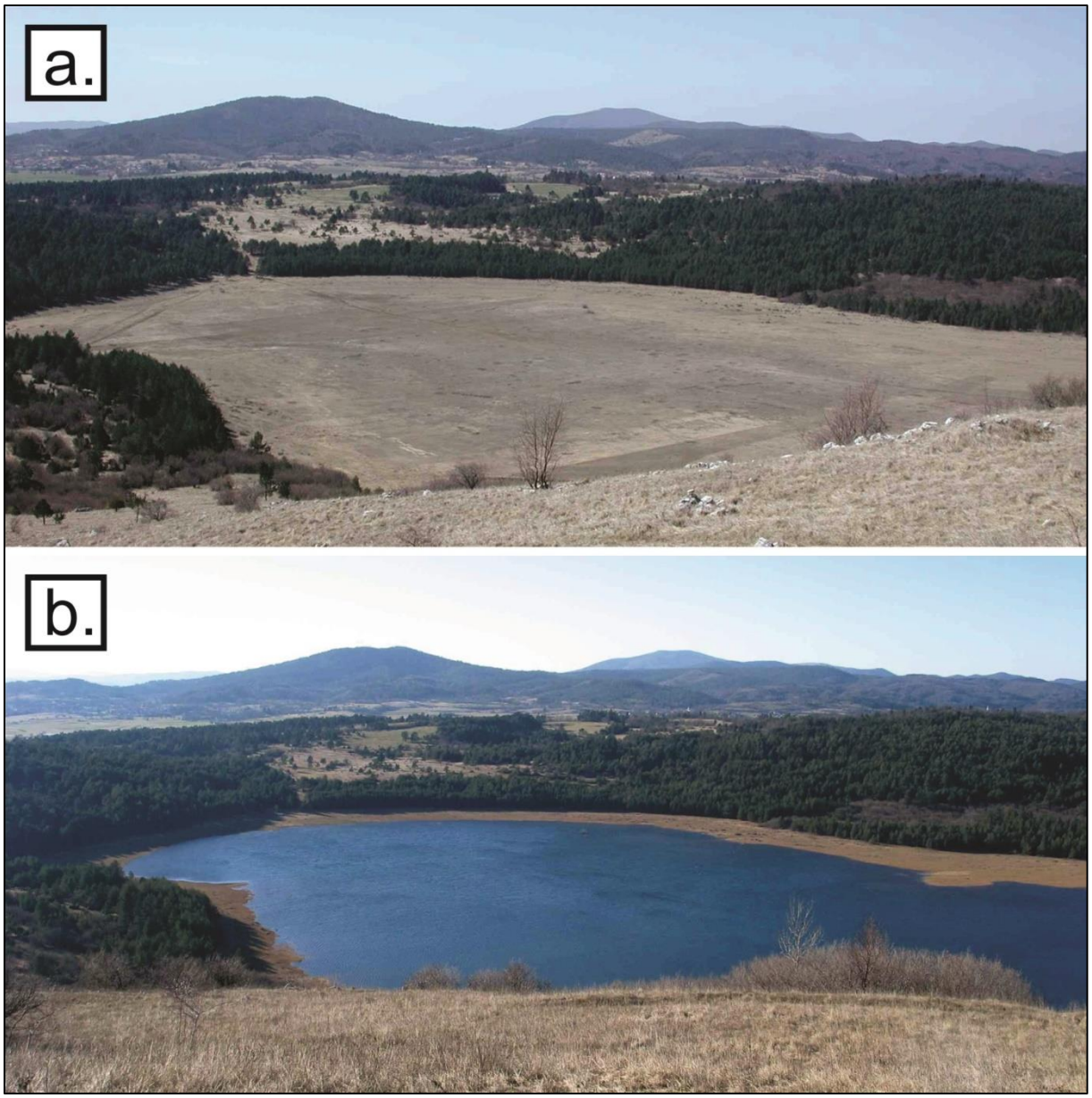



***Fig. 2.03:*** *The intermittent lake Petelinjsko Jezero (for location see Figs. 2.01 & 2.02). At low groundwater level, the karst hollow is dry (a). When the level of groundwater rises, the depression is flooded and forms a lake (b) (Photo: N. Ravbar).*

**THE CAVE OF MATIJEVA JAMA**

Matijeva Jama is an estavelle that provides most of the inflow and outflow of the Palško Jezero. The cave is located on the lake's eastern edge (Figs. 2.01, 2.02 & 2.04). The entrance is about 2x2 m large opening, which continues with an approximately 20 m deep shaft. It is followed by a narrow passage that steps down to a larger hall (10x10x10 m) and ends with a siphon. At low water conditions, the water level is located at about 516 m a.s.l. (Fig. 2.05). The water level fluctuations at this location might exceed almost 50 metres and the cave is able to discharge or swallow several $m^3/s$ of water depending on the hydrological situation (Kovačič & Habič 2005).


***Fig. 2.04:*** *Dry (a) and flooded (b) Palško Jezero with entrance of Matijeva Jama (Photo: C. Mayaud).*

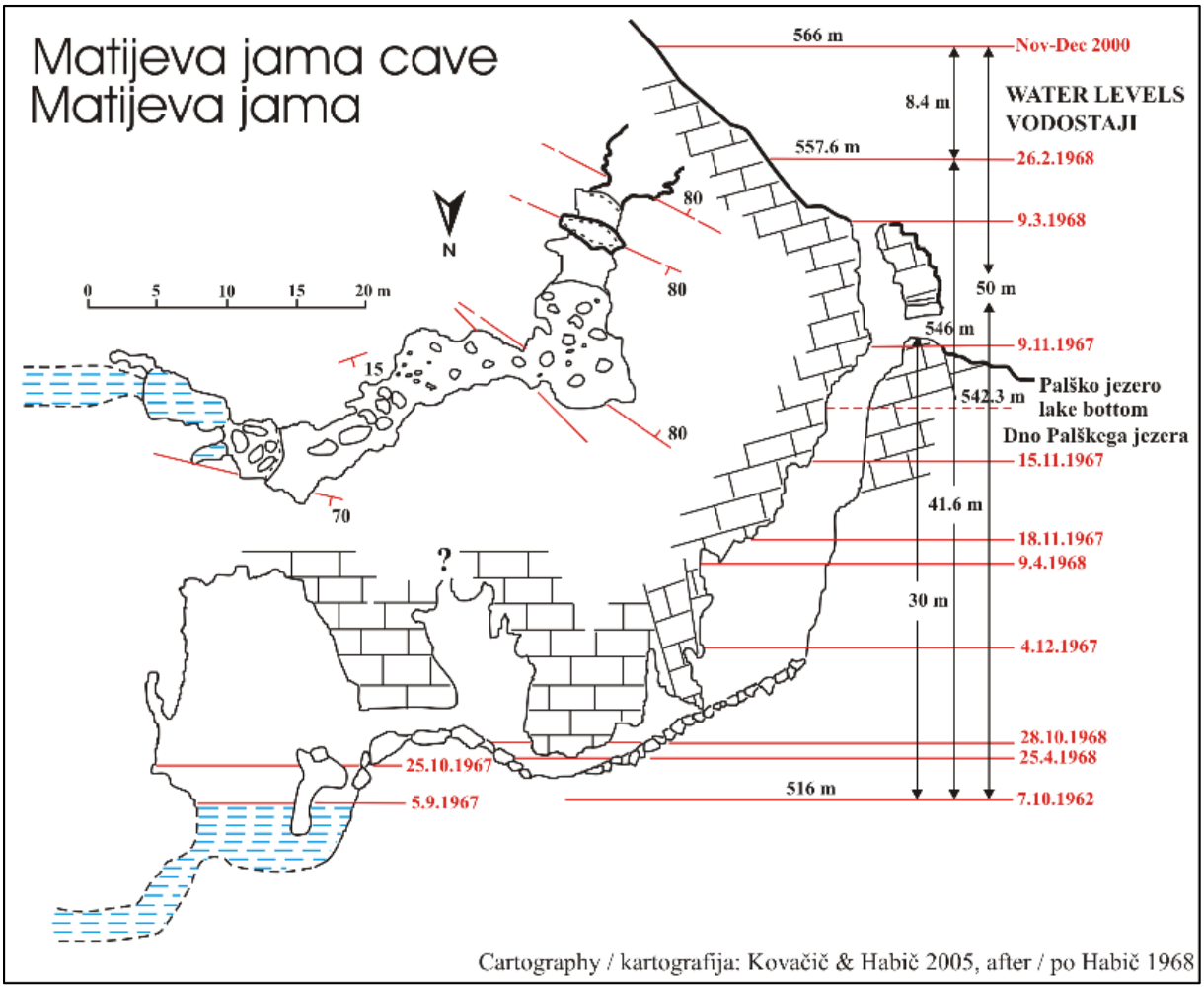



***Fig. 2.05:*** *Plan and cross-section of the Matijeva Jama with measured water levels depending on the hydrological situation (Kovačič & Habič 2005).*

During the summer 2017, two diving actions in the siphon of the Matijeva Jama were carried out. The exploration shown that the cave has an about 100 m long siphon, which is followed by a larger room splitting into two branches (Fig. 2.06). The southern branch ends with a shaft whose bottom goes below the level of the siphon, whereas the northern branch terminates directly with another unexplored siphon. The length of the newly explored part of the cave is of about 150 m, which makes the total length of the cave to reach 200 m.

## GROUNDWATER MONITORING

Since August 2016 water level, temperature (T) and electrical conductivity (EC) are being monitored at a half-hourly basis in the siphon of Matijeva Jama (Fig. 2.07a). This allowed to record up to eight high water periods, where the Palško Jezero was partly or entirely flooded. The flooding generally begins with a steep rise of the water level in the siphon and responds fast to rain event (Fig. 2.07a). A comparison with other groundwater monitoring stations located on the eastern side of the Javorniki massif (Gorenje Jezero) as well as in the Planinska Jama (Javorniški tok) about 15 km northward, shows that all monitoring points react almost simultaneously (Fig. 2.07b). This proves that they all belong to the same hydrogeological unit. The Palško Jezero starts to be flooded when the water level reaches the entrance of the Matijeva Jama at an elevation of 545 m a.s.l. The flood in the lake can last from a few days to more than a month, reaching an altitude up to more than 20 m above the

cave entrance (Fig. 2.05). The EC and T signals show the estavelle functioning. An influence of the external air temperature on the water T recorded at the siphon is visible when the lake starts to recede (Fig. 2.07a).

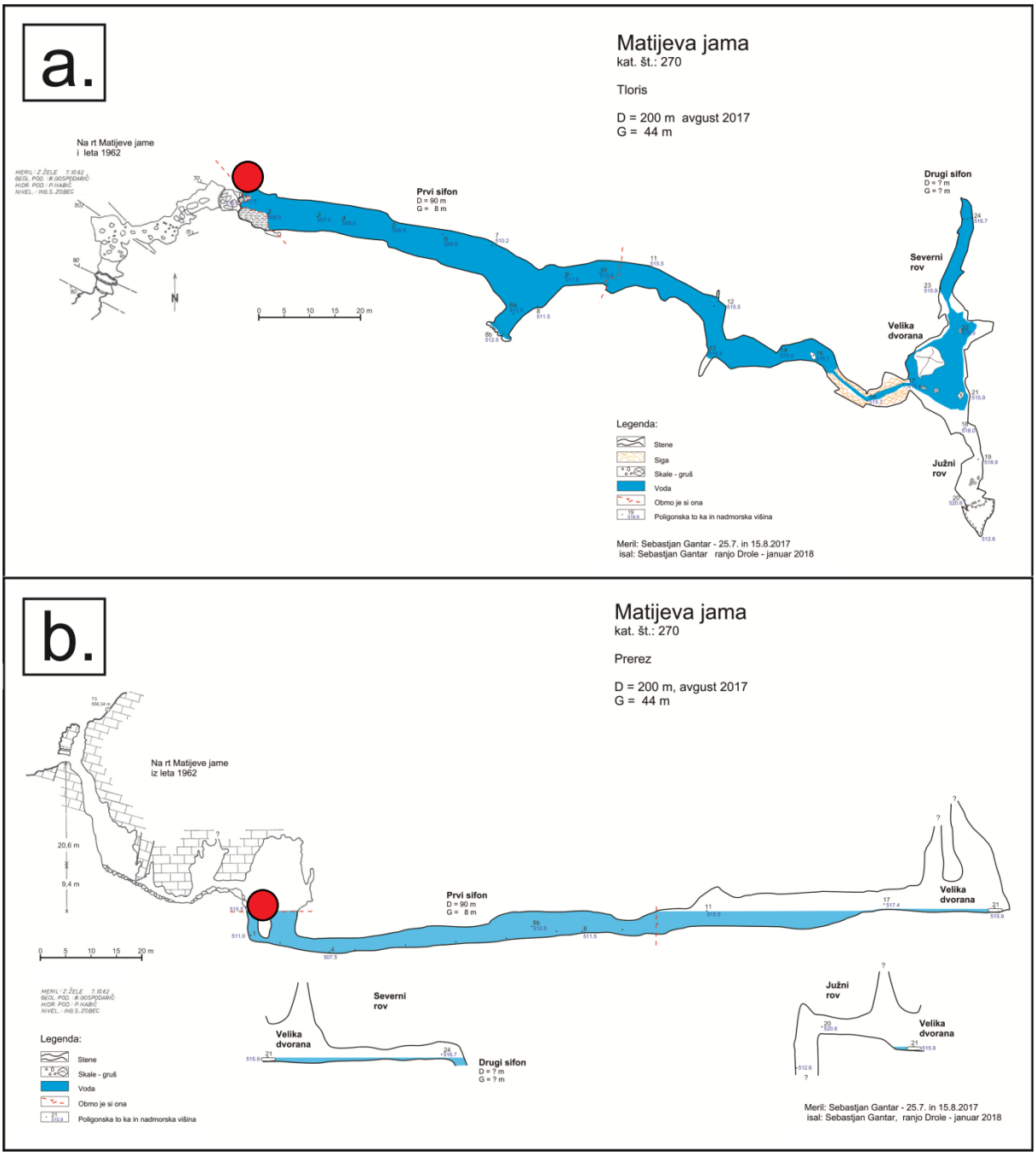



***Fig. 2.06:*** *Plan (a) and cross-section (b) of the parts of the Matijeva Jama that were explored and mapped in August 2017. The location of the groundwater monitoring point is marked with a red circle (Cave Register 2019).*

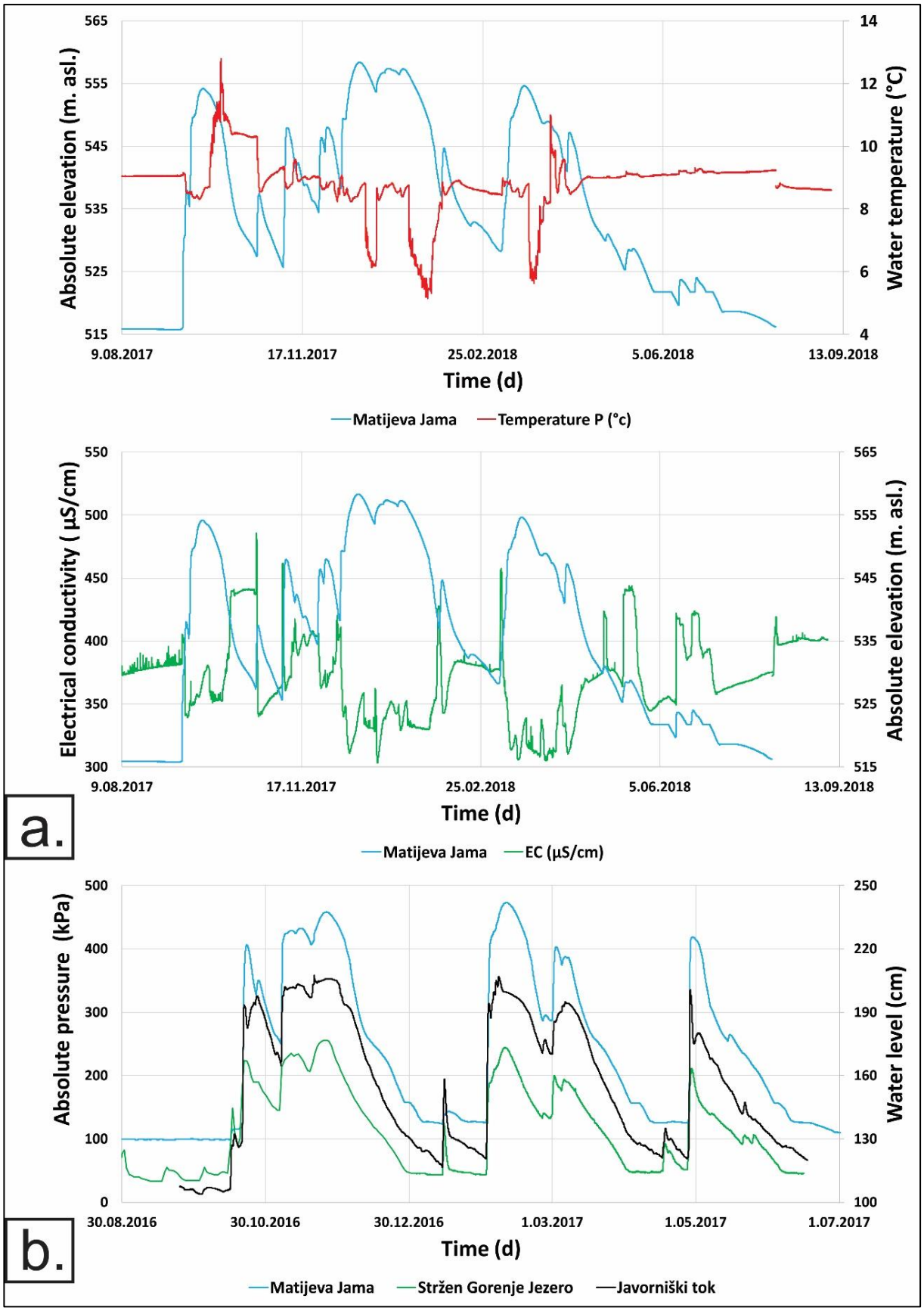



***Fig. 2.07:*** *Water level, temperature and electrical conductivity recorded at the siphon of Matijeva Jama during one year (a). Water pressure of Matijeva Jama compared to other monitoring stations in the region (b).*

**PUMPING TEST IN THE SIPHON OF MATIJEVA JAMA**

In August 2018, a pumping test was performed in Matijeva Jama to determine if the siphon represents stored perched water and is thus less convenient for water exploitation (Gabrovšek *et al.* 2019). Additional purposes were to determine the aquifer permeability as well as the size of the siphon and the rate of filling of the underground channels of Matijeva Jama. In order to check if the pumped water would eventually flow back to the cave, and because we were interested in the hydraulic connection of the bottom of the Palško Jezero with Matijeva Jama, a multi-tracer test was simultaneously carried out.

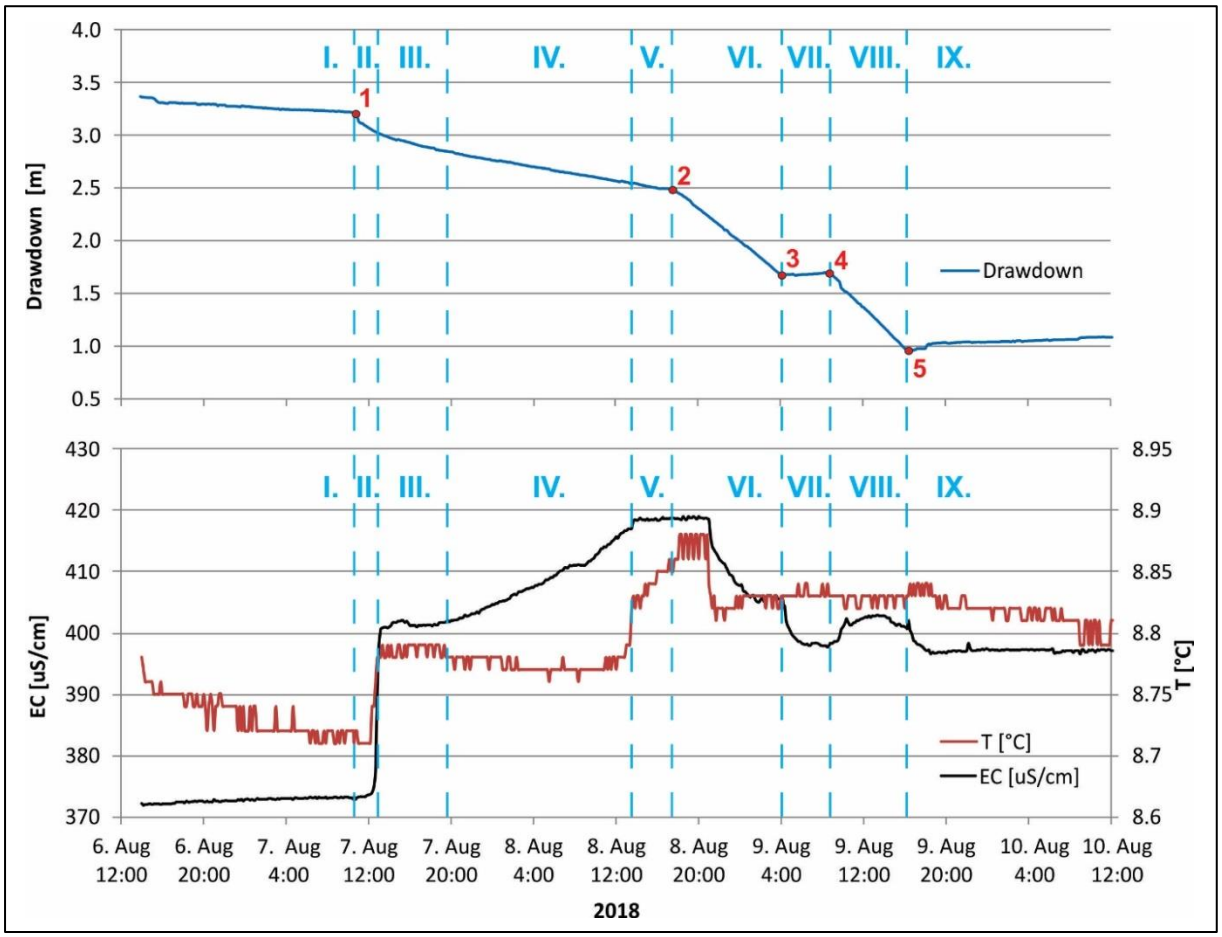



***Fig. 2.08:*** *Temporal variation of physical and chemical parameters of water during the pumping test.*

The obtained results were divided into several phases (Fig. 2.08):

**I. Phase: Situation before the pumping experiment.** The water levels were decreasing for 0.35 L/s (0.5 cm/h) on average due to the general low water conditions in the whole catchment. The surface of the flooded underground channel is determined to be of 245 $m^2$. The transition 1 indicates the start of pumping (6$^{th}$ August 2018).

**II. Phase: Start of the pumping test and injection of uranine.** Pumping started with a rate of 11.2 L/s. Simultaneously with the water discharge from the siphon 198 g of uranine has been released into the outflow, which was located about 200 m away from the cave entrance and its known parts. Firstly, the water level dropped by 9 cm/h. No significant inflow into the cave was noticed.

**III. Phase: Impact of pumped water on the water level.** On 7$^{th}$ August the values of electrical conductivity (EC) and temperature (T) increased abruptly. During this time, the water level decreased only by 2.1 cm/h. In the evening there were still no tracers detected. We concluded that the infiltration of the pumped water caused a piston effect of the more mineralized and warmer water

stored in cracks and channels. This water was pushed towards Matijeva Jama already an hour after the start of pumping.

**IV. Phase: The pumped water is detected back into the cave.** The EC was constantly increasing until 8th August, while the T was stable. The water level decreased very slowly with an average speed of 1.7 cm/h. As a tracer has been detected in one of the collected samples (C = 11.2 µg/L) it was proven that the pumped water released at the surface started to return back to the cave (Figs. 2.08 & 2.09). To prevent this effect, additional pipes were added, in order to split the pumped water into two parts. They enabled releasing the water further away from the cave. Again 210 g of amidorhodamine G and 0.5 kg of naphtionate has been released into the new outflows.

**V. Phase: The steady state conditions.** All measured parameters stabilize, therefore we conclude that the drainage pathways towards the Matijeva Jama are saturated with water. The difference between recharge and pumped outflow is of about 2 L/s with a return flow rate to the cave of 8.9 L/s. At this height, the surface of the flooded underground channel has been estimated of approximately 470 $m^2$.

**VI. Phase: Reduction of return flow.** By extending the drainage pipes, the water outlet point was prolonged. The water level immediately began to decrease more rapidly by an average of 7.8 cm/h (Transition 2 in Fig. 2.08), which was similar to the rate measured at the beginning of the pumping. The EC and T are initially stable and then suddenly drop. We could conclude that there were no significant additional inflows into the cave.

**VII. Phase: Temporary interruption of pumping**. In order to prevent failure of the pump due to a hypothetical drop of the water level below the pump level, pumping was temporary stopped on 9th August. Meanwhile, the water level increased by an average of 1.12 cm/h. The EC decreased, while the T remained constant. This shows that a weak inflow of water entered into the system, at a flow rate of about 0.6 L/s. At this time, the lake had an area of about 490 $m^2$. We have then put the pump to the lowest possible level.

**VIII. Stage: New pumping phase.** The average drop of water level was 10.0 cm/h. At the lowest water level, the flooded underground channel had an area of about 390 $m^2$.

**IX. Phase: Refilling of the siphon.** The pumping was definitely stopped on the 9th August. The recovery of uranine until the end of pumping was estimated at 37 %. The apparent dominant water flow was estimated at 7 m/h. The water level steadily increased by 25th August at an average of 0.24 cm/h. The other two tracers amidorodamine G and naphtionate, which we injected into the extended outflow, did not appear in Matijeva Jama during the observation period. Therefore, we can conclude that after the drainage pipes were extended and divided into two, the pumped water was no longer flowing back to the cave. Thus, the influence of this water on the water level in the cave can afterwards be excluded.

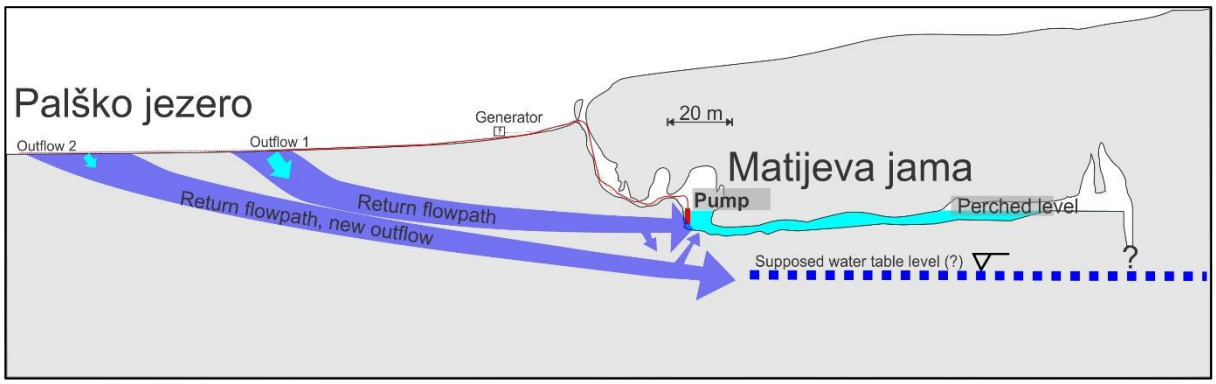



***Fig. 2.09:*** *Cross-section of the conceptual hydrogeological model between Palško Jezero and Matijeva Jama during the pumping test.*

## CONCLUSION

At high water level, the water in Matijeva Jama belongs to the regional water body, which also shows a good correlation with other monitoring points in the region (Fig. 2.07b).

At low water level, the water in Matijeva Jama belongs to an isolated perched aquifer. This was proved by the pumping test; where 1.665 $m^3$ of water was pumped out. The water level decreased by 2.26 m with a maximum drawdown of about 10 cm/h. Since the changes of water level are proportional to the cave net outflow / inflow and inversely proportional to the surface of the lake at the selected height, we were able to estimate the channel surface at different heights. This ranges between 250 and 500 $m^2$.

The combined pumping and tracer test showed an immediate flow back into to cave from the depleted water, with a maximum recharge flowrate of almost 9 L/s. This proves that the bottom of the Palško Jezero, where agricultural activity predominates, is very well permeable and has a direct connection to the cave. As soon as the water outlet point was prolonged, the recharge flowrate decreased to 0.6 L/s. Therefore, the known water bodies of Matijeva Jama are not suitable for exploitation.

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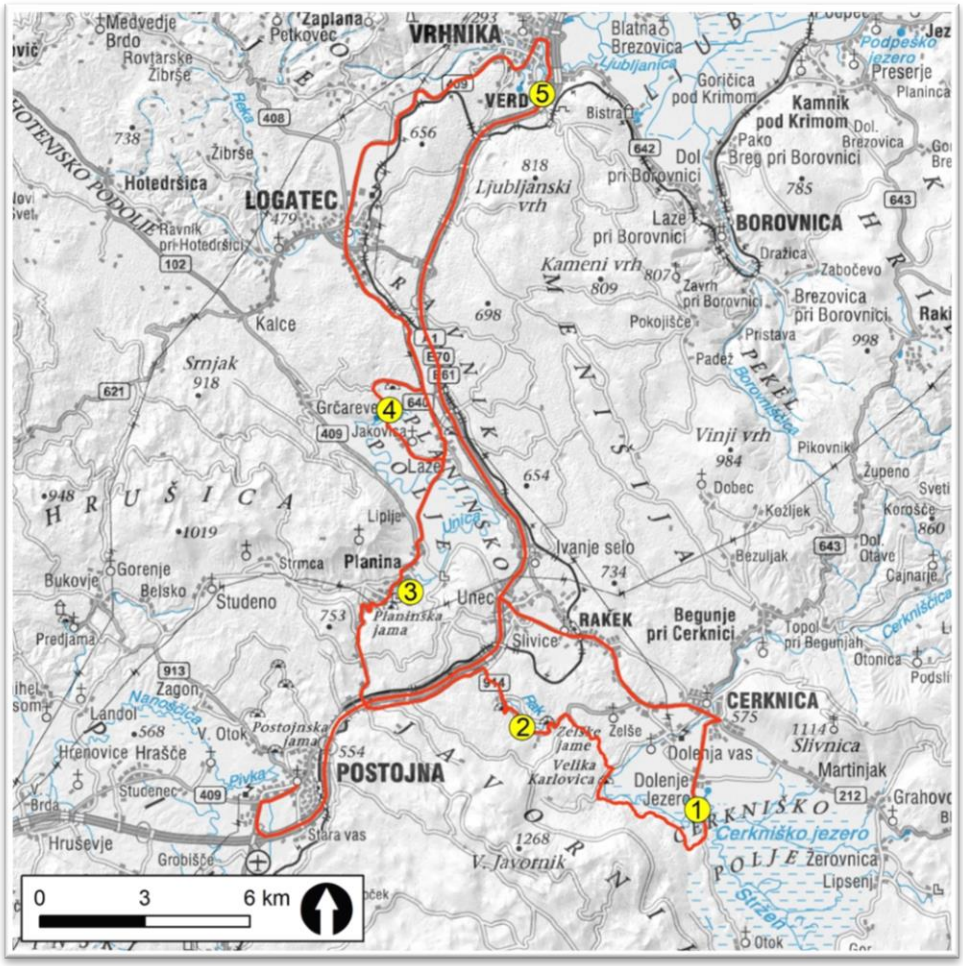
**Whole-day field trip (C):**

# GROUNDWATER FLOW IN THE LJUBLJANICA RECHARGE AREA

Thursday, 20. 6. 2019, 8:00–18:00

*Stops:*
**1** – Outflow zones of Cerkniško Polje
**2** – Hydrology of the Rakov Škocjan karst valley
**3** – Planinska Jama with underground confuence of rivers
**4** – Outflow zones of Planinsko Polje
**5** – Collapse dolines and springs of Ljubljanica River near Vrhnika




**Značilnosti podzemnega toka v zaledju Ljubljanice**
*Celodnevno terensko delo (D); četrtek, 20. junij 2019;*
Za porečje Ljubljanice je značilno menjavanje kraških polj in kraških planot. Niz kraških polj s ponikalnicami ima dinarsko smer (SZ–JV), del vode pa se priključi z JZ, s Pivške kotline. Prvi del terenskega dela predstavlja nekaj izbranih kraških polj (Cerkniško polje, Planinsko polje) ter Rakov Škocjan z značilnimi kraškimi pojavi (kraški izviri, požiralniki, jame, vodotoki). Drugi del je posvečen izvirom Unice in Ljubljanice. Poudarek terenskega dela je v predstavitvi zadnjih raziskav, ki so se v največji meri nanašale na proučevanje toka vode v Rakovem rokavu Planinske jame ter toka vode dolvodno od Planinskega polja. Ugotovljene so bile nekatere nove smeri pretakanja, ki se v času lahko spreminjano. Prepoznani so bili tudi prelivni kanali in potencialne geološke pregrade, ki prav tako lahko vplivajo na dinamiko pretakanja podzemne vode in poplavljanje na površju.

**GENERAL INTRODUCTION: HYDROGEOLOGY OF THE LJUBLJANICA RIVER RECHARGE AREA**

The central part of the Slovene Dinaric karst drains towards the springs of Ljubljanica River, which are located at the southern rim of the Ljubljana Basin (Fig. 3.01). Although the area comes about 26 km of straight-line distance close to the Adriatic Sea, the intensive tectonic activity triggered the drainage towards the Sava-Danube catchment that flows towards the Black Sea. The total estimated size of the Ljubljanica recharge area is almost 1800 km$^2$, of which about 1100 km$^2$ is karstic. The karst catchment has been delineated during the extended tracing campaign that was carried out in the seventies (Gospodarič & Habič 1976).

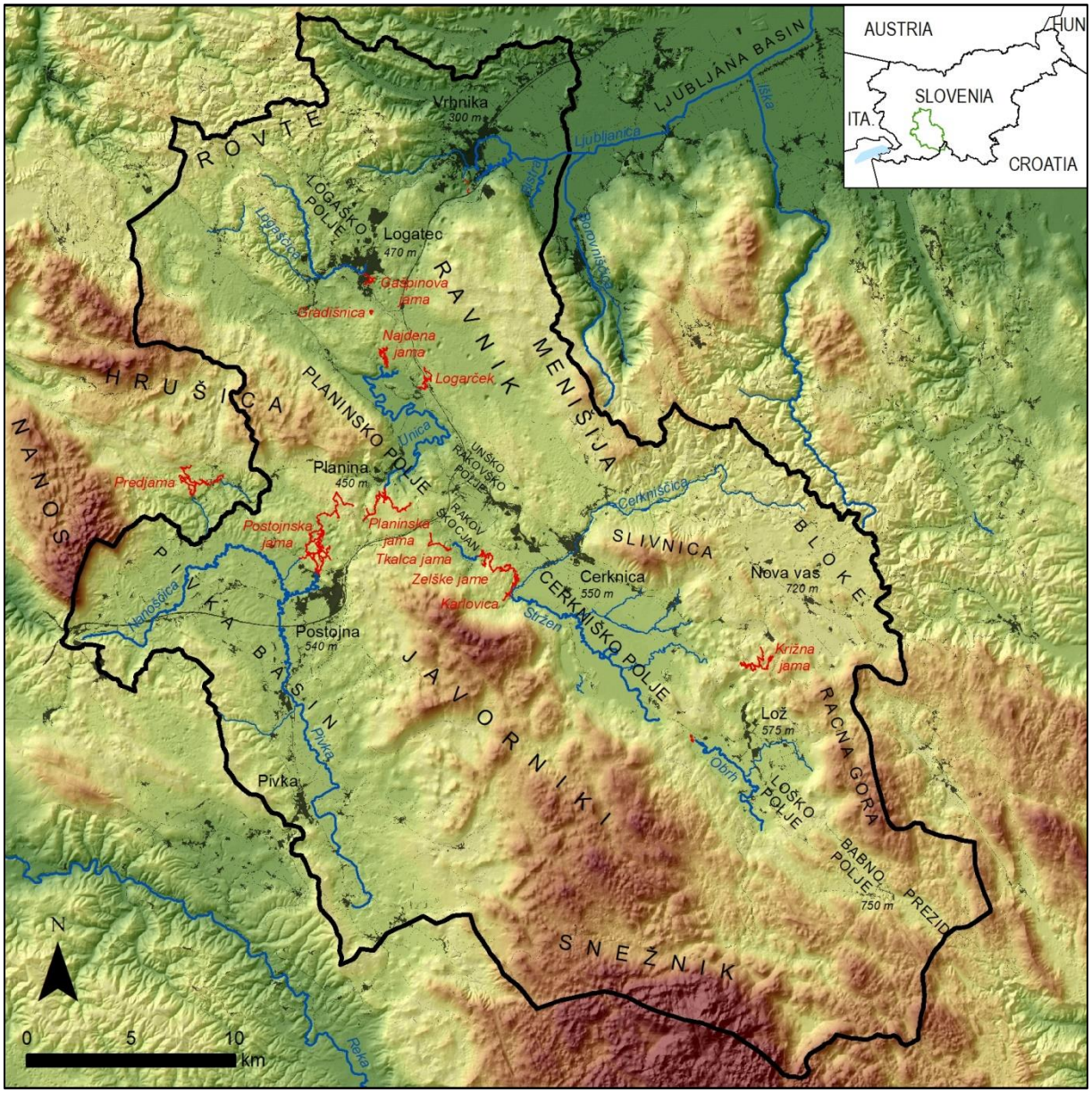



***Figure 3.01:*** *Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.*

The karst rocks are mostly of Mesozoic age. These are generally micritic, locally oolitic limestones and dominantly late-diagenetic dolomites. They were formed on the Dinaric platform under conditions of continuous sedimentation which enabled high rock purity, generally with less than 5 %, but locally as little as 0.1 %, insoluble residue. The total thickness of the carbonate sequence is almost 7 km.

Structurally, the whole of the Ljubljanica catchment belongs to the Adriatic plate. The area is composed of several nappes that were over thrust during the peak of Alpine orogeny in Oligocene in a NE to SW direction (Placer 2008; Placer *et al.* 2010). Later change of the plate movement direction resulted in the formation of the Idrija Fault Zone, a dextral strike-slip fault, which crosses the area in a NW-SE direction (Fig. 3.02) (Vrabec 1994). The Idrija fault zone largely determines direction of the regional flow (Fig. 3.02). Generally, 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 for the groundwater flow and forces the water to surface in the poljes. At the same time, it deflects the flow along the Dinaric (SE-NW) direction (Šušteršič 2006).

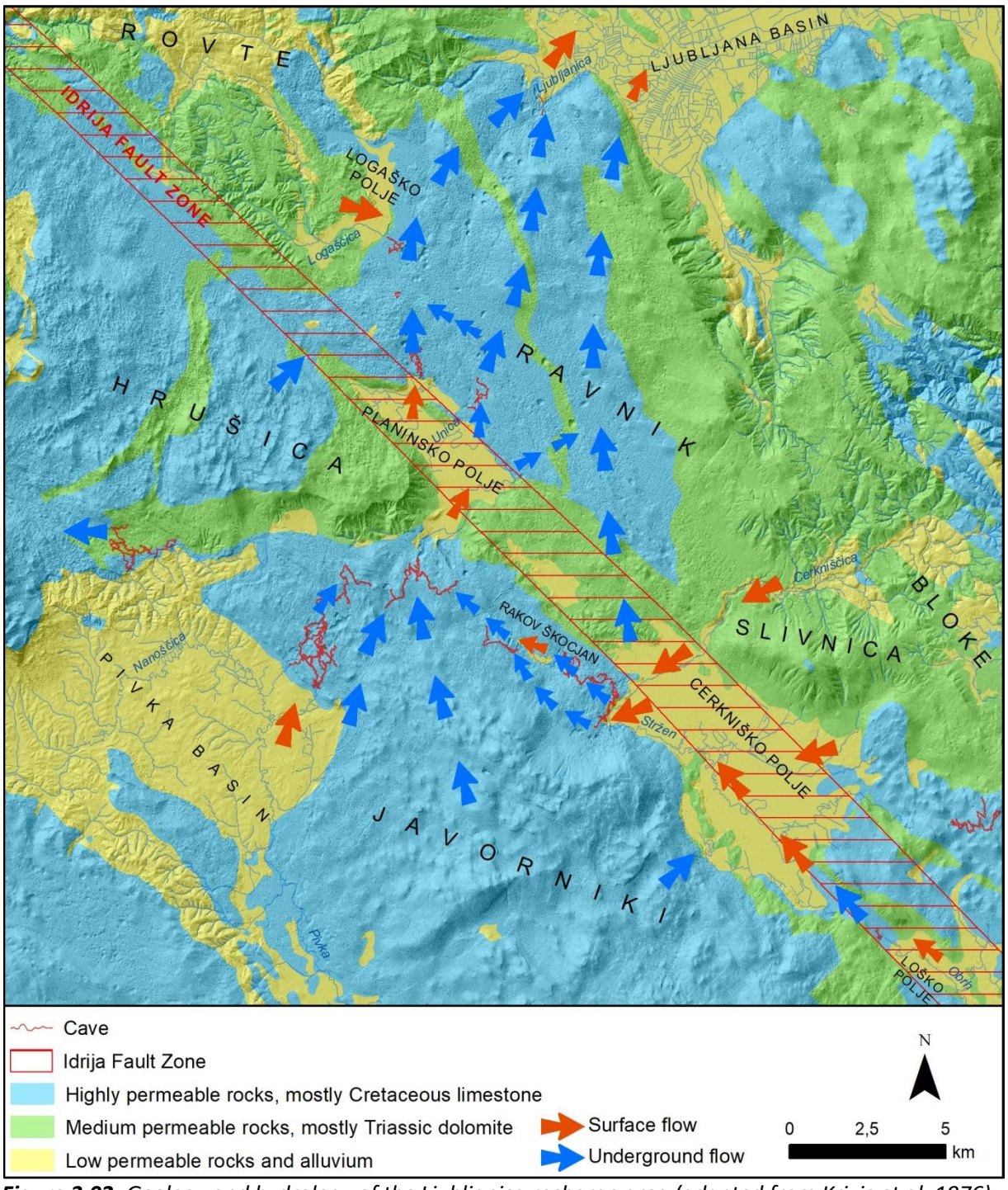



***Figure 3.02:*** *Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).*

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

Generally, the water follows the SE–NW direction with surface flow on the poljes and groundwater flow in-between (Fig. 3.03). Additional water enters the flow system at numerous springs draining the areas of Snežnik and Javorniki mountains on the South of the Idrija Fault Zone. Several sinking rivers that drain dolomite or flysch areas also contribute to the system (Gams 2004). The elevation of the poljes drops from about 750 m to 450 m. The streams flowing on them have different names: Trbuhovica, Obrh, Stržen, Rak, Pivka and Unica. Apart from a relatively small amount of water, which flows directly from Cerkniško Polje to the springs of Ljubljanica, most of the water surfaces at the southern rim of Planinsko Polje. The water sinks back underground along its eastern and northern border and flows northwards towards several large and many small springs aligned along the southern edge of the Ljubljana Basin, which is connected with gradual tectonic subsidence of the area (Krivic *et al.* 1976; Gams 2004). The average annual discharge of the Ljubljanica springs is 38.6 $m^3$. An additional amount of water flows from the low to medium permeable plateau of Rovte and contributes to the Ljubjanica springs by sinking in 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 (Fig. 3.03).

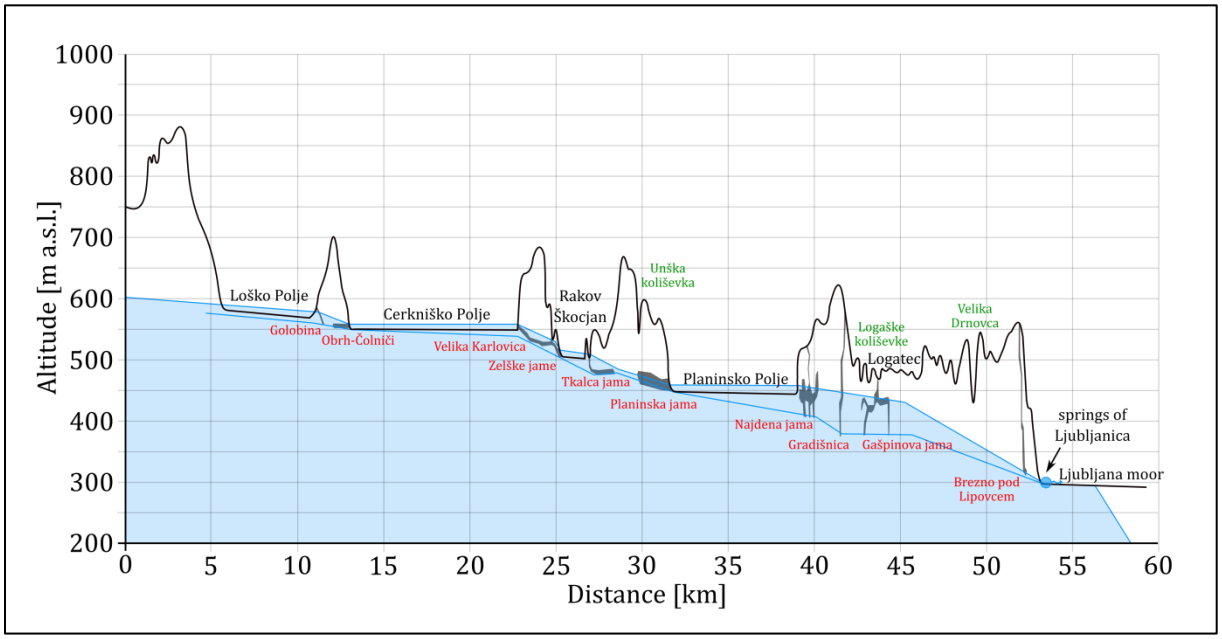



*Figure 3.03: Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in green.*

**CERKNIŠKO POLJE**

Cerkniško Polje is the largest karst polje in Slovenia (Gams 1978, 2004). Due to its regular flooding it is often called Cerkniško Jezero (Lake of Cerknica) (Fig. 3.04a). When full, the intermittent lake covers up to 26 $km^2$ out of 38 $km^2$ of the polje's total surface area. The bottom elevation is about 550 m. Its intermittency has attracted many scholars since the beginning of the New age including polihistor Valvasor, who published his famous study on Cerkniško Jezero in 1689 (Shaw & Čuk 2015). The main part of the polje is underlained by Upper Triassic dolomite in its N, E and SE borders. Conversely, areas on the W and NW are mainly underlain by Cretaceous limestone (Fig. 3.02).

***Figure 3.04:*** *(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, mostly during autumn, winter and spring time (Kovačič & Ravbar 2010).The main inflows into the polje comes from a set of karst springs named Žerovniščica, Šteberščica and Stržen which are located at its eastern and southern borders. The springs located on its SW side (e.g. Suhadolca, Vranja jama) present important recharge during floods. In addition, an important allogenic component comes from the Cerkniščica River, which

drains an about 44 km$^2$ large dolomitic area located in the E (Gams 2004). Finally, several estavelles (Vodonos, Rešeta) contribute also to the polje inflow.

Besides the estavelles, several ponor zones located in the inner part of the polje drain some amount of water directly to the springs of Ljubljanica (Krivic *et al.* 1976) (Fig. 3.04b), whereas the main ponors are aligned along the W side of polje, with Velika and Mala Karlovica being the most prominent. Both caves extend over 8.5 km between Cerkniško Polje and the Rakov Škocjan karst valley. Up to now, only a small segment between Velika Karlovica and Zelške Jame (located in Rakov Škocjan) is unexplored due to the presence of an important collapse zone. Recent studies have shown that during low to medium hydrological situations (Gabrovšek *et al.* 2010; Ravbar *et al.* 2012), important part of the water sinking in the ponors of Mala Karlovica arrives at the Kotliči springs positioned in the middle of the Rakov Škocjan and a smaller part to the Zelške Jame, which would be the most logical direction.

During the last centuries, several plans have been made to change the hydrological behaviour of the polje, but none was finalized. In 1960-ies a plan to transform Cerkniško Jezero into a permanent lake started. The entrances of the caves Velika and Mala Karlovica were closed by concrete walls, and a 30 m long tunnel was made to connect Karlovica with the surface. However, a small effect on retention of waters during dry periods was assessed (Shaw & Čuk 2015).

## RAKOV ŠKOCJAN KARST VALLEY

Before reaching Planinsko Polje, the water sinking in the main ponors of Cerkniško Polje surfaces in an about 1.5 km long and 200 m wide karst valley called Rakov Škocjan (Fig. 3.05). On the upstream (SE) side, the water emerges as Rak River from Zelške Jame (Zelše Caves). Zelške Jame is about 5 km long and ends in the large collapse doline of Velika Šujca, where water arrives from Cerkniško Polje via the Karlovica cave system. The entrance part of the Zelške Jame is a fragmented system of channels and collapse dolines. The most prominent feature is Mali Naravni Most (Small Natural Bridge), where an impressive narrow arch that belonged to the former cave ceiling, crosses the collapse doline (Gams 2004).

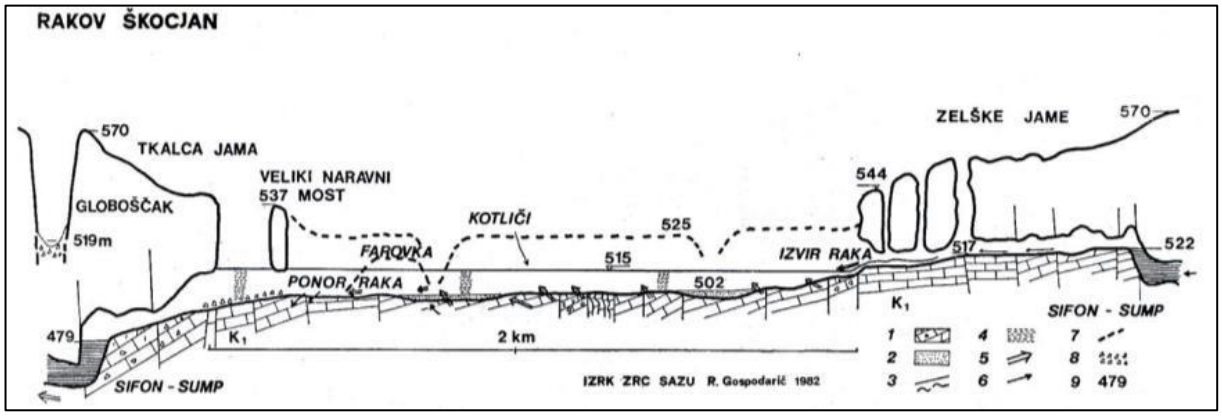



***Figure 3.05:*** *Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring: 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.*

Downstream, the valley widens and several springs located along the SW side of the valley (i.e., 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. 3.06). 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 composed of thick-bedded and anticline-folded Lower Cretaceous limestone.

After Veliki Naravni Most, the channel opens into a 150 m long canyon that ends in the entrance of Tkalca Jama, an almost 3 km long cave that drains water towards Planinsko Polje. The connections of the Rak with water from Cerkniško Polje and with the Unica springs at Planinsko Polje were proved 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. The floods can reach an elevation of 19 m above the cave entrance (located at 496 m a.s.l.), and large parts of the Rakov Škocjan karst valley are frequently inundated (Drole 2015). Before the 1st World War, Rakov Škocjan was a private park owned by the Windischgrätz family; whereas the Italians used it as a military area between 1st and 2nd World War. Since 1949, Rakov Škocjan is a Landscape Park open for the public.

***Figure 3.06:*** *Veliki Naravni Most (Big Natural Bridge) during dry period in summer (left) and high water event in winter (right) (Photos: M. Blatnik).*

**PLANINSKA JAMA – THE MYSTERIOUS LAKE**

Planinska Jama (Planina Cave) is a major spring located on the southern rim of Planinsko Polje (Figs. 3.01 & 3.10). The cave is about 6.6 km long and mostly composed of large active river passages with cross-sections frequently larger than 100 $m^2$ (Fig. 3.08 left). The cave is known for being the confluence of two important regional streams (Fig. 3.07): the Pivka River that drains a large allogenic catchment through Postojnska Jama (Gabrovšek *et al.* 2010; Kaufmann *et al.* 2016) and arrives at the cave confluence via the Pivka Branch, and the Rak River that brings water from Rakov Škocjan and Cerkniško Polje via the Rak Branch. Finally, an important amount of water also enters additionally the Rak Branch via the siphon of the Javornik current that is located in bellow the Mysterious Lake (Fig. 3.07). The water emerges from the cave under the common name of Unica with a discharge ranging between 0.2 and 75 $m^3/s$ (Frantar 2008).

There are significant differences in water contribution of the different parts of the aquifer that recharge the Unica spring (Savnik 1960). 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 massive. Then, the nearby Malenščica spring (Fig. 3.07), which is predominantly fed by the allogenic water coming from Rakov Škocjan and by the autogenic Javorniki water reaches a maximum discharge of 9–10 $m^3$/s (Kogovšek 1999; Kovačič 2010, 2011). Because the spring is damped, the Rak Branch activated and acts as an overflow, while the Unica also receives waters from the Pivka Branch. Under low water conditions, after the emptying of Cerkniško Jezero, the outflow is solely directed towards the Malenščica spring, while the Unica spring is exclusively fed by the Pivka Branch (Kaufmann *et al.* 2019).

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 conditions (between 20 and 25 m/h) compared to low water conditions (~ 4 m/h). In the well-developed conduit networks of Karlovica-Zelške Jame, Tkalca-Planinska Jama, and Postojnska-Planinska Jama, the flow velocities during high waters were up to fifty or even ninety times higher (between 170 and 1000 m/h) in comparison to the velocities observed at low waters (~ 4–23 m/h) (Petrič *et al.* 2018).

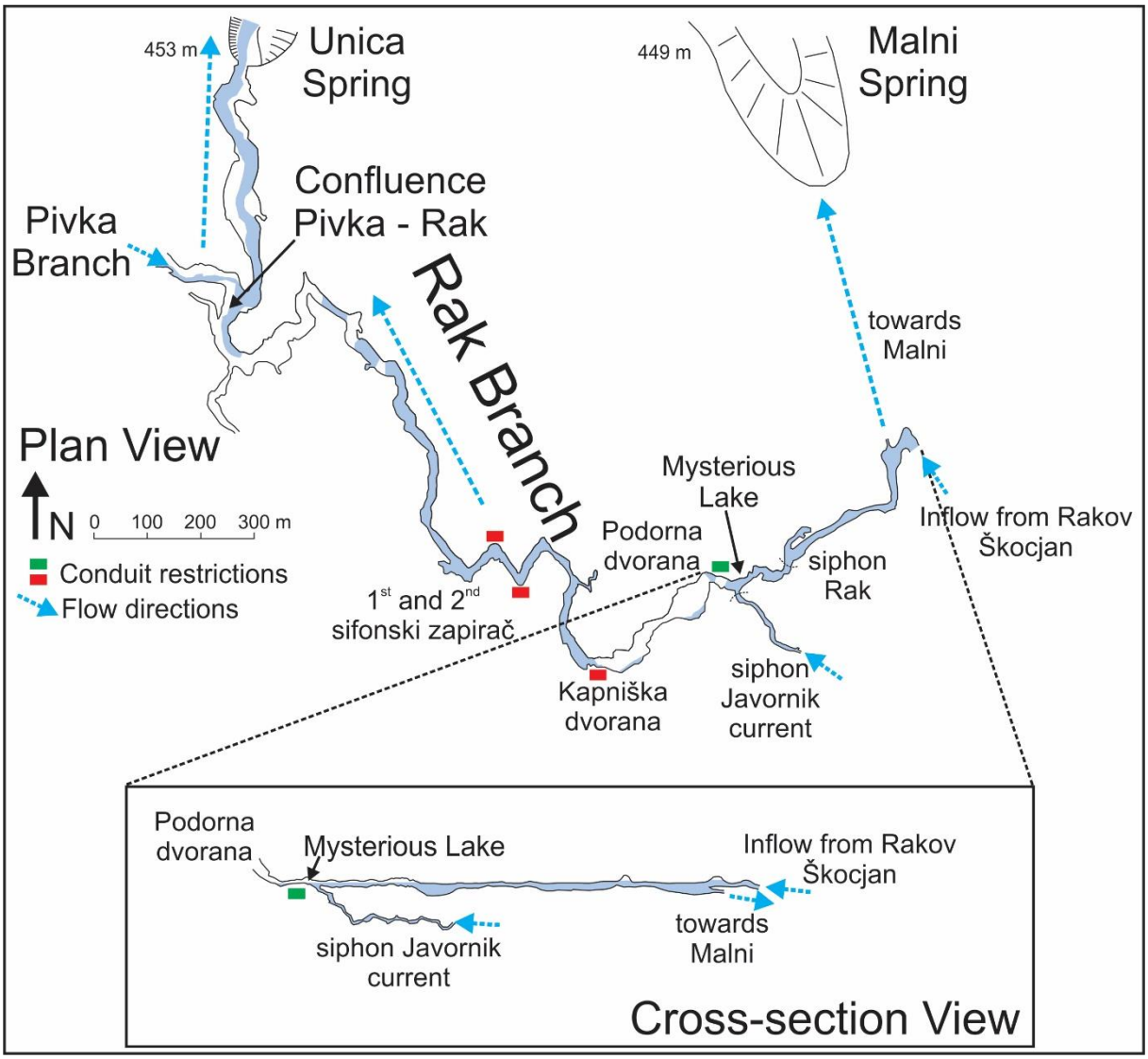



***Figure 3.07:*** *Detailed view of the Rak Branch of Planinska Jama and cross-section of its terminal siphon in the Mysterious Lake (Gams 2004; Cave Register 2019).*

The cave entrance is located in Upper Cretaceous limestones and dolomites. The entrance part and the Rak Branch are developed in Lower Cretaceous bedded limestones, limestones with chert and limestone breccia. Conversely, the Pivka Branch and Rudolfov Rov (passage to the south of the Rak Branch) are developed in Upper Cretaceous massive limestone and breccia with Caprinidae and Chondrodontae (Habič 1984). Both parts of the cave end with sumps that have been dived, but no connection to the upstream systems has been yet accomplished. However, the recent dive explorations in the terminal siphon of the Pivka Branch give reasonable hope that a connection to Postojna cave system could be realized in a near future.

***Figure 3.08:*** *Planinska Jama. Left: example of typical large cave passage in the Rak Branch. Right: recent diving exploration in the Mysterious Lake and Javornik Current (Photos: M. Blatnik).*

Last three years of research carried out in Planinska Jama were mostly focused on studying the hydrological behaviour of the Javornik current (Gabrovšek *et al.* 2019), a partly explored siphon that joins to the Rak Branch in the so-called Mysterious Lake (Fig. 3.07 & 3.08 right). To do so, water pressure, electrical conductivity and water temperature have been automatically recorded in the Mysterious Lake as well as in the sump of the Javornik current. The main goal was to see if the water coming out from the siphon would be suitable for human consumption in order to use it as a back-up reservoir for the municipalities of Postojna and Pivka (Gabrovšek *et al.* 2019).

While the discharge coming out of the siphon is relatively constant, the origin of the water and its hydrogeological behaviour are more complicated. For many years, it was expected that the siphon of the Javornik current is solely recharged by autogenic waters infiltrating through the Javorniki and Snežnik Mountains (Petrič *et al.* 2018). However, recent observations recorded by the automatic data-loggers are showing a much-complicated dynamics (Fig. 3.09). Measurements of temperature and EC indicate an evident switching of flow direction within the siphon of the Javorniki Current. This means that, depending on the hydrological situation, the flow direction is from Mysterious Lake into the siphon or vice versa. In former case, the water in the siphon is almost the same as in Mysterious Lake dominated by inflow from Rakov Škocjan. In the latter case, the water in the syphon is the "true" Javorniki current. The exact mechanism and conditions is yet to be determined (Gabrovšek *et al.* 2019).

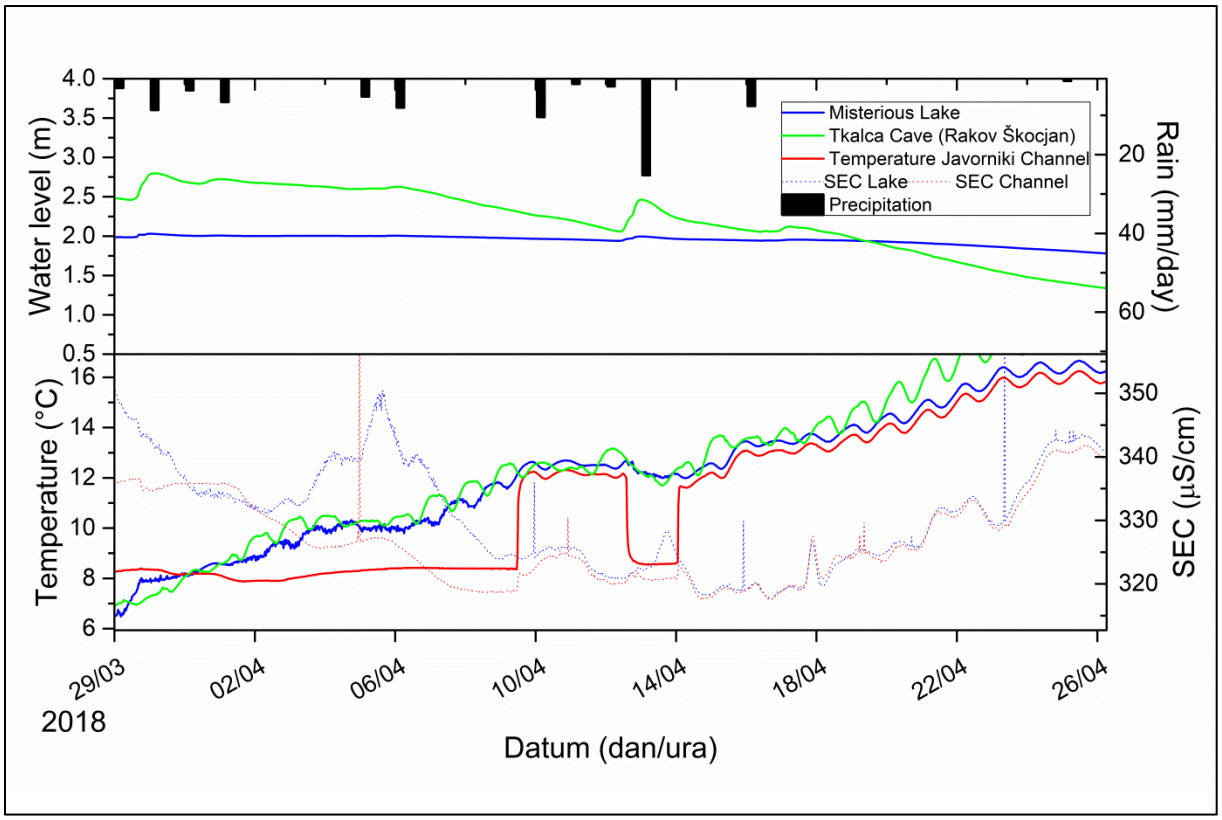



***Figure 3.09:*** *Example of hydrological event showing a flow reversion in the siphon of the Javornik current.*

**PLANINSKO POLJE: OUTFLOW ZONES AND FLOOD BEHAVIOUR**

Planinsko Polje is a typical example of overflow structural polje (Gams 1978; Šušteršič 1996). Its springs are located on one side and recharge the Unica River that sinks in two major outflow zones located along the polje eastern and northern borders (Savnik 1960) (Fig. 3.10). The polje surface is slightly undulating and about 10 $km^2$ large, with a bottom elevation between 444.5 m and 450 m a.s.l (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 a.s.l. and by mountains reaching up to 1000 m a.s.l. 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).

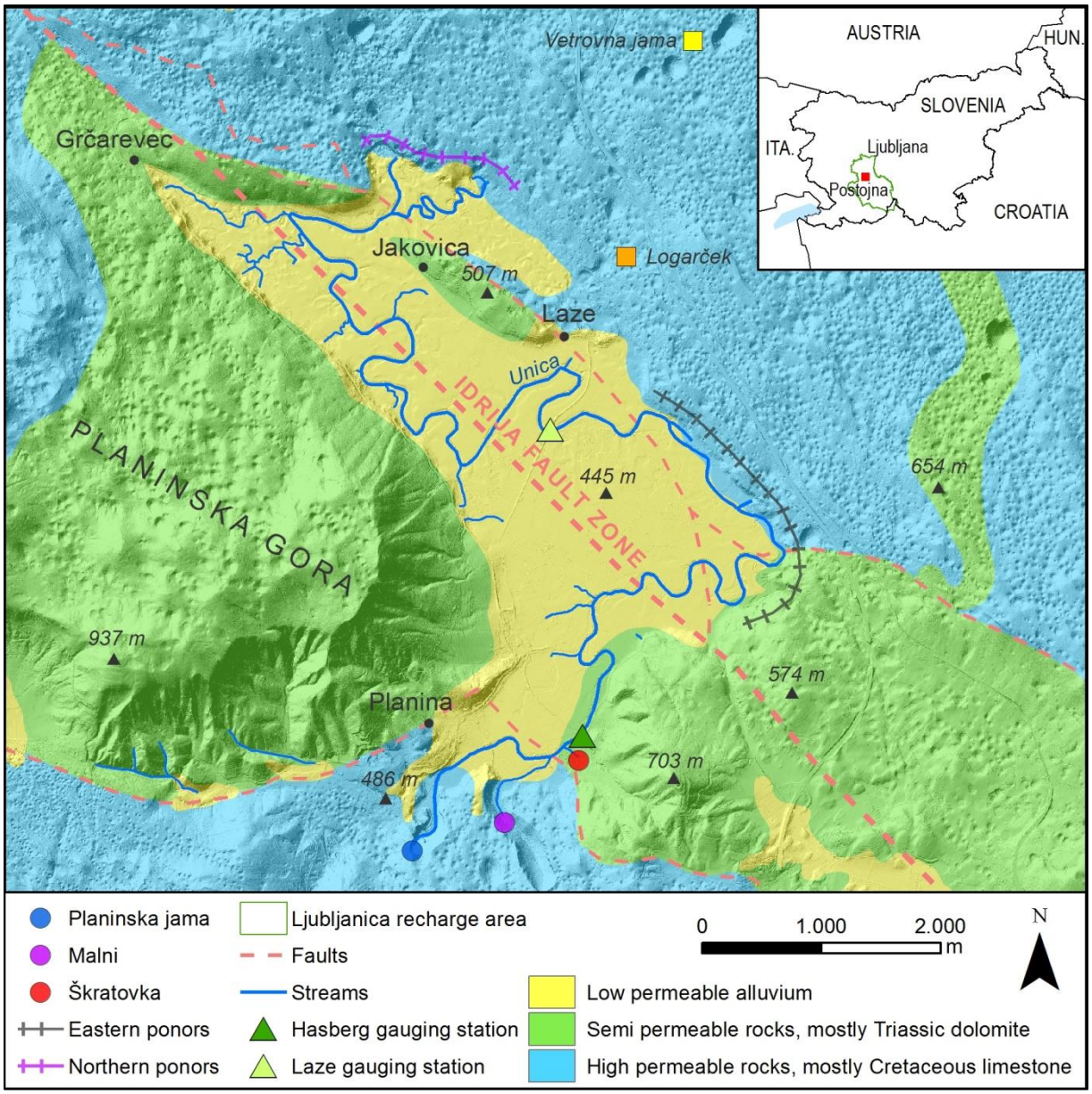



***Figure 3.10:*** *Planinsko Polje and its surrounding area with the position of caves, springs, ponor zones and main gauging stations. The upper right insert shows the regional position of the area in Slovenia.*

Besides Planinska Jama, the most important recharge input is the spring of Malni (Malenščica River, $Q_{min}$ = 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 Malni spring is used as a water supply for more than 20,000 inhabitants (Petrič 2010). The Unica River flows rather uninterrupted over the polje's surface for the first 7 km. 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. 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. 3.11). A recent 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 northern group of ponors was estimated between 40 and 60 $m^3/s$ (Šušteršič 2002).

***Figure 11:*** *Two of the many ponors draining Planinsko Polje. Left: Velike Loke located at the eastern border. Right: So-called Putick's Well (Putickova štirna) located at the terminal outflow zone at the northern border (Photos: M. Blatnik).*

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 cold part of the year, tied to the mid-autumn rainfall peak, winter rains and snowmelting (Fig. 3.12). 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 a.s.l.; and in 1923 when water level reached 453.4 m a.s.l. (Gams 1980). In February 2014, the floods reached altitude of 453.2 m a.s.l. 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 fourty houses and other facilities have been flooded (Mihevc 2014).

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). To prevent extreme flooding in Planinsko Polje, different measures have been undertaken in the beginning of $20^{th}$ century (Putick 1889). They consisted to increase the outflow capacity of the ponors zone by mean of different constructions to prevent their plugging by flotsam (Fig. 3.11).

In a recently published work, Mayaud *et al.* (2019) listed and tested the parameters that could potentially control flooding in poljes. If the method is applied on Planinsko Polje and focus on the high flood event of February 2014, the role of ponor zones can be emphasized. Due to the sudden arrival of an important quantity of melted water carrying a lot of flotsam, all the ponors were plugged. This can explain the high amplitude and long duration of the flood. This result is confirmed when comparing this flood with the high flood of November 2014. Despite a much higher amount of precipitation released within a similar time span, the maximum stage in the polje that was three meter lower than the flood of February 2014. The only explanation is that all ponor zones have been cleaned in between (Mayaud *et al.* 2019).

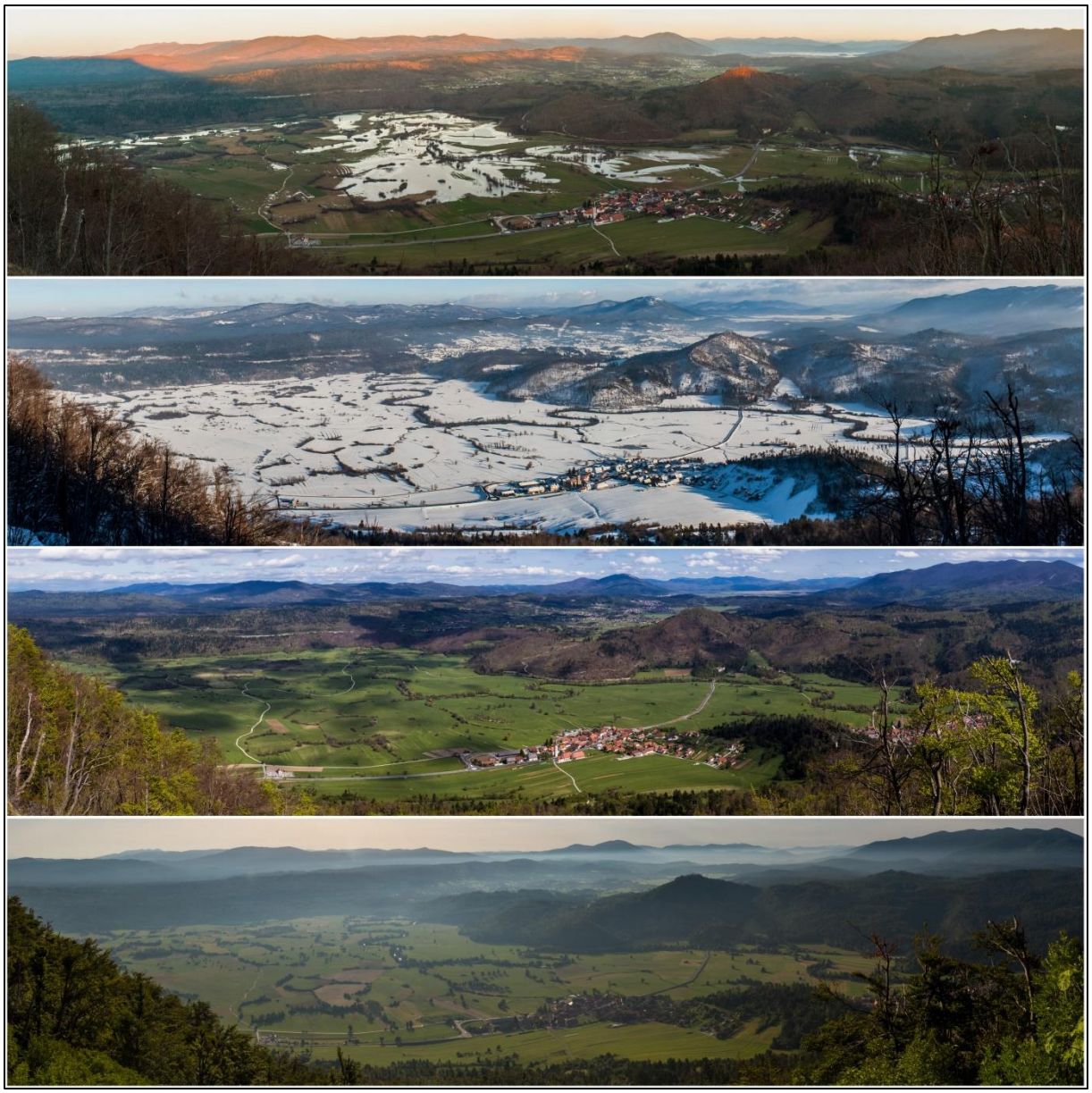


***Figure 3.12:*** *Planinsko Polje under various hydrological situations (Photos: M. Blatnik).*

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). Data loggers are installed in 7 caves (Logarček, Vetrovna Jama, Najdena Jama, Gradišnica, Gašpinova Jama, Brezno pod Lipovcem, Veliko Brezno v Grudnovi Dolini) and three ponors on the rim of Planinsko Polje (Velike Loke, Pod Stenami, Škofov Lom). Figure 3.13 presents the recorded dynamics of underground water in March and April 2018.

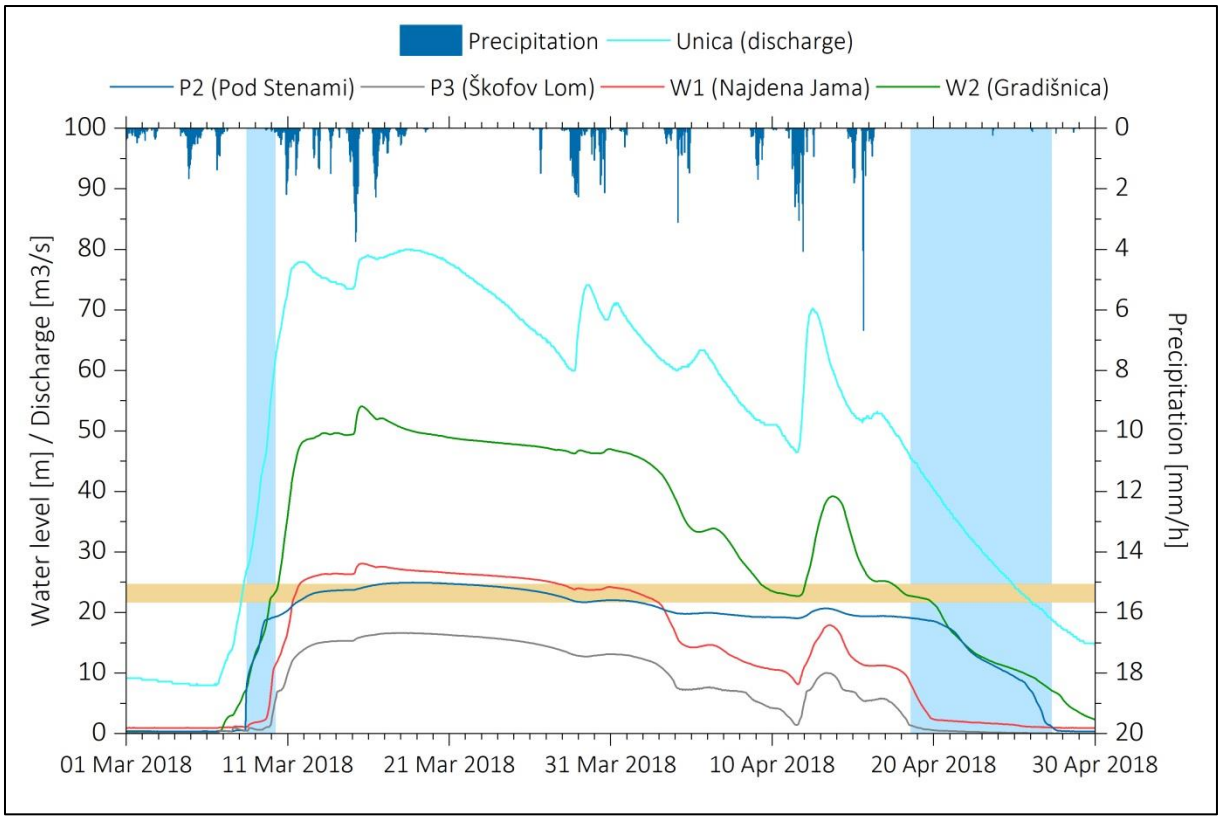



***Figure 3.13:*** *Water level dynamic in selected caves between Planinsko Polje and Ljubljanica springs during high water event in March and April 2018. Blue areas denote different response of water level change, orange area denotes temporal slower increase(decrease of water level in cave Gradišnica.*

Water level measurements showed complex dynamics in water level variations (up to 60 m, Fig. 3.13) and different rate of changes of groundwater level (from several hours during increase to several weeks during decrease). The duration of the high water event is dependent on the duration of flooding of Planinsko Polje (Fig. 3.12). During all high water events there is different response in water level increase. When the discharge of the Unica River is increasing, water reaches different ponor zones at different time (in Planinsko Polje first eastern, then northern ponors), resulting in different response in downstream located caves (Figs. 3.14 & 3.15). This dynamic explains late response in cave Najdena Jama in comparison to nearby located ponor zone Pod Stenami. There, water bypasses cave Najdena jama, which is recharged through more apparent ponor zone Škofov Lom (Fig. 3.14). Considering geological structure, this explanation is plausible (Blatnik *et al.* 2019). Water level hydrographs also shows inflection points, presenting temporal slower increase/decrease of the water level. This dynamic indicate presence of overflow passages at certain levels. Temperature and EC hydrographs have been interpreted for the travel time estimation between successive observation points.

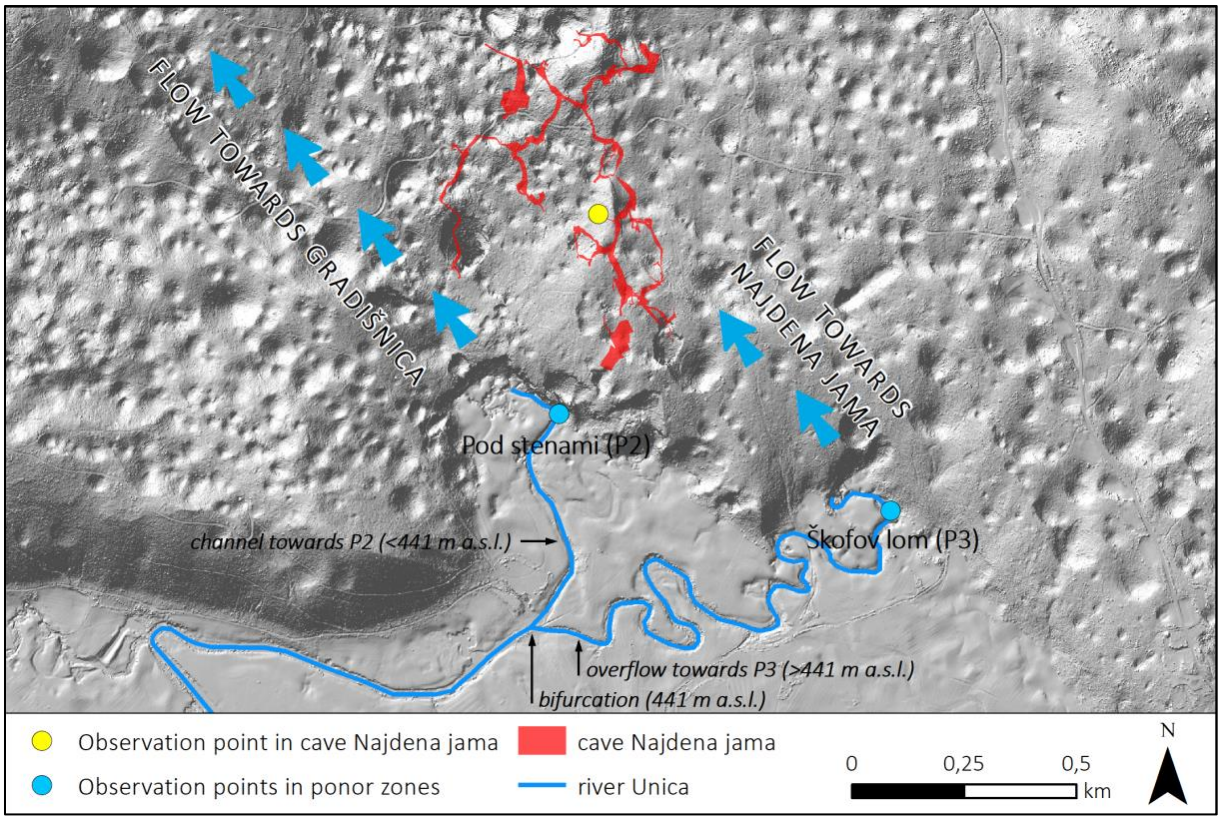



***Figure 3.14:*** *Assumed groundwater flow directions between the northern ponors (Pod Stenami and Škofov Lom) and Najdena Jama and Gradišnica.*

***Figure 3.15:*** *Main chamber of the cave Gradišnica during low water conditions. Dark colour on the rock wall indicates the position of high water level (Photo: M. Blatnik).*

## COLLAPSE DOLINES IN THE HINTERLAND OF THE LJUBLJANICA SPRINGS

Collapse dolines are large closed depressions formed by subsidence and/or partial collapses of cave ceilings. Large collapse dolines form in the crushed/fractured zones above the main groundwater flow, where dissolutional yield is high due to high (rock surface)/(water volume) ratio (Gabrovšek & Stepišnik 2011).

Between Logatec and Vrhnika several large collapse dolines formed along the main drainage pathways of underground Ljubljanica River (Celarc *et al.* 2013). Table 3.02 lists the bottom elevations, and dimensions of the largest. Estimated volume of the biggest of them (Velika Drnovica) is around 1.6 million $m^3$.

***Table 3.02:*** *Some characteristics of collapse dolines along the main pathways of Ljubljanica River.*

| Name | Bottom elevation (m) | Radius (m) | Average depth (m) |
|---|---|---|---|
| Velika Drnovica | 409.0 | 157 | 106 |
| Velika jama | 424.0 | 143 | 66 |
| Mala Drnovica | 520.0 | 101 | 60 |
| Stranski dolec | 457.0 | 90 | 69 |
| Masletova koliševka | 435.0 | 89 | 70 |
| Srednja Lovrinova koliševka | 443.0 | 96 | 57 |

Seven collapse dolines are located in immediate hinterland of main Ljubljanica spring (Tab. 3.03). The bottoms are relatively levelled and covered with over 30 m thick loamy sediment. The elevation of bottoms of all these dolines are within 10 meters apart. Recent floods are observed in Grogarjev dol. The estimated volume of Paukarjev dol is around 1 mio $m^3$ (Gabrovšek & Stepišnik 2011).

***Table 3.03:*** *Some characteristics of collapse dolines located in the near hinterland of the Ljubljanica springs.*

| Name | Bottom elevation (m) | Radius (m) | Average depth (m) |
|---|---|---|---|
| Paukarjev dol | 297.3 | 125 | 55 |
| Meletova dolina | 297.7 | 84 | 33 |
| Grogarjev dol | 294.0 | 80 | 35 |
| Tomažetov dol | 304.4 | 66 | 35 |
| Babni dol | 295.0 | 58 | 27 |
| Susmanov dol | 298.9 | 50 | 18 |
| Nagodetov dol | 300.8 | 38 | 18 |

## THE SPRINGS OF LJUBLJANICA

The water of the Ljubljanica karst catchment emerges at many springs located near Vrhnika, at the rim of the Ljubljana Basin. The line of spring generally follows the contact of Jurassic limestone and Quarternary sediments underlain by Triassic dolomite (Celarc *et al.* 2013) (Figs. 3.10 & 3.16). Most important springs are aligned along the gradually retreating pocket valleys of Močilnik and Retovje. The springs at Močilnik ($Q_{av}$≈ 6–7 $m^3$/s) feed Mala (=small) Ljubljanica and springs at Retovje ($Q_{av}$≈ 16 $m^3$/s) feed Velika (= big) Ljubljanica, the main tributaries related to karst springs of the Ljubljanica River. Easterly, another tributary Ljubija ($Q_{av}$≈ 6–7 $m^3$/s) is also fed by several springs. The eastern-most set of springs at Bistra are already positioned in Triassic dolomites and add on average 7 $m^3$/s

to the last true karstic tributary of Ljubljanica. Mean annual discharge of the Ljubljanica karst springs is about 24 $m^3/s$ (Gospodarič & Habič 1976).

Temperature monitoring at springs have shown, that major springs show similar temperature dynamics, however, easternmost spring at Bistra differs quite substantially from the others (Fig. 3.17). The temperature lag is higher and the hydrograph lacks short-time disturbances. This indicates longer retention time (Blatnik *et al.* 2019). Water tracing in in 1970s also revealed, that the direct flow from the Cerkniško Polje, mostly goes to the Bistra springs (Gospodarič & Habič 1976) (Fig. 3.18).

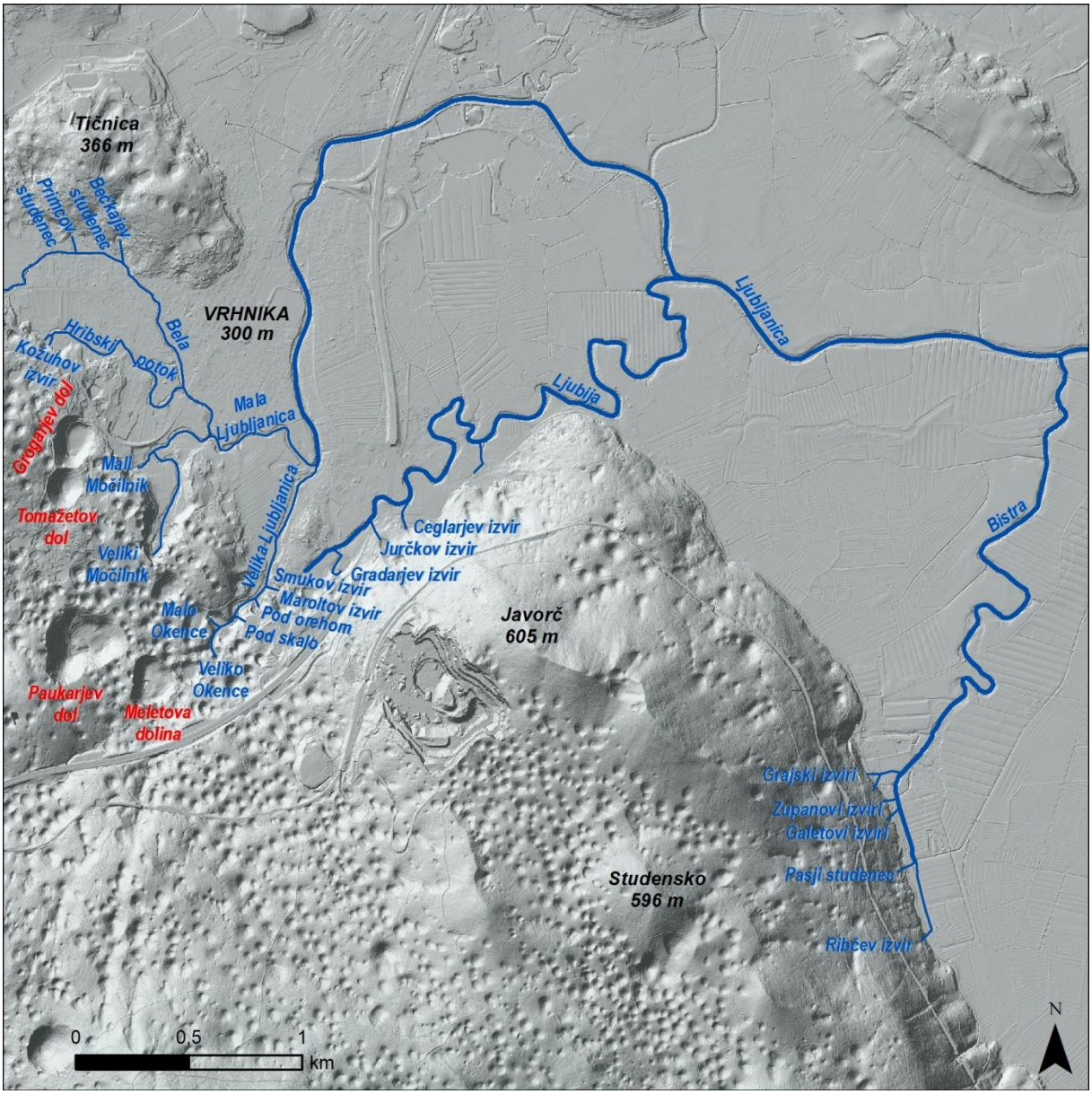



***Figure 3.16:*** *Location of collapse dolines and Ljubljanica springs near Vrhnika.*

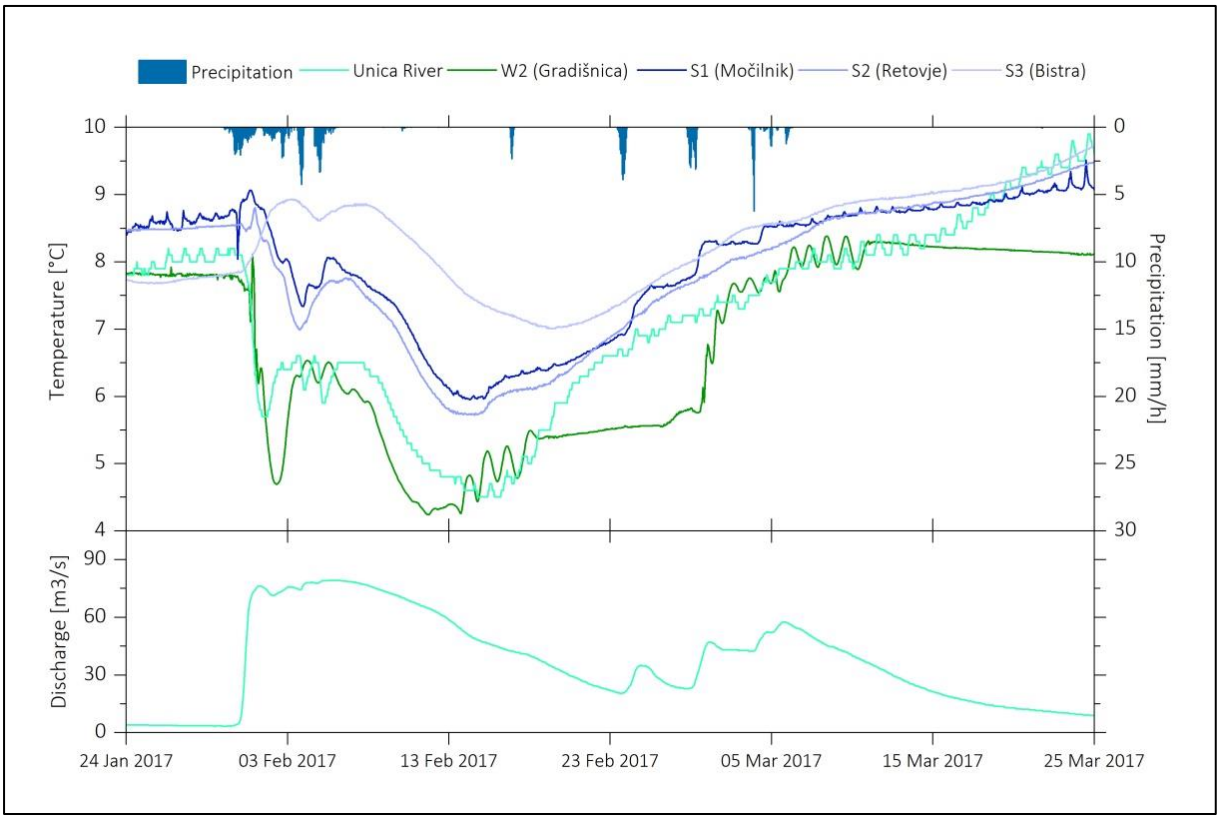



***Figure 3.17:*** *Temperature hydrographs at springs of Ljubljanica compared to the cave Gradišnica and Unica River.*

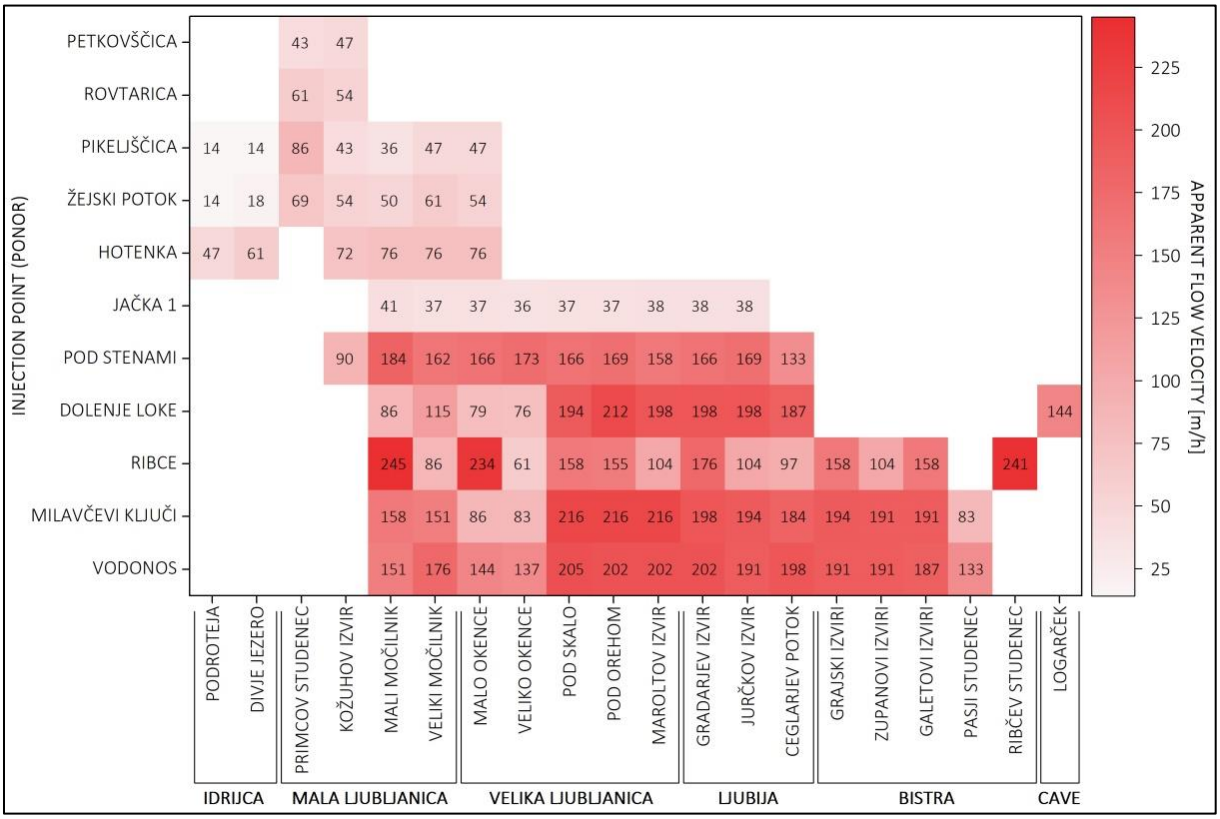



***Figure 3.18:*** *Apparent flow velocities between the studied ponors and the springs obtained from the dye tracing campaign in 1975. On vertical axis injection points (ponors or surface streams) whereas on horizontal axis locations of sampling points (springs or caves) are listed.*

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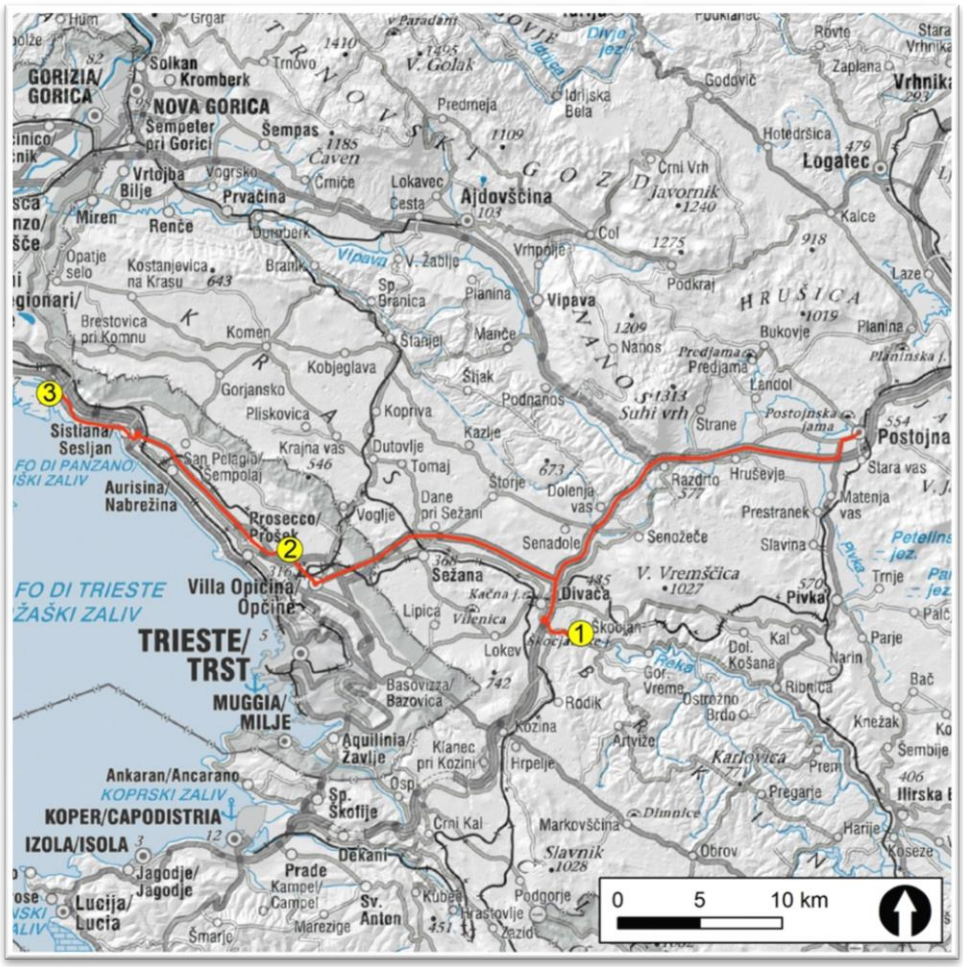
**Whole-day field trip (D):**

## REKA-TIMAVO FLOW SYSTEM IN KRAS/CARSO

Friday, 21. 6. 2019, 9:00–18:00

*Stops:*
**1** – Škocjan Caves
**2** – Grotta Gigante
**3** – Springs of Timavo




**Sistem Reka-Timava in tok vode skozi planoto Kras**
*Popoldansko terensko delo (D)*
Kras se razteza med Škocjanskimi jamami, Sočo, Vipavsko dolino in Tržaškim zalivom. Zaradi specifičnega razvoja in strukturne zgradbe, je vodonosnik Krasa izjemno kompleksen, kar se kaže tudi v veliki dinamiki podzemne vode. To v veliki meri pogojuje režim reke Reke, ki ponira v Škocjanskih jamah. Izjemna spremenljivost pretoka Reke povzroča veliko in hitro spreminjanje nivoja podzemne vode v celotnem vodonosniku. Iz dolgo časovnih zapisov nivojev in temperature lahko sklepamo tudi o strukturi vodonosnika. V Škocjanskih jamah, ki jih bomo med ekskurzijo obiskali najprej, smo februarja 2019 zabeležili največji poplavni dogodek po letu 1964. Poplavne dogodke lahko zaznavamo tudi z geofizikalnimi in natančnimi geodetskimi meritvami. S temi meritvami se bomo seznanili v Veliki jami v Briščikih (Grotta Gigante). Vodonosnik Krasa izteka skozi številne izvire med Nabrežino (Aurisina) in Tržičem (Monfalcone). Največji so izviri Timave pod vasjo Štivan (San Giovanni di Duino), ki ob nižjih vodostajih večino vode dobijo iz Soških naplavin, ob poplavnih dogodkih pa je prevladujoč dotok Reke. Izviri Timave so tudi vhod več kot 2 km dolgega jamskega sIstema.

## THE AQUIFER OF KRAS/KARSO PLATEAU

***Geological and hydrogeological settings of the Kras/Carso plateau***

The Kras/Carso Plateau extends in a northwest–southeast (NW–SE) direction between the Bay of Trieste in the southwest (SW) and the Vipava Valley in the northeast (NE) (Fig. 4.01). The plateau is ~40 km long and 13 km wide. Apart from the some higher mountains in the central part, it has a low relief and is covered by numerous dolines and other karst features, with about 4000 known caves. The surface generally dips from SE to NW, between 400–500 m a.s.l. (metres above sea level) in the SE, down to 100 m a.s.l. in the NW.

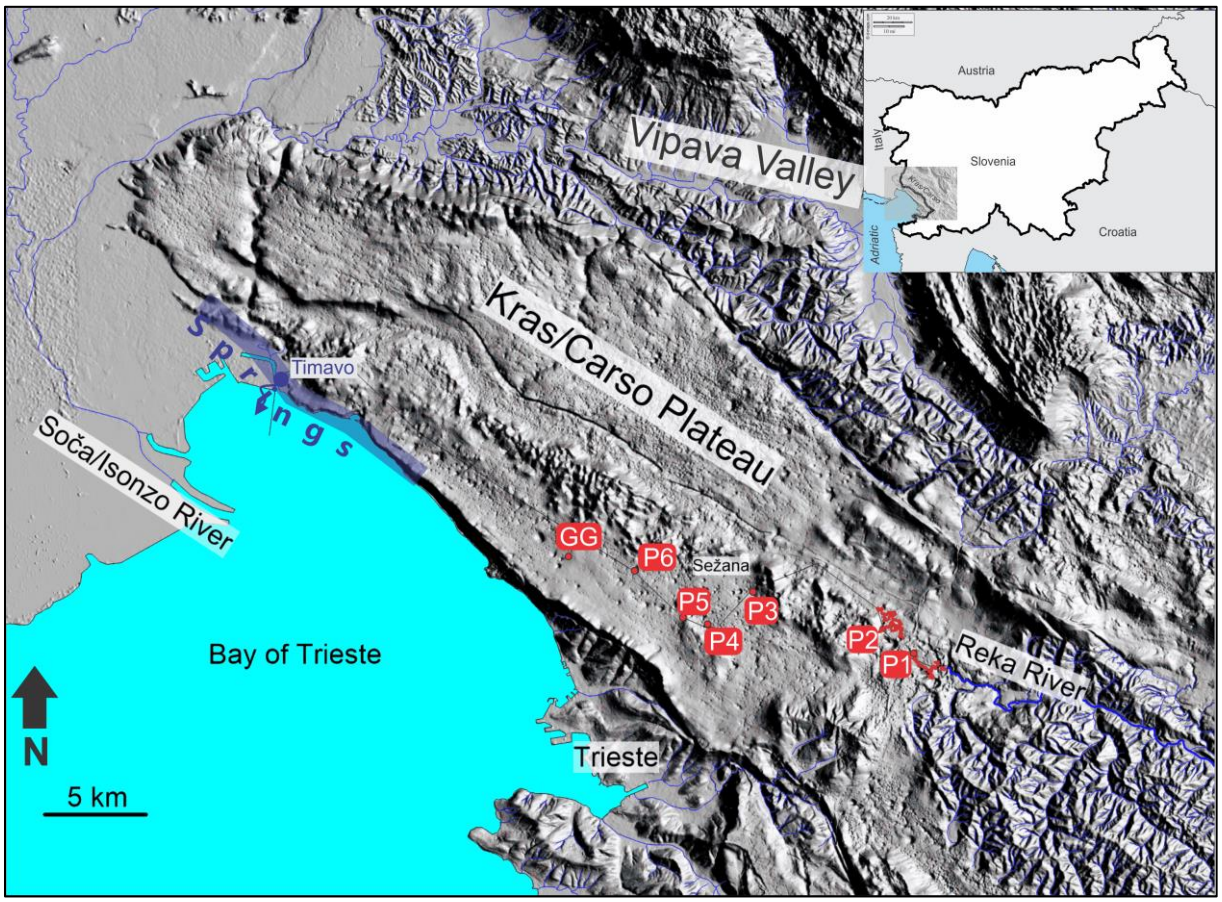



***Figure 4.01:*** *A relief map of Kras/Carso Plateau limited by the Soča River alluvium in the west, the Adriatic Sea in the south and southwest and flysch areas with clear fluvial network (blue lines) on other borders. Points P1–P6 denote the main reaching the groundwater flow; 1. Škocjan Caves, 2. Kačna Jama (Snake Cave), 3. Jama 1 v Kanjaducah, 4. Brezno v Stršinkni dolini, 5. Abisso di Trebiciano (Labodnica), 6. Grotta Meravigliosa di Lazzaro Jerko, GG. Grotta Gigante. Upper right: broader geographical position of the area. The thick blue transparent line shows the outflow region (Made by F. Gabrovšek based on DEM by A. Mihevc).*

Figure 4.02 presents the simplified geological situation. The plateau is made up of a succession of Cretaceous to Lower Paleogene carbonates deposited on the Adriatic–Dinaric Carbonate Platform (Buser *et al.* 1968; Jurkovšek *et al.* 2016). The geological structure of the broader area is a result of the collision between the Apulian and Eurasian lithospheric plates. The Kras Plateau is an anticlinorium, which structurally belongs to the External Dinaric Imbiracted Belt, a part of the thrust system of External Dinarides, which furthermore underthrusts below the Southern Alps. Underthrusting also resulted in an en-echalon formation of strike slip faults. Several fault systems cross the area, typically along the so-called Dinaric SE–NW and cross-Dinaric direction. The most recent structural description of the area can be found in Placer (2008, 2015). Some faults have been

identified that affect the ground water flow (Šebela 2009; Žvab Rožič *et al.* 2015) The carbonates are surrounded by flysch, which provides the input of allogenic water on the SE, while at the same time prevents outflow along the SW boundary. This way, the main flow is forced to follow the Dinaric (SE–NW) direction. Along the NW coast of the Trieste Bay, the topographical elevation of the limestone flysch contact is low enough to permit outflow through numerous karst springs. Among these, the Timavo Springs, with an average discharge of almost 30 $m^3/s$ are the most important.

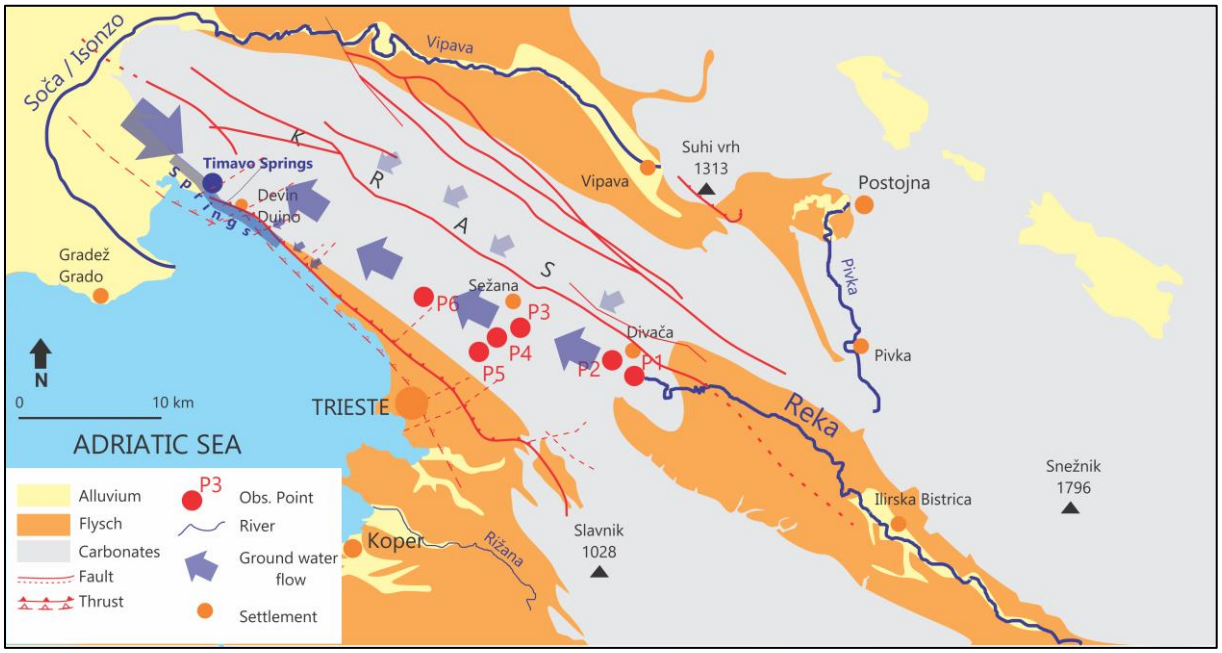



***Figure 4.02:*** *Simplified geology of the area with the main lithological units and structural elements. P1–P6 mark the position of the caves with groundwater flow. Blue arrows indicate the general ground water flow direction towards the springs.*

The Reka River is the main allogenic input to the system; ~41 % of its catchment is karstic and ~54 % is underlain by flysch. It flows ~50 km on the impermeable flysch rocks, continues for another 7 km as a surface flow on a limestone terrain, sinks at the Škocjan Caves and contributes to the springs in the Trieste Bay (Fig. 4.01). The straight-line distance between the Škocjan Caves and the Timavo Springs is ~33 km. The average discharge of the Reka River in the period 2007–2013 was 7.1 $m^3/s$, while the long-term average (1952–2013) is about 8 $m^3/s$. The ratio between the highest and the lowest flow rate is ~1700, with the maximum measured discharge 305 $m^3/s$, and the minimum 0.18 $m^3/s$. It should be noted, that the Reka River makes an important contribution to the Timavo Springs during high flow, however, during mean and base flow, most of the spring water originates from the Soča alluvium in the NW (Doctor 2008) and from diffuse infiltration from rainwater (Civita *et al.* 1995). In other words, the Soča River provides the base flow while the Reka River and diffuse infiltration from the surface contribute the variability of the Timavo and other springs.

The climate of the area is transitional from Mediterranean to continental, with precipitation ranging from 1400 mm/y close to the Adriatic Sea to < 1800 mm/y in the inland NE part of the Kras Plateau. Yearly precipitation in the mountainous catchment of the Reka River can reach > 2000 mm. These areas form an important orographic barrier where extreme precipitation events (e.g., 250 mm in 12 hours) have been recorded.

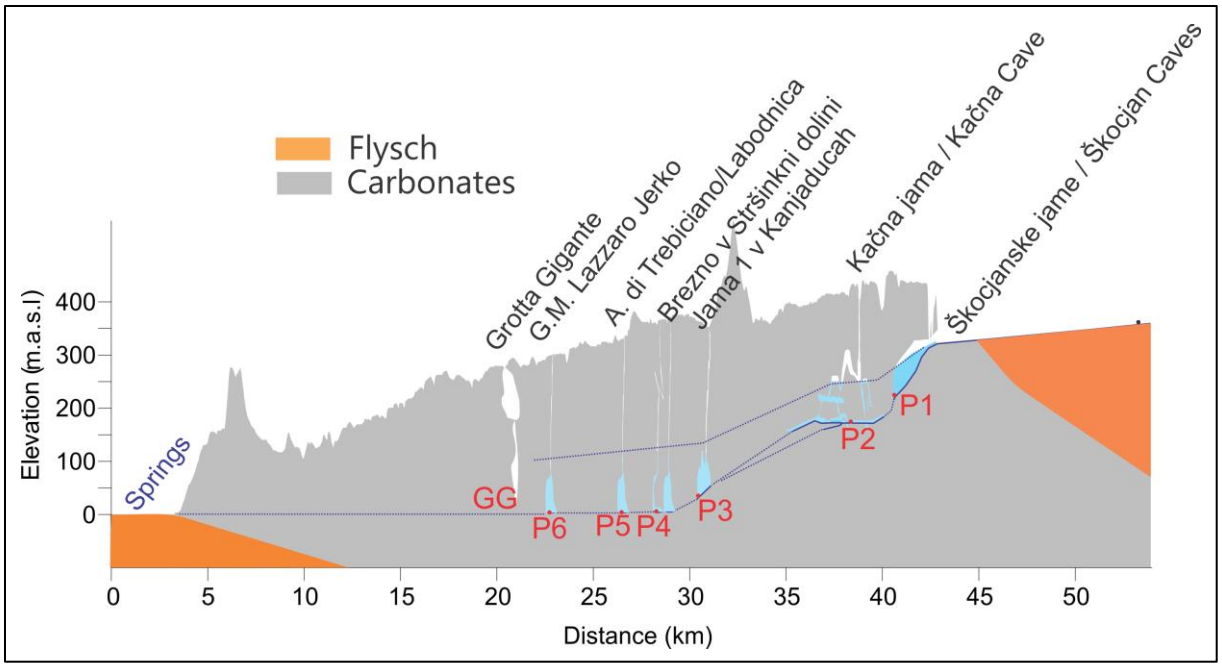



***Figure 4.03:*** *Simplified cross-section of the Kras/Carso Plateau between the Škocjan Caves and the springs along the NW coast of Trieste Bay. The dotted blue lines denotes the position of the base flow and extreme floods. P1 to P6 indicate the positions of the observation points used in this work. Vadose parts are filled white, while phreatic and epiphreatic parts are filled by light blue. Higher base flow line between P2 and P3 denotes flow along the partially known overflow channels in this segment (Figure by F. Gabrovšek).*

***The epiphreatic flow of the Reka–Timavo system***

The Kras/Carso Plateau is a complex speleological environment with many relict caves distributed through the entire thickness of the vadose zone. The sediments in the oldest, topographically highest caves, were dated to > 5 Ma (Gabrovšek *et al.* 2018).The Reka River reaches the flysch–limestone boundary ~7 km upstream from the Škocjan Caves. Before sinking underground, it flows along a limestone canyon where it already loses some flow. The Reka starts its underground flow at Škocjanske Caves (**P1** in Figs. 4.01, 4.02 & 4.03), where flow is more or less uninterrupted and follows the channels of extreme dimensions until the available cross-section drops by three orders of magnitude at Martel's chamber. Škocjan Caves end with a sump, not yet explored. About 800 m NW Reka reappears in Kačna Jama (**P2** in Figs. 4.01, 4.02 & 4.03). The cave is >13 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 a.s.l. The base level sump has limited flow capacity, as soon as the recharge surpasses 15 $m^3$/s, it is diverted to the sequence of large overflow galleries. More than 2 km of the overflow channels, interrupted by perched sumps, have been explored. Currently sump No. 4 is waiting for eventual new explorers. The underground flow can be reached again ~5 km to the SW in the Jama 1 v Kanjaducah (**P3** in Figs. 4.01, 4.02 & 4.03). The cave is 330 m deep and ~1.5 km long. Its geometry is rather simple, dominated by the large inclined gallery, which sinks practically uninterruptedly from 20 m below the surface to the Reka River channel. The main channel of the Reka River is > 60 m high, < 50 m wide and 600 m long. It narrows and lowers only near the inflow and outflow sumps. Both sumps have been explored; behind the outflow sump over 300 m of vadose passages were found that again end in sumps. About 2.6 km SW from P3 is the next observation point in Brezno v Stršinkni dolini (**P4** in Figs. 4.01, 4.02 & 4.03). The entrance is at 344 m a.s.l., the cave follows a system of vadose shafts that lead to a large chamber where the underground flow is reached at an altitude of about 10 m a.s.l. Along the floodwater maze, the cave connects to another, more recently explored cave. These caves share a typical geometry with other caves in the lower part

of the Reka–Timavo system: a system of vadose shafts that generally increase in size with depth and end with a large chamber (often > 100 m high and > 1000 $m^2$ in cross-section). The system of vadose shafts is connected via small channels that often required a lot of digging to pass. The upstream sump from Brezno v Stršinkni dolini was explored by divers to a maximum depth of 60 m, which is 38 m below sea level. The most well-known among the caves in the lower part of the Reka–Timavo system is Abisso di Trebiciano (Labodnica Cave) (**P5** in Figs. 4.01, 4.02 & 4.03), about 1 km west from the Brezno v Stršinkni dolini, just across the border in Italy. When explored in the 19$^{th}$ century, it was the deepest cave at the time. Its depth is 329 m and reaches the Reka–Timavo flow at about 12 m a.s.l. The last observed cave was Grotta Miravigliosa Lazzaro Jerko, a further 3.4 km NW from the town of Trebiciano (Italy). The low ground water stand in the cave is about 4 m a.s.l. (**P5** in Figs. 4.01, 4.02 & 4.03). Few kilometres from the P2 is the Grotta Gigante (**GG** in Figs. 4.01, 4.02 & 4.03), which deepest point is also reached by the high waters. Between Grotta Gigante and the springs of Timavo, Abisso Massimo and Grotta Lindner reach the groundwater level. Recent explorations will surely open new paths to the level of the Reka-Timavo flow. These caves could become the future observation sites. Little is known about the structure of the deeper phreatic zone. However, the base level in the geological past was often well below the present, favouring conduit development in what is now a deep phreatic zone. A well-karstified phreatic zone is also indicated by the observation that during very dry periods, when the discharge of the allogenic Reka River falls below 500 l/s, the stream loses all its water before reaching the Škocjan Caves.

***Characteristics of flood propagation through the Reka-Timavo system***

During last two decades epiphreatic flow was monitored with autonomous loggers in most caves reaching the flow. Figure 4.04 shows the response of the system (P1-P5, see Fig. 4.01, 4.02 & 4.03) to a large flood in December 2008.

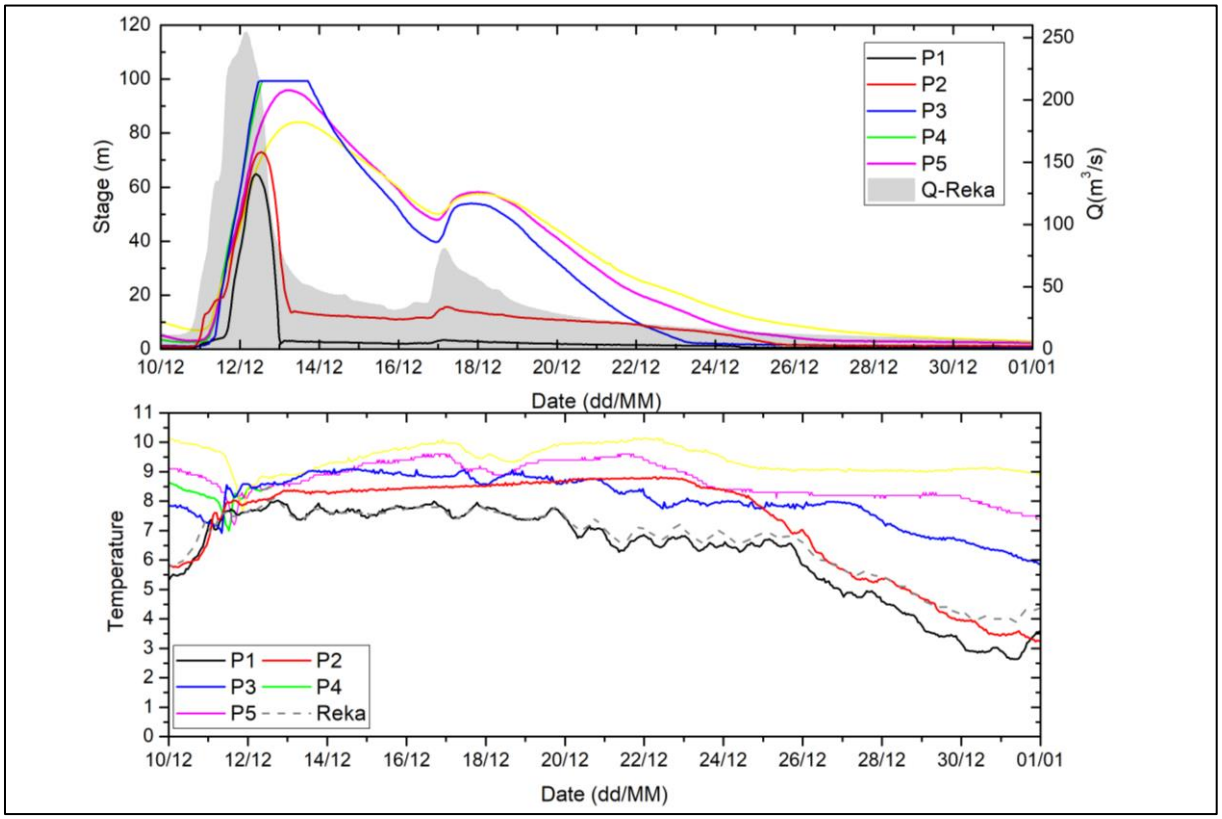



***Figure 4.04:*** *Level and temperature hydrographs recorded in caves of the Reka-Timavo system during major flood in December 2008 (Figure by F. Gabrovšek).*

Details on monitoring, interpretation and modelling can be found in Gabrovšek *et al.* (2018). Here we outline just some conclusion of their work:

- Floods in Škocjan Caves (P1) and Kačna Jama (P2) are controlled by local restrictions. During large events, back-flooding of Škocjan Caves and Kačna Jama are caused by the same restriction.
- The base outflow sump in Kačna Jama drains water effectively until the discharge is below 15 $m^3/s$. When this is surpassed, the flow is diverted along higher positioned overflow galleries. This can drain efficiently flow rates up to 130–150 $m^3/s$. At higher discharge the levels in Kačna Jama and Škocjan Caves rise very fast with increasing flow. The rate of the level rise can reach 10 m/h.
- Analysis of temperature hydrographs showed that a large amount of perched water is stored in the galleries between P2 and P3 between successive floods.
- The level in the lower part of the system P3–P6 reacts very simultaneously, indicating uniform variations of water level in this part of the system.

***Flood event in February 2019***

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 Reka at the gaging station Cerkvenikov Mlin peaked at 300 $m^3/s$. During the event the water in Škocjan Caves rose with rates up to 10 m/h and reached the level of 305 m a.s.l. in Martel's chamber and about 307.5 m a.s.l. in Šumeča Jama. The flood was 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.

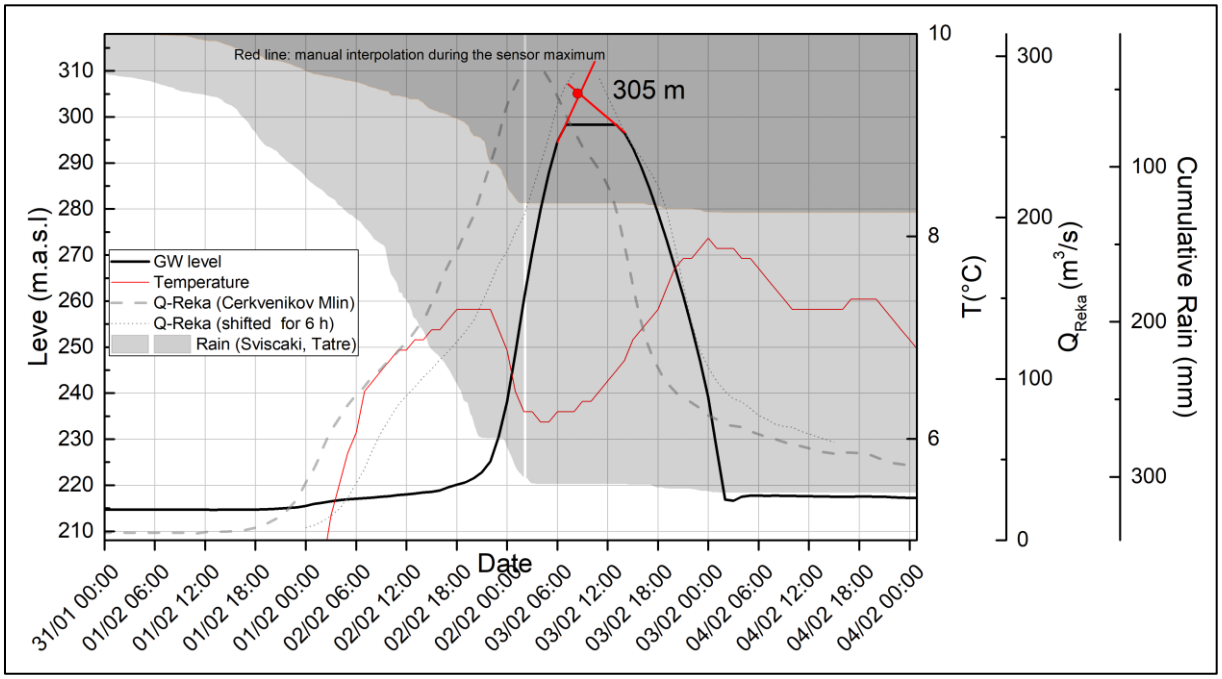



***Figure 4.05:*** *The flood event of 2019: Cumulative rain at two stations, discharge of Reka and level and temperature in Martel's chamber. Dotted grey line shows discharge shifted for six hours, an estimated travel time from gaging station to Martel's chamber (Figure by F. Gabrovšek).*


***Figure 4.06:*** *The water rose for over 90 m during floods in February 2019. The flood caused severe damage in infrastructure and deposited a thick layer of mud. Lower right: a satellite picture of Timavo springs region on February 5th (Photos: Borut Lozej, Škocjan Caves Regional Park). Below: rough cross-sectional schematic view of water level during the 2019 flood (Figure by F. Gabrovšek).*

***Geophysical and geodetic response to floods***

Continuous recording gravity stations were installed above the Škocjan Caves and inside Grotta Gigante in 2018 (Pivetta *et al.* 2019). The Škocjan Caves serve as a test site because the cave geometry and the hydraulic system here are well known. Gravitational response of 2019 flood was clearly recorded and the records are currently being analysed. Furthermore, high overpressure (up to $10^6$ Pa) may form in conduits during flood propagation. This could result in measurable terrain uplift as discussed in recent paper by Braitenberg *et al.* (2019).

## ŠKOCJANSKE JAME (ŠKOCJAN CAVES)

***A brief speleological review***

Škocjanske Jame (Škocjan Caves) are 5.8 km long cave (Fig. 4.07) formed by the river Reka that enters the cave at an altitude of 314 m a.s.l., flows towards Martelova Dvorana (Martel's Chamber) at 214 m a.s.l. and to terminal sump at 190 m a.s.l. (i.e. 124 m lower). At low water levels the Reka sinks before it enters the cave. Floods usually reach up to 30 m. The largest known flood in the 19th century raised the water table level by 132 m. The largest chambers are Martelova Dvorana, with a volume of $2.6 \times 10^6$ m$^3$, and Šumeča Jama with $0.87 \times 10^6$ m$^3$ (Mihevc 2001). Some of the big chambers have been transformed into collapse dolines like Velika and Mala dolina. Škocjanske Jame are developed on a contact area of Cretaceous thick-bedded rudist limestone and Paleocene thin-bedded dark limestone (Šebela 2009).

The first paths in the cave area were made in 1823, but construction of paths for exploration and for the visitors started in 1884. Cave exploration was done by cavers of DÖAV (Littoral section of Austrian Alpine Club) from Trieste. The most important explorers were Anton Hanke and Joseph Marinitsch. In 1891 they had already reached the final sump in the cave.

In 2019 a new connecting surface and Martel's chamber was explored. In the cave two large passages were found that offer promising leads along the high flood pathways. In 2018 and 2019 a complete lidar scan of the caves was made.

Because of the caves' extraordinary significance for the world's natural heritage, the Škocjanske Jame were included in UNESCO's World Heritage List in 1986. The Republic of Slovenia pledged to ensure the protection of the Škocjanske Jame area and therefore adopted the Škocjanske Jame Regional Park Act.

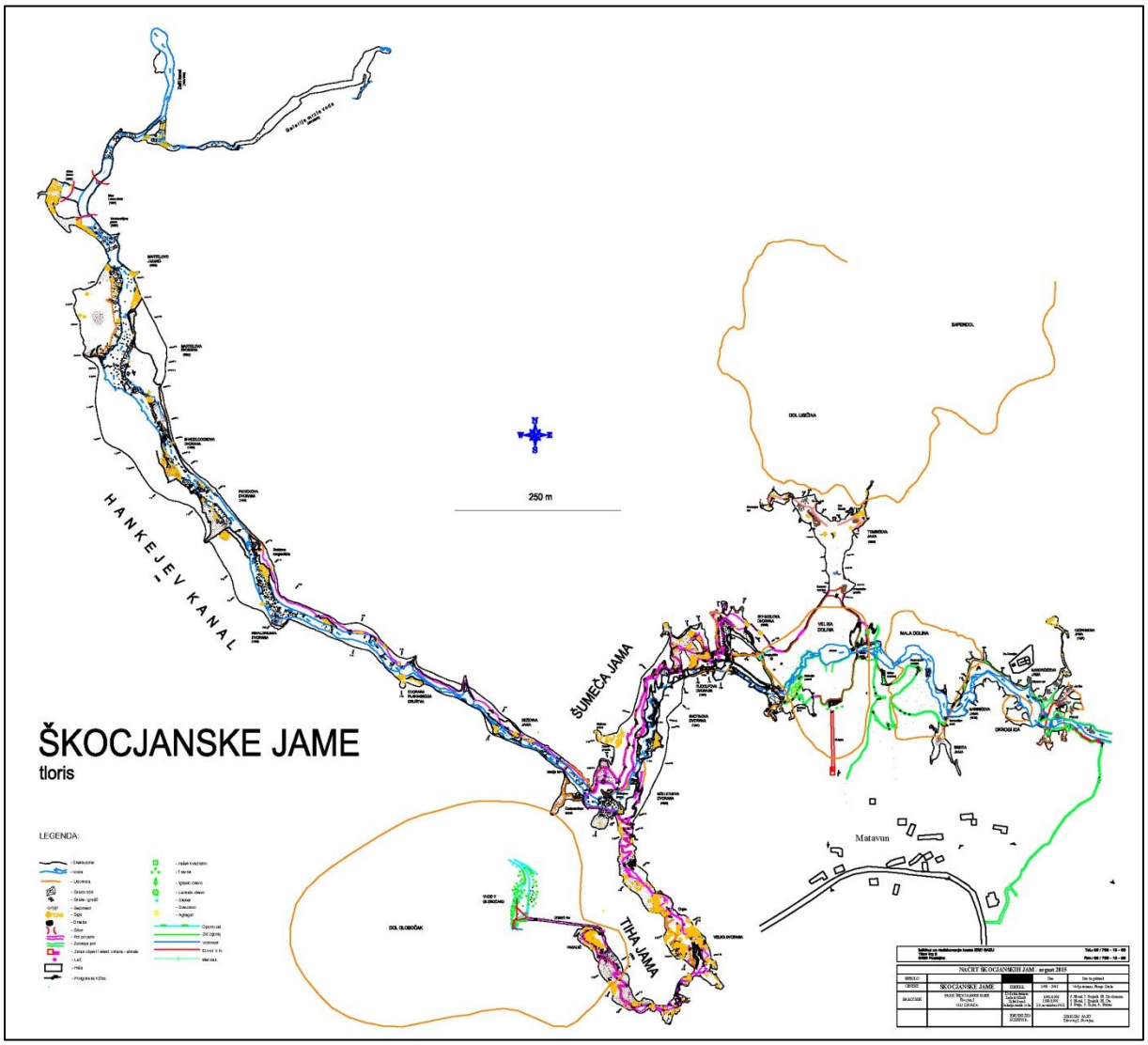



***Figure 4.07:*** *Map of Škocjanske Jame (Cave Register 2019).*

***Speleogenesis (by Andrej Mihevc)***

The cave is composed of passages that were mostly formed in phreatic conditions but later modified by paragenesis or gravitational entrenchments and collapses. The proto-channels of today's cave developed in phreatic conditions, formed along tectonized bedding-planes (Fig. 4.08). Large quantities of water could slowly flow through all these passages. Only fine sediments, clays and silt are preserved in them. Coarser material, sand and rubble were transported through epiphreatic caves about 150 m above them. A remnant of such a cave is the unroofed cave at Lipove Doline, located on the surface above the present cave at an altitude of about 450 m a.s.l. The water flow demanded a high degree of phreatic rising and falling between individual bedding- planes which are in the area of the chambers Svetinova dvorana and Müllerjeva dvorana approximately 175 m. As these phreatic jumps (i.e. loops) utilize fractured zones they destabilize them with the formation of parallel shafts. Later, when the flow increased, these shafts were the basis for the extensive passages collapses and widenings.

In the morphology of the cave there can be seen a long stable period expressed by paragenetic features and the deposition of sand comprised mostly of quartz. Due to the regional low gradient which can be connected to the formation of Vremska Dolina also. For a long period of time the water table in the cave was 340–300 m above sea level and the gradient was towards the SW. The Reka formed new passages or adopted old passages by bypassing or paragenesis, respectively. The large galleries with paragenetic ceilings were formed in the entrance part of Škocjanske Jame (Mahorčičeva and Mariničeva Jama, Tominčeva Jama, Schmidlova Dvorana and Tiha Jama).

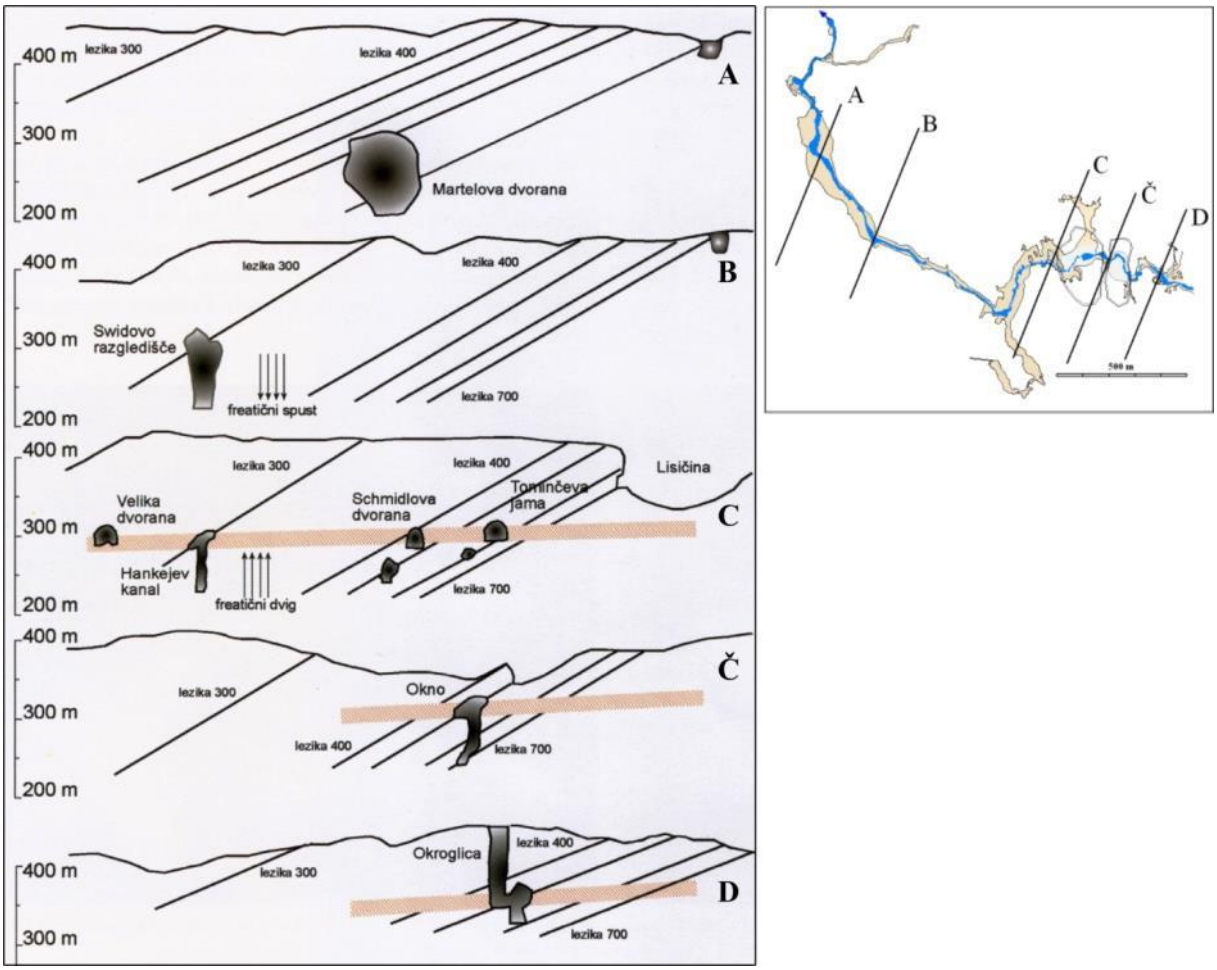



***Figure 4.08:*** *Schematic cross sections of characteristic parts of the cave and relation to main bedding plains of Škocjanske Jame. Important tectonized bedding planes, sections of the main parts of the cave and level of paragenesis are presented (after Mihevc 2001).*

The next phase of the cave evolution included important changes. Gradient increased and turned towards NW. This resulted in the entrenchment of the main stream passage. In the inner parts of the cave, in Hankejev Kanal, cutting resulted in an 80 m gorge, while in the entrance part of the cave, down cutting did not exceed 10 m. These changes can be connected with regional tectonic activity, i.e. uplift and tilting of the whole Kras delayed by the time needed for adaptation of all caves in the Reka system.

## GROTTA GIGANTE

***Speleology and history of exploration***

The *Grotta Gigante* cave is for historical reasons and speleological significance among the most important natural phenomena in Classical Karst. The cave is developed in the Cretaceous limestone in the central part of Kras/Carso plateau (Fig. 4.01). The dominant feature of the cave is the main chamber, Grande Sala, 167 m long, 76 meters wide and almost 100 m high, with the total volume about 365,000 $m^3$. The chamber may be accessed from the surface along two wide galleries. Several other galleries branch off from the main room, the most far-reaching being Ramo Coloni. There the depth of 252 m was reached in 2006, only 20 m above the sea level (Fig. 4.09).

Serious explorations of the cave started in 1840 by Anton Friedrich Lindner, who was searching for the underground water of the Trieste Karst for the water supply of the town, whose population had greatly increased under the Habsburg Empire. Because of technical difficulties, the intense explorations started about fifty years later, when two other accesses were discovered. The present entrance was enlarged in 1904 and the cave was opened to the public in 1908.

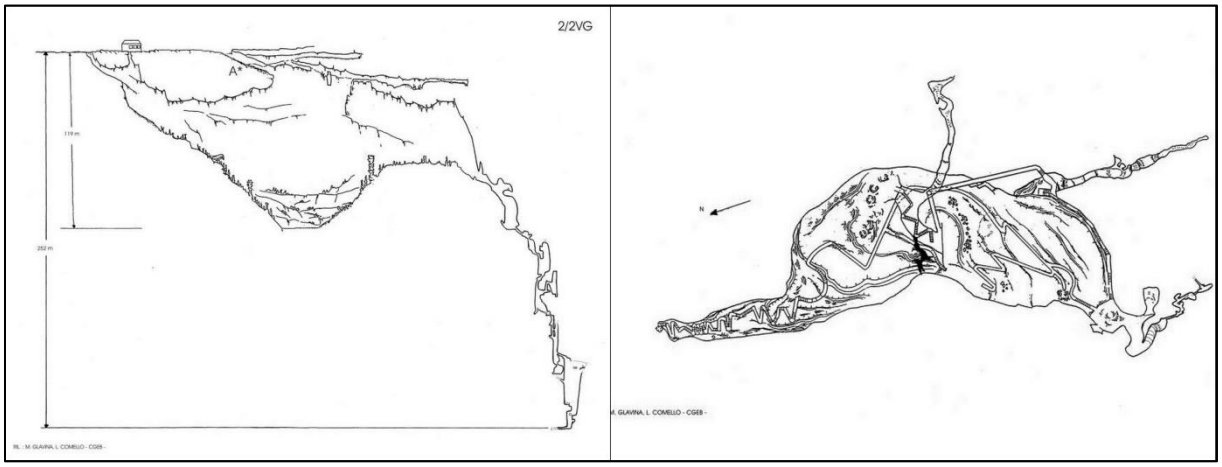



***Figure 4.09:*** *Cross section and ground plan of Grotta Gigante (from:* http://www.catastogrotte.fvg.it).

***Figure 4.10:*** *Left: The Grande Sala with plastic tubing, protecting the wire of the couple of horizontal pendulums. Right: Palm shaped stalagmites in Grande Sala (Provided by A. Fabbricatore & Prof. F. Cucchi).*

***The Grotta Gigante as a laboratory***

In the cave and on the surface, several long-term geophysical and karstological observations have been established. Inside the cave, *horizontal pendulums,* i.e. sensitive instruments able to detect the movements of the earth's crust, were installed by geodesist Antonio Marussi in 1959 (Figs. 4.10 & 4.11). The *pendulums* provide a unique historical series of continuous measurements of the deformation of the earth's crust.

These instruments are sensitive to deviations from the perpendicular, rotations and shear strains of the cave. Some movements are aperiodic, others regular, such as the Earth Tides caused by the lunar and solar gravitational fields. The upper and lower mountings of the pendulums are at a distance of 95 m, and this enables the instruments to detect tectonic movements with high precision and make them relatively immune to some of the noise which affects smaller instruments. The pendulum beam is suspended horizontally by two steel wires, the upper one fixed to the ceiling of the cave, the lower one fixed to the floor. The pendulum beam rotates in a horizontal plane around a virtual, nearly vertical axis that passes through the upper and lower mounting points. The Earth's crust (the outer brittle layer of our planet, on average 35 km thick in continental areas) moves up and down by 10 cm during the day due to the attraction of the Moon and Sun, and is accompanied by local tilting of some parts in the order of some billionths of a radiant. The movements of the pendulums have helped us to recognize the free oscillations of the Earth and the North-West direction of the long-term tilting of the cave. The marine tides of the Adriatic have a loading effect on the cave.

The pendulums also *sense* the floods in the Kras/Carso aquifer. The tiltmeters generally tilt towards SW and return back to their original position during the floods in the time frame of about 7 days. A typical movement in response to a flood is shown in the cartoon of Figure 4.12.

The *Grotta Gigante* tiltmeters are the only existing instruments to have recorded four of the five largest earthquakes in the last 50 years: the 1960 Chile earthquake (the largest earthquake ever instrumentally recorded) and the 2010 Chile earthquake (the fifth largest megaquake recorded world-wide), the one that caused the Tsunami in the Sumatra- Andaman islands in 2004 (third largest quake) and the one in Japan in 2011 (fourth largest quake), allowing an absolute-amplitude comparison of these events. These measurements are carried out by the *Department of Mathematics and Geosciences of the University of Trieste.*

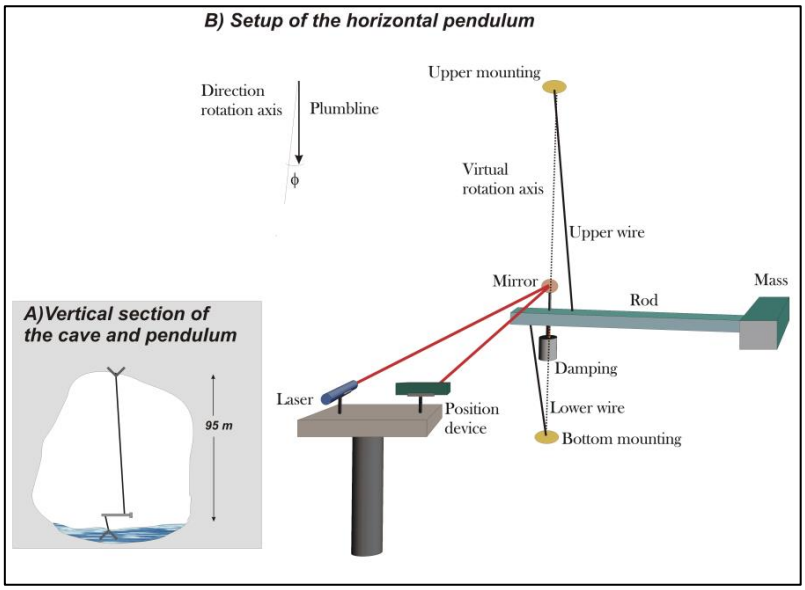



**Figure 4.11:** Schematic drawing of the Marussi Horizontal Pendulums and their mounting in Grotta Gigante (Figure provided by prof. C. Breitenberg).

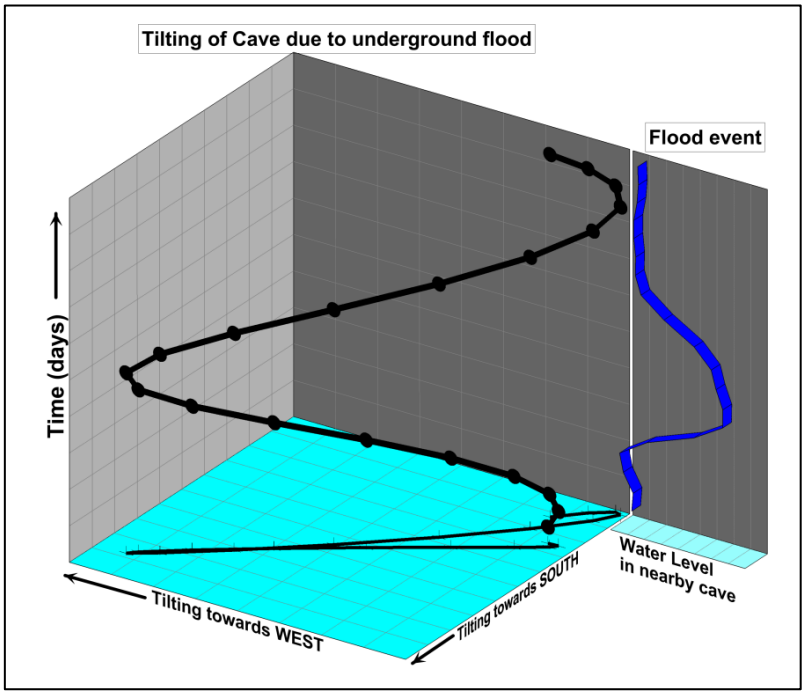



**Figure 4.12:** Response of tiltmeters to floods in the aquifer (Figure provided by prof. C. Breitenberg).

**SPRINGS OF THE TIMAVO**

The recharge of Kras/Carso massif is mainly threefold: the autogenic recharge from the surface of the massif; the allogenic input of the Reka River and the input coming from the Soča/Isonzo alluvial aquifer. The autogenic input is estimated to be 20 $m^3$/s, the average flow rate of Reka River is about 8.5 $m^3$/s, and about 10 $m^3$/s is estimated as the contribution of Soča alluvial.

The water from the aquifer is drained by several springs located between Aurisina and Monfalcone, along the NW coast of the Trieste Bay (Fig. 4.1). The main spring is the Timavo, with an average discharge of 29.3 $m^3$ /s, the second by size is is Sardos (1.9 $m^3$ /s), followed all the other smaller springs: Aurisina (0.3 $m^3$ /s), Moschenizze (0.5 $m^3$ /s), Pietrarossa and Sablici lakes (1.2 $m^3$ /s), Monfalcone (0.2 $m^3$ /s), Lisert (1.0 $m^3$ /s). There are known submarine springs located between Aurisina and Timavo with an estimated discharge of 0.5–1 $m^3$ /s (Zini et al. 2014; Doctor 2008).

The springs between Aurisina and Timavo are mostly recharged from the Kras massif (Reka-Timavo system), i.e by the autogenic water from Kras/Carso and allogenic input of Reka River. Water from Isonzo alluvial dominates the western springs Moschenizze, Lisert and Sablici. Sardos and Timavo receive water from both systems, depending on the hydrological conditions: during low water regime water from the Soča alluvium is prevailing in both springs. During high water Sardos receives water from the Reka-Timavo system and from the Soča alluvium, while Timavo drains only Reka-Timavo system. During average flow, Timavo spring discharges only Reka-Timavo system and Sardos spring receives all its water from the Isonzo alluvial.

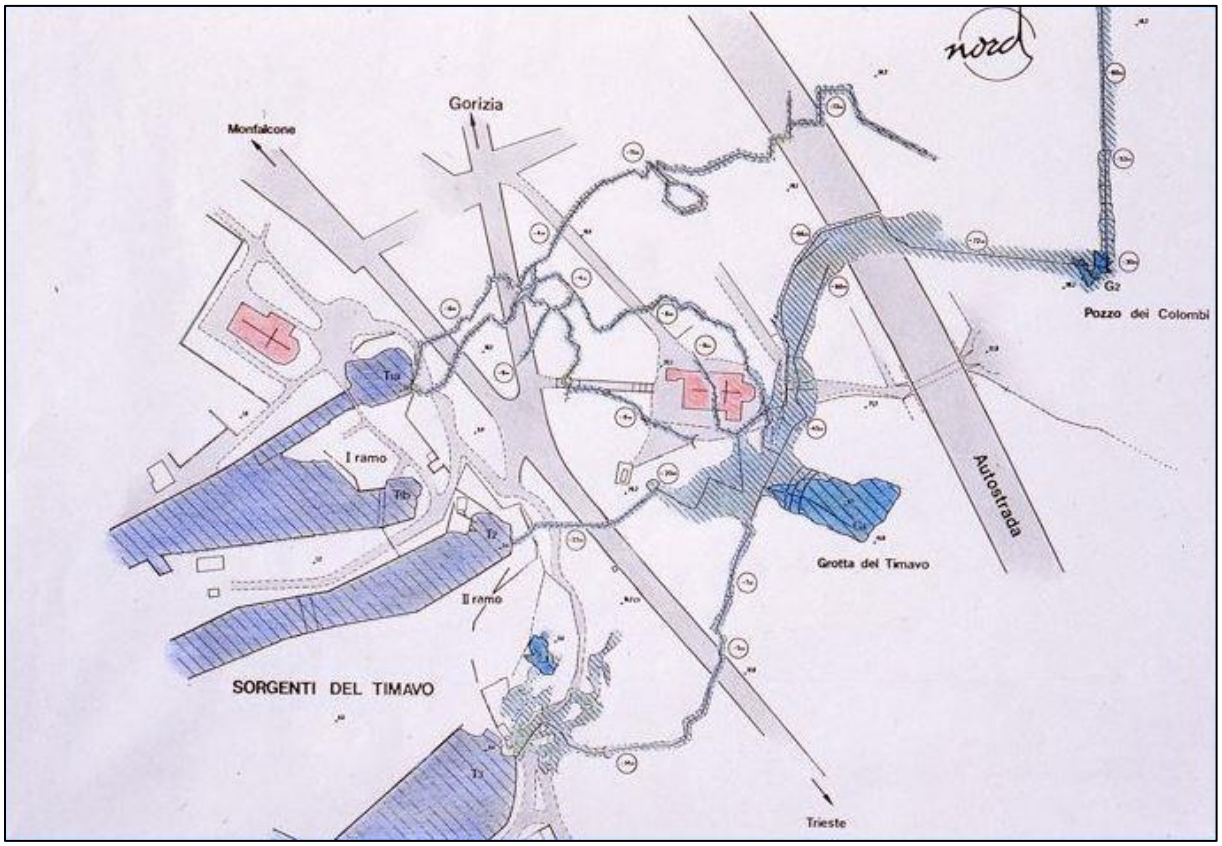



***Figure 4.13:*** *Map of the Timavo Springs and Timavo Cave System at San Giovanni di Duino (Figure provided by Prof. F. Cucchi).*

The springs constitute Timavo River, which flows for about two kilometres to the Adriatic Sea. Three main branches of Timavo River present outflow from the Timavo Cave System (Pozzo dei Colombi di

Duino, Risorgiva ramo 3° del Timavo and Grotta del Timavo) (Fig. 4.13). The total system is over 2100 m long with altitude difference of 106 m; the highest entrance is at 24 m a.s.l. and the deepest point is at -82 m b.s.l). The system is mostly submerged and explored by diving (Calligaris *et al.* 2017).

The Reka was in the past heavily industrially polluted; therefore the Timavo Spring was despite the abundance, not a good source for the water supply of Trieste (Cucchi *et al.* 2015). Several pollution events forced the water providers to search and use other sources. Springs less influenced by the Reka (Sardos) were the exploited and can nowadays provide about 20 % of the regional demands; however, the main water source of Trieste is now a series of pumping wells drilled into the alluvial aquifer of the Soča River Plain.

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# ABSTRACTS

## IZVLEČKI

*sorted according to the family names of the first authors
*razporejeno glede na priimke navedenih prvih avtorjev

## Integrated approach for the geochemical characterization of vermiculations from Pertosa-Auletta Cave (Southern Italy)

### Integriran postopek za geokemijsko analizo vermikulacij v jami Pertosa-Auletta (Južna Italija)

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Vermiculations are little known structures occurring in underground environments. They are thin, irregular and discontinuous deposits of incoherent particles, with diverse morphology (dots, dendritic, hieroglyphic…), colour (red, brownish, grey, white…) and size (Parenzan 1961), typically found on walls and roofs of natural or artificial caves all over the world (Hill & Forti 1997). The origin of vermiculations is widely debated due to the development of data-driven theories still hindered by the scarcity of quantitative analyses on their chemistry and biology (Bini *et al*. 1978).

The aim of this study was to investigate the geochemical characteristics of vermiculations from one of the most important karst systems of southern Italy, the Pertosa-Auletta Cave, using an integrated approach involving elemental, mineralogical and microscopic analyses. The research provides the first quantitative record of all these features in vermiculations, giving a comprehensive overview on their geochemical nature and contributing to the understanding of their genesis.

The vermiculations of Pertosa-Auletta Cave exhibit an extraordinary diversity in their morphology and colour, the widest recorded from a single karst system to date. Elemental analysis also highlighted wide variations in C, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, N, Na, Ni, P, S, Ti, V and Zn concentrations among vermiculations. Field emission scanning electron microscopy with Energy Dispersive X-ray Spectrometry, as well as X-ray Diffractometry, showed that vermiculations are mainly composed of calcite, associated to clays, quartz and various biologically-mediated $CaCO_3$ crystallization features (rods and vaterite spheres). The constant association of clay minerals, occurring along cavities and niches of calcite, with microbial-like filaments, and the presence of microboring and etching patterns, indicate that microbial activity likely plays an important role in the development of vermiculations.

## The challenge of building infrastructures with the presence of karst formations

### Izzivi pri gradnji infrastrukture na kraškem območju

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Qatar is experiencing an infrastructure booming where roads, stadiums, tunnels, metro lines, new subdivisions are being built all over the country. Also, Qatar is well known of having karst formations including depressions, sinkholes, caves, and solution hollows. Some reports listed the presence of more than 9700 large and small depressions, and several exposed sinkholes and caves (Sadiq & Nasir 2002). In this study the impact of Karst on infrastructure facilities and the mitigation measures that can reduce the risk of karst are being discussed. The Ministry of Municipality and Environment is carrying out a few national projects using remote sensing techniques, hydrogeological and geological mapping. These projects will help in mapping the karst features and outline their risk on the infrastructure and the people of Qatar. This paper will discuss the available outcome of those projects and some of the mitigation measures that the ministry of Municipality and Environment are taken to effectively minimize the impact of karst on infrastructures.

## National groundwater quantity assessment - karstic case studies for Slovenia
### Ocena količine podzemne vode na državni ravni – primeri kraških območij v Sloveniji

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Slovenian Environment Agency is national authority responsible for monitoring and analysing the groundwater quantities and status assessment. One of the most important Agency's goals is the annual groundwater quantity report on a national scale. GROWA-SI water balance model is used as a fundamental tool for renewable groundwater quantity estimation. Groundwater quantity estimation in karstic aquifers, which covers about 44 % of the country's area, is additionally evaluated using trend analysis of karstic springs and streams discharges at low hydrological conditions on an annual and monthly scale.
The newly mGROWA-SI water balance model was developed in the period 2016–2017 and became operational last year with improved temporal resolution according to the GROWA-SI model. mGROWA-SI model was tested on karstic watershed of Rižana spring. The results of the model were compared with discharge data at Kubed gauging station, which lies about a kilometre downstream from the spring and with the discharge data at the spring itself. The results show a correlation between mGROWA-SI groundwater recharge and Kubed gauging station, but not between Rižana spring and model results, or Rižana spring and Kubed gauging station. Analysis of low discharges has not shown any clear correlations, which can be a result of the karstic nature of the Rižana spring. Percentile analysis revealed correlations between medium discharge levels at gauging station and medium groundwater recharge or medium spring discharge.

## Assessing the safe yield of a karst aquifer by rainfall-discharge modelling
### Ocena zalog vode v kraškem vodonosniku z modeliranjem padavin in odtoka

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Groundwater flows and storage in karst aquifer are heterogeneous, deeply impacted by karst conduit network. Two main structures are usually used to describe flows: matrix and conduits. This conceptual view of the aquifer is useful to reduce the karst hydrodynamic functioning to few parameters that can be modelled. Another main property of karst is the drainage of the aquifer by springs, connected to the karst network. Groundwater outflow can then be described by two components: baseflow and quickflow. Quickflow is mainly occurring during floods. Baseflow is the sustainable flow, varying between seasonal low and high flow, and during floods. Quickflow discharging at springs during flood is a part of the water budget that is not stored in the aquifer and is then not available for water supply.
It results that groundwater availability at a spring, i.e. at the outlet of the aquifer, can be assessed by separating the quick and base flows. Studying a spring over years or decades gives insight the mean annual baseflow. We propose to define the safe yield that can be withdrawn from a karst aquifer close to the outlet as the mean inter-annual baseflow. For this purpose, lumped rainfall-discharge models are efficient tools to easily separate flow components from spring data.
The modular karst modelling tool KarstMod is used in this study. This is a free open tool, made by the French National Karst Observatory Service. We focus on the Dardennes springs case study (South-East France). This aquifer is already used for water supply; twenty years of data are available. This is a typical karst aquifer, with huge flash flood up to 30 $m^3/s$ in few hours, and a mean total discharge

close to 0.7 $m^3/s$. We show that the mean annual baseflow is quite constant over the years while the rainfall is highly variable.

## Karstic conduits connectivity, natural and disturbed hydraulic behaviours of the multi-layered aquifer system of Barrois limestone – IHLLW Cigéo Project (France)

### Povezanost kraških kanalov, naravno in vsiljeno hidravlično delovanje večplastnega vodonosnika v "Barrois" apnencu – projekt IHLLW Cigéo (Francija)

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The French National Radioactive Waste Management Agency (Andra) conducted site investigations programs to study a deep geological disposal of intermediate and high level long lived (IHLL) radioactive waste (Cigéo project) in the Meuse/Haute-Marne region. Surface installations and underground structures as ramps and shafts concepts and their environmental impacts rely on hydrogeological conceptualization of the Barrois limestone surficial formations. Barrois limestone consists of multilayered karstic aquifer system with tree connected karst conduits networks associated to the following limestones layers (Sublithographic, Dommartin and Cariés) and separated by semi permeable layers (Pierre Chaline and Oolithe de Bure).
The karstic geometry is modelled using a formulation of the stochastic differential equation of Langevin, a simplified description of the coupled physico-chemical processes governing karstification (Jaquet 1995). The generated karstic networks respect the available hydrogeological information. Conditioning information is integrated using a potential field that comprises: (i) general flow direction, (ii) karstic springs (by hydrologic unit): karstic conduits are forced to pass the spring locations because of an attractor in the potential field.
Recently, tracers experiment results confirm the general trend of the kart conduits horizontal distribution and demonstrated the vertical connection karst networks associated to the multi-layered aquifer system.
Resulting hydrogeological concept is applied to develop a variably saturated flow model in order: (i) to reproduce the observed natural flow and (ii) to analyse hydraulic behaviour induced by the construction of 2 ramps and 5 shafts to access the planned IHLL radwaste repository of Cigéo project.

## Monitoring of Karst Water – Methods and Techniques

### Meritve vode v krasu – metode in tehnike

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Monitoring of karst water comprises several methods depending on the karstic environment under study and on specific objectives. It is obvious that different methods entail also different techniques. Karst water as the term is used here can be surface water (surface streams in karst, karst lakes), water in karst springs, underground water in caves or deep groundwater (accessible only by boreholes), and water in the mixing zone of fresh and salt water in coastal or submarine environments. The overall aim is usually to collect a reliable set of data for a comprehensive investigation of the hydrology, hydrogeochemistry (including isotopes), or microbiology in the

studied karst system. The desired result is a better understanding of processes and their interaction among each other as well as water/rock interaction. In the wide field of water management applications the results of properly performed monitoring programs are used to support efforts for a high quality of water for all purposes of daily life and various industrial or other commercial use.
As karst water is usual sensitive and vulnerable to contamination because of its quick response on changes in the hydrometeorological conditions it is often a challenge to get reliable data, e.g. from short discharge events and their respective rapid and often very high variation of measured parameters, such as water level, discharge, temperature, electrical conductivity and other physico-chemical parameters. Today a monitoring strategy with continuous online-monitoring and real-time data provides better information and allows to react properly upon contamination.
Continuous online-monitoring needs selective and sensitive sensors which are robust against rugged environmental conditions. A variety technical systems are today available to meet these requirements, but there are still some parameters which cannot be measured easily, and need therefore to be measured from distinct water samples (e.g. alkalinity, various isotopes etc.). Data from such monitoring systems have to be stored at least temporarily, have to be transmitted and transferred into databases. They have to be checked for plausibility before an interpretation can start. Only such data can be used as input for modelling and simulation of different scenarios.

## Preliminary results of the characterization of the linkage between soil moisture dynamics and discharge at a karst region in Southwest Germany

### Prvi rezultati raziskovanja povezav med dinamiko vlage v prsti in pretokom vode na kraškem območju na jugozahodu Nemčije

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Karst groundwater represents an important source of drinking water for the world's water supply. The most typical approach to characterize a karst system is the disintegration and analysis of its output signal measured at the karst spring using, for example, discharge observations, hydrochemical signal or tracer information. However, the value of soil moisture observations to identify and characterize karstic recharge processes has been receiving limited attention. In this ongoing study, we explore the usability of soil moisture observations to characterize the input signal to the aquifer, i.e. the karstic groundwater recharge dynamics. At a test site at Southwest Germany, observations of climate, soil moisture (90 profiles, at 10 cm and 20 cm depth, distributed across forest and grassland), and discharge are available. We hypothesize that recharge initiates after the saturation of the soil, which will be indicated by an increase of discharge. We express this interplay of soil moisture and discharge by hysteresis curves, which vary in shape according to precipitation characteristics, antecedent soil moisture and groundwater conditions. For some of our soil moisture profiles, we find the expected reaction: discharge initiates after soil saturation expressed by a rectangular hysteresis curve. However, at some sites, we find an almost simultaneous reaction of soil moisture and discharge or a reaction of discharge without a soil moisture increase, expressed by a flat shape of the hysteresis curve. We interpret this as the result of preferential flow that occurs close to the soil moisture profile or direct infiltration in the system. Although our analysis and data do yet not provide quantitative information on karstic recharge, it provides new insights into the spatial dynamics of the onset of karstic recharge and the importance of subsurface heterogeneity for the infiltration processes of karst systems.

## Numerical geological modelling of the karst system from Lajedo Arapuá, Jandaíra Formation, Potiguar Basin

### Numerično geološko modeliranje kraškega sistema Lajedo Arapuá, Jandaíra Formation, Potiguar Basin

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A numerical geological model is the basis for various development strategies of an oil field, this includes estimating the original volume of hydrocarbons in subsurface; leasing and quantification of the number of producing and injector wells; individualization of production zones for management and optimization of productive capacity; and even assisting the guidelines for ship-platform design (FPSO's). The pre-salt reservoirs of Santos Basin consist of carbonate rocks that have complex porous systems, composed of matrix porosity, fractures and karstic systems with even development of caves. This work aims to present a workflow proposal for modelling the karstic features of reservoirs with the aid of an analogous outcrop of Jandaíra Formation, Potiguar Basin.
A drone image of Lajedo Arapuá area; scanlines with fracture attributes; and the karst-facies vertical stacking pattern from an outcrop near this area represent the main data integrated in a three-dimensional model. Initially a facies framework was constructed, to which porosity and permeability values for the matrix were assigned. Subsequently, a model of discrete fractures (DFN) with their respective values of aperture and permeability was built. Both matrix properties and fracture properties served as the basis for the construction of the pipe network that guided the karst skeleton simulation.
In this study three feasible scenarios of karstification were generated from the same pipe network, the first one presenting the architecture for an epigenic karst, the second for a hypogenic karst and the last scenario reflects the superposition of these two processes of karstification.
It is concluded that it is fundamental to understand with accuracy what the prevailing karstification process is in a reservoir for its adequate representation in numerical models, since the conceptual model taken into account will directly affect the numerical modelling, and, consequently, the whole subsequent process of decisions regarding the development of an oil field with karstic features.

## Karst depressions: geoheritage hotspots on karst surface

### Kraške depresije: vroče točke geodediščine na kraškem površju

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Karst geoheritage is based on rich karst surface and subsurface morphology, which is generated by soluble carbonate rocks. One of the most common and diagnostic landforms of the Dinaric Karst are different karst depressions, e.g., solution dolines, unroofed caves, collapse dolines. Dolines can be recognized as geoheritage hotspots because of specific characteristics: concave landform (micro terrain), sediment fill (pedosediment complex), microclimate (micro refugia), connection with caves, and traditional land use practices (e.g., traditional charcoal production, traditional lime kilns, dry stone walls, water ponds, water tanks, pastures, fields). As concave landform, dolines collect water from their slopes and as they also have more soil as in surrounding areas, they are moisture hotspot in otherwise dry karstic environment.
In the paper we present karst depressions from three geographically different karst regions, considering geology, hydrology, pedology, terrain, vegetation, and climate. Non-invasive methods of electrical resistance tomography (ERT) was used along with geomorphological mapping and GIS. The

first region is the Classical Karst region of Kras Plateau (Slovenia) with more than a century-long and intensive exploration, where more than 14.000 dolines were identified. The second region is Krk Island (Croatia) where investigations of karst depressions intensified in the last decade. The third region is the cross-border karst massif that extends from Snežnik Mountains (Slovenia) to Gorski Kotar Mountains (Croatia). Selected study sites in Sežana area and Škocjan Caves (Kras Plateau), Platak area (Gorski Kotar Mountains) and Punat area (Krk Island), are study areas in the cross-border project between Slovenia and Croatia (titled KRASn'KRŠ) in which karst depressions were identified as a potential, but not yet valorised geoheritage hotspots. To change these, selected karst depressions in the framework of the project will be innovatively presented through four interpretive centres and their own interpretive in-situ polygons that will strive to promote knowledge on karst depression and karst landscape in general.

## Dissolved oxygen as a tracer of flow characteristics in a karst hydrogeological system
## Uporaba raztopljenega kisika za proučevanje značilnosti toka v kraškem hidrogeološkem sistemu

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Monitoring of various natural tracers in a spring water provide insight in groundwater flow characteristics and processes happening within the karst hydrogeological system. Electrical conductivity, temperature, turbidity, stable isotopes, organic carbon, nitrates, etc. are more and more commonly monitored on karst springs in order to provide information on infiltration mechanisms, epikarst function, mean groundwater transit times, interrelation and dynamics of fast and slow flow, etc. Supersaturation of gases or "air excess" in spring water is a phenomenon which occurs periodically or permanently in some karstic springs. Fish farming literature is well aware of this phenomenon, as gases oversaturation can cause fatal "gas bubble disease" in fish. In contrary, this phenomenon was very rarely investigated within the karst hydrogeological research. Some of the karst springs in Dinaric karst of Croatia are known among local community as occasionally fatal for fish due to gas oversaturation, but this was never monitored or researched in more detail. Krbavica Spring in Lika Region of Croatian Dinaric karst is captured for the local water supply. In a spring capture reservoir bubble formation is visible with variable intensity during different periods of the year. Within the monitoring program of multiple natural tracers in spring water, high temporal resolution monitoring of dissolved oxygen was established. Dissolved oxygen was monitored as an indicator of excess air in spring water. Preliminary analysis and interpretation of the observed data points to the gas oversaturation as a good indicator of flow characteristics within the system, e.g. indicator of "closed flow" through fractures of the vadose zone, as well as flow through dominantly phreatic conduits in the deeper parts of the system.

## The pollution in Pazinčica stream and its effects on Pazinska jama Ponor (Croatia)
## Onesnaženje Pazinčice in posledice v Pazinski jami (Hrvaška)

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Pazinčica is the largest sinking stream of Istra Peninsula in Croatia. The catchment area, derived from DEM, is 78.1 km$^2$. It is a textbook example of the allogenic denudation system. Nearly complete (95 %) catchment area is non-karst system with stream sinking at the contact of impermeable and karstified beds. It is mostly built of impermeable flysch and alluvial deposits with well-developed drainage network formed by fluvial and slope geomorphological processes. Pazinčica sinks into

Pazinska jama Ponor cave developed in karstified Cretaceous limestone. Ponor is partially accessible due to the infillings of various materials in the submerged passages. According to tracer test water from Pazinska jama drain into springs SE of the Ponor up to 28 km away and one of them is used for water supply. Part of Pazinčica valley is NATURA 2000 site and Ponor is protected by Nature protection law as Geomorphological Natural Monument. But, due to the high intensity of anthropogenic activities in the basin they are occasionally exposed to pollution. The first recorded heavy incident was in 1997. The most recent incidents occurred in 2018 and 2019 from the landfill Lakota in the City of Pazin and nearby area. The pollutants recorded in the stream, during these recent and previous incidents, were: fuel oil, sewerage and drainage water, mud originated from industrial stone powder, municipal and forest waste. The influence on Pazinčica stream fauna was not known but influence on cave fauna was recorded. Besides that, there are other sources of pollution, but Pazinska jama is the most remarkable one due to the significant point inflow. All that have high influence to the karst landscape and ecosystem, karst aquifer and tourism activities. Therefore, Pazinčica is an example of poor policy of karst environment and aquifers protection, and general problems in nature protection system.

## Strategy to investigate and understanding complex aquifers: the karst systems of "Gorge de l'Ardèche, France"

### Strategija za proučevanje in razumevanje kompleksnih vodonosnikov: primer kraškega sistema Gorge de l'Ardèche, Francija

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In South-East of France, the Mediterranean climate is a major driving factor for the functioning and the dynamic of the karst aquifers. The climate is mainly hot and dry during summer, with a rainy period in winter. But very heavy rains append in spring or in autumn during Mediterranean or Cevenol Episodes. These events give very intense flash floods. With the global warming, the effect of climate change become more and more important for the water supply during summer. In such context, understanding karst aquifers is an important challenge, for the management and the development of this territory and the preservation of the karst heritages.

In Ardèche, for several decades, numerous studies tried to understand the organization and the relationships between the different karst aquifers in the area of the gorge de l'Ardèche and the confluence with the Rhône Valley. The extension of the canyon is 31 km long with more than 30 1 springs flowing out between Vallon-Pont-d'Arc and Saint-Martin-d'Ardèche. The different catchments of these karst systems represent an area of 540 km².

The studies were based on dye tracing, deep drilling technics, pumping, discharge measurements and chemical and isotopic analyses. If the results were pretty good to understand global system and for the management of the water supply, it was not strong enough to understand the dynamic of the karst aquifers during extreme events (flooding or drought) and the interaction between Ardèche River, karst systems and deep aquifers.

Ten years ago, collaboration between speleologists, scientists and local organization has started to study these different aquifers by direct observations and measurements, high density and high-resolution monitoring at the scale of the galleries, the cave, the karst system and the fluviatile system.

The results obtained made it possible to understand the seasonal dynamic of the aquifers and their interaction with the Ardèche River. Several intense flood events and heavy drought episodes have been recorded and analysed.

## Impacts of salinity and global warming on groundwater ecosystems: a case study in southwestern Australian aquifers

### Vpliv slanosti in globalnega segrevanja na ekosisteme v podzemni vodi: primer raziskave v vodonosnikih jugozahodne Avstralije

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Groundwater (GW) comprises 97 % of the freshwater global resources available for direct human consumption. It harbours a unique ecosystem, composed of groundwater-adapted species (i.e. stygobionts), which provide ecosystem functions linked with nutrient recycling and water purification, which is threatened by anthropogenic activities.
Throughout the world, the salinization of landscapes and increasing temperatures associated to global warming effect present threats to the conservation of GW and GW-dependent ecosystems and, yet little is known how aquifers' ecosystems respond to these changes.
The aim of this study is to examine the effects of salinity and temperature increment on stygobionts. Such knowledge is critically needed for understanding the effects of antropogenic stressors and for establishing environmental risk assessments (ERA) for GW ecosystems. We selected representative stygobiont crustaceans' species from two aquifers of in southeastern Australia: one harpaticoid (Somersby); one cyclopoid and one syncarid (Wellington). Salinity and temperature effects were tested independently in the three species. We tested acute lethal concentration for NaCl and the upper limit thermal tolerance for each species.
Ecotoxicological data for subterranean species is indispensable to the ERA for issues such as salinization and desertification. Further testing of the interactive effects at environmentally relevant conditions and the use of species that covers all ecological features are still required for a better understanding of anthropogenic impacts in groundwater biota.

## The geochemistry of the glacier ice and cave ice in the Triglav area, Slovenia

### Geokemija ledeniškega in jamskega ledu na območju Triglava, Slovenija

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The Triglav Glacier in the limestone Julian Alps in the northwest of Slovenia is one of the southernmost glaciers in Europe and thus represents an important component of mountain geomorphosities from the environmental perspective. Excellent historical data of the Triglav Glacier is available due to continuous detailed measurements of the Triglav Glacier by the Anton Melik Geographical Institute ZRC SAZU, and current alarming trends are showing that ice masses continue to undergo mass loss as the overall climate warms. The surface ice mass shrunk to glacieret size and consequently exposed a number of pit caves, some still containing ice. Glacier ice and cave ice represent a wealth of paleoclimatic information, so rapid sampling of these deposits is needed if any such information is to be saved. We present the first comprehensive glaciochemical, geochemical

and water isotope data from glacier ice and cave ice in the Triglav area, including meltwater and spring water, collected in 2018. The samples primarily reflect the initial precipitation signal that has been greatly modified by the input of local $CaCO_3$-rich dust with lesser amounts of marine aerosol and vegetation debris. There is little variation between the glacier ice and meltwater in their major elemental composition. The $H_4SiO_4$ also varies little, indicating the lack of silicate mineral weathering in those environments. The dissolved $PO_4^-$ concentrations are very low while the dissolved inorganic nitrogen (DIN) concentrations vary by more than an order of magnitude. This produces DIN:P ratios that also vary greatly and thus limit our ability to evaluate the sources of and the ecological impacts of these nutrients within this environment. The $\delta^{18}O$ and $\delta D$ values of the sample fall very close to the regional meteoric water line indicating very little modification of the primary precipitation by other processes, such as evaporation.

## Recent advances on the characterization of karst-river interactions during floods

### Trenutne smernice v raziskovanju odnosa kras-reka v času poplav

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Flood hazard and groundwater resource management in karst catchments require a better understanding of hydrogeological processes and notably groundwater/surface water interactions. This is a great challenge due to the heterogeneity of karst aquifers and due to the diversity of karst types (small perched units, wide sedimentary basins, barren/covered karst, etc.). The aim of this communication is to present recent developments on the characterization of karst-river interactions through two main approaches: a spatial approach aiming at localizing karst areas promoting surface flows, and a temporal approach aiming at modelling lateral flows from karst units in rivers.
The first spatial approach is based on the GIS index IDPR (Index of Development and Persistency of River networks, developed by BRGM©), quantifying the hydrological connectivity to the hydrographic network. From the standard version of the IDPR over France (25 m resolution), we propose to compare IDPR calculations differentiating intermittent and perennial reaches of rivers in order to detect infiltrations zones that contribute temporary to rivers, as many karst units.
The second approach is a modelling framework based on the inverse problem for the diffusive wave model, to simulate lateral flow during floods on a reach between two stations. Knowing the upstream and downstream hydrographs, we can model the lateral one, given information on the hydrological processes involved in the intermediate catchment. Applying such approach on river reaches crossed by karst units is a new way to quantify river losses and gains, characterizing localized recharge and aquifer drainage to rivers, respectively.
We propose to illustrate these two approaches through several case studies in France, where a better characterization of karst-river interactions and flood risk management are critical issues.

## Hydropower development in Nikaj-Merturi regional park (Albania): an attempt to over-exploitation carbonate aquifers and water caves

### Trend rabe hidroenergije v regionalnem parku Nikaj-Merturi (Albanija): poskus prekomernega koriščenja karbonatnega vodonosnika in vodnih jam

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In the period 2003–2016 over 524 concessions for small hydropower (HPP) projects were awarded throughout Albania on pristine rivers and inside protected areas even when they could have serious negative environmental and socio-economic impacts. One of these concession, approves the construction of 11 (eleven) hydroelectric power stations on the waterfalls of the Curraj/Kuqit/Pajës rivers and all the sub-services needed (pipes, roads, electric stations, underground galleries), into the very heart of regional park "Nikaj-Merturi" (Northern Albania, Tropojë district) established in year 2014 (17,500 ha). All the springs and sources of freshwaters to be catch comes from karts areas: in addition of the ongoing risk on the underground feeding of caves like "Shpella Zeze" and "Shpella Lumit", the main project provide very poor information with major gaps or weaknesses, which would prevent the proper decision making process proceeding.

## Comprehensive hydraulic and hydrochemical interpretation of a karst area in South Hungary

### Obsežna hidravlična in hidrokemična interpretacija kraškega območja na jugu Madžarske

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The Villány thermal karst area is situated in the southern part of Hungary, where the karst aquifer is build-up of Mesozoic carbonates. The outcropping carbonates and their subsurface continuation covered by young sediments in the adjacent basin basement form a thick (up to 1700 m) karst reservoir. The area is characterized by natural thermal water discharge at the boundary of outcropping carbonates and adjacent sedimentary basin. These regional thermal water discharge areas are favourable sites for hypogenic cave development as well. Some caves here are characterized by phenomena related to thermal waters and some of the caves are connected to thermal waters even today. The thermal waters and the caves were hitherto investigated separately. However, all these phenomena belong to one single system, a hypogenic karst system and they can be evaluated only if their context is understood, i.e. if their common cause is revealed: the pattern of groundwater flow and its thermal and geochemical characteristics. The aims of the present study in the Villány thermal karst area and in the adjacent sedimentary basin are 1) to evaluate the groundwater flow system based on measured hydraulic data applying the hydraulic continuity approach, 2) to characterize the geochemical composition of the waters, using natural tracers to identify different fluid components e.g. from the sedimentary basin, 3) to evaluate the cave forming and recently active processes. To achieve these goals, the hydraulic interpretation, a dissolution experiment in one of the hypogenic cave and a hydrogeochemical analysis have been completed.
The National Research, Development and Innovation Fund has provided financial support to the Villány project under the grant agreement no. PD 116227. This study is also part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 810980.

## Geochemical and hydrogeological characteristics of the Santa Cesarea terme sulfuric acid cave systems (Apulia, Southern Italy)

## Geokemijske in hidrogeološke značilnosti z žvepleno kislino bogatega jamskega sistema Santa Cesarea terme (Apulija, Južna Italija)

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Santa Cesarea Terme (Apulia, southern Italy) stands as an important spa area, known since the nineteenth century. Several emergences of slightly thermal sulfidic waters flow out along a coastal sector of the Salento peninsula, and exhibit temperatures ranging between 22–25 °C. The carbonate sequence, consisting of over 5-km-thick Jurassic and Cretaceous limestone and dolostone, rests above Late Triassic evaporites and is unconformably overlain by Cenozoic calcareous successions. Starting from the Early Triassic, the area was part of the Apulian carbonate platform, characterized by shallow-water carbonate sedimentation. Since Cretaceous times, it experienced a number of transgression-regression phases, giving rise to a succession constituted by multiple unconformities. Eventually, during the Middle Pleistocene, the area underwent a severe regional uplift. The Santa Cesarea Terme area shows extensional and trans-tensional structures, with related pull-apart features. The NW–SE trans-tensional faults are the most diffuse, with subordinate presence of other fault systems, and appear to be the youngest set, controlling the development of the main karst landforms in the area. At the surface, these are mostly represented by sinkholes and dry valleys of different sizes and typologies, and by typical low-incised karst valleys. Apart from a number of inland caves (mostly of limited development), the most relevant karst features are distributed along the coast and correspond to three caves within the spa area and an additional cave further south. The four caves are carved at sea level and all have a direct access to the sea. Here, rising sulfidic waters meet and mix with seawater producing solutions with different geochemical contents. The sulfidic springs and the village of Santa Cesarea Terme are located on a structural high, with the caves elongated along the NW–SE fault zones. Inside the caves, that show quite large halls and galleries ending abruptly, it is possible to observe cupolas, rising channels, megacusps, submerged feeders, weathered walls, replacement pockets, and important deposits of gypsum, with abundant native sulphur coatings and jarosite. All these features allow to define the caves as Sulfuric Acid Speleogenesis (SAS) systems.

During the last four years, geochemical data have been collected in order to characterize the composition of water flowing inside the caves, and a variety of parameters have been measured (including temperature, dissolved oxygen, conductivity, pH, etc.). They fall into the Na-Cl-$SO_4$ sector of the Ludwig-Langelier diagram, with pH ranging from 7.2 to 7.8 (the latter value being mainly influenced by seawater-deep water mixing), and are colonized by whitish bacterial filaments (streamers). Brownish vermiculation deposits and white gypsum moonmilk diffusely cover walls and ceilings, especially where the amount of $H_2S$-degassing is important. Experiments with limestone tablets are demonstrating the dissolution-corrosion to be an intense on-going process for present-day sulfuric acid speleogenesis.

## Limestone and gypsum tablet weight loss in sulfuric acid speleogenetic caves of Southern Italy

### Analiza raztapljanja sadrinih in apnenčastih ploščic v z žvepleno kislino bogatih jamah v Južni Italiji

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The dissolution-corrosion (DC) is one of the most important key factors for the understanding of karst speleogenesis. Dissolution can be measured using tablets, balancing weight-loss/gain during the exposure in cave.
In sulfuric acid environments, the oxidation of $H_2S$ is the most important process inducing speleogenesis (from here on, sulfuric acid speleogenesis is indicated as SAS). Here, the exposed surface of carbonate rocks is actively corroded by sulfuric acid ($H_2SO_4$). In aerate settings, $CaCO_3$ can be easily replaced by $CaSO_4 \cdot 2H_2O$, the most common SAS by-product, and produces an initial weight gain. The understanding of dissolution-corrosion (DC) rate in active SAS systems is a very important issue that can help in evaluating the speleogenetic stages of a cave, and in correlating them with landscape evolution, as demonstrated by previous studies carried out in the Grotta del Fiume at Frasassi, central Italy.
Italy hosts 25 % of the known worldwide SAS caves, and some of them are still-active. In some of these, especially in those located in southern Italy, dissolution-corrosion rate studies started at the end of the 2015-beginning of 2016, and will continue until the beginning of 2021 (for a total of five whole years), to have a better distribution of weight loss/gain rates.
The SAS systems under investigation are Ninfe Cave and Sibarite spa (in Calabria), Fetida Cave (Apulia), and Acqua Fitusa Cave (Sicily).
Carbonate and gypsum tablets, 28 $cm^3$, with a mean initial weight of 74 g, have been placed in the cave atmosphere, underwater, and at the interface zone. DC measurements showed interesting results, and demonstrated environmental parameters to be the essential controls in weight loss/gain rate. We observed that at the beginning of the experiment, DC was faster in underwater conditions, whereas during the last period of monitoring (after 582 days of permanence in cave) the dissolution at the interface zone increased, becoming even greater than the rate observed in subaqueous conditions.

## Karst hydrogeological investigations in the Bükk Mountains (NE Hungary)

### Hidrogeološke raziskave krasa v hribovju Bükk (SV Madžarska)

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The Bükk Karst Water Monitoring System (BKWMS, Bükk Mountains, NE Hungary) initially included 5 observation wells, planned and carried out by Tivadar Böcker in 1983. The first automatic water level loggers were installed in 1992 during a water scarce period.
The objective of the hydrogeological monitoring system is to obtain information on the actual water budget, to assist the water supply and to mitigate the effects of floods. The collected data includes water level, electric conductivity and temperature. The frequency of measurements is generally once in every 15–60 minutes. Precipitation data is also collected in different locations.
Current presentation focuses on the analysis of time series of the measured values in order to obtain a better understanding of karst system of Bükk Mountains. Spectral analysis of long term time series, spanning over 27 years, have been carried out, complemented with spring and well hydrograph analysis. We want to present the results of the following methods: Fourier-transformation, auto- and

cross-correlation function, cross spectrum and phase function, coherence, Gain-function and recession curves analysis.
By using the mentioned methods, we investigated the periodicity and memory effect of hydraulic heads, the delay between the precipitation and the flow, flow velocities, spatial and temporal boundaries of the different types of flow regimes, boundaries of the well karstified zone. Water level forecast have also been carried out.
As a result of these, new insights have been obtained about the karst system. The novel approach proved to be useful and will help decision makers and stakeholders of water works.

## Historiographic analysis and 3D light simulation of Hautecourt Cave (Ain, France) during the two last centuries

### Zgodovinska analiza in 3D svetlobna simulacija jame Hautecourt (Ain, Francija) v zadnjih dveh stoletjih

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An interdisciplinary program research, started in 2017, is currently working on the Hautecourt Cave (Ain, France), which have been visited for touristic reasons during 19th and 20th centuries. Before its Nature Reserve classification in 1980, the cave experienced two main periods: touristic occurrences and an underground laboratory (researches about cave biology lead by the Biological Laboratory of Lyon). The present work will focus on the touristic period and human occurrences onto the cave during this period. It is based on historiographic analysis by using signatures dated on the cave walls / 670 dates were recorded on a several cavity walls. Two peaks of frequency can be determined by this study: 1849 and 1884. Each ones of those peaks correspond to important infrastructures developments onto the cave (mainly new ladders). In addition to this, an experimental work is trying to propose a reconstitution of the past underground landscape and the lighting atmosphere in the cave during 19th century, using 3D modelling and 3D simulation of lighting. The main objective is to understand the perception of the cave by the visitors as a patrimonial in heritage.
This study allows us to understand the panel of various lighting sources used during the 19th century, to appreciate the location of soot traces in the cave and to propose an historical timeline of lighting uses depending on touristic seasonality and infrastructures.

## Monitoring and methods to assess the groundwater quality degradation risk in karstic island aquifers (Bantayan Island, Cebu Province, Philippines)

### Monitoring in metodologija za ocenjevanje tveganja poslabšanja kakovosti podzemne vode na kraškem otoku (otok Bantayan, provinca Cebu, Filipini)

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Karst islands such as those found in the Philippine Archipelago present challenges for stakeholders to manage their water resources in a sustainable manner. Anthropogenic climate change, an increasing population and changes in land use have all combined to alter the water balance on these fragile islands. Karst features (the potential for dissolution), the combination of point source pollution with a shallow depth to groundwater and saltwater intrusion contribute to the challenges for sustainable water resource development.

Bantayan Island (Cebu Province, Philippines) has been selected as the study area. The single freshwater lens of this island is vulnerable to salt water intrusion due to several factors including karts geology and abstraction well discharge.
A multi-methodological approach for the assessment of the quality of the freshwater lens is proposed based upon field monitoring and spatio-temporal analysis of groundwater quality changes. The tools to provide suitable data to users are modest and inexpensive. The purpose is to obtain a potentiometric surface coupled with a quality assessment of the freshwater lens. The spatial and multi-temporal analysis of typical chemical and physical data is used to establish a spatial vulnerability of the aquifer to salt water intrusion. The multi-parameter field data collection provides a nimble methodology for rapid groundwater quality classification for each monitoring location. This study introduces the water quality trends expressed in terms of salinity and derives salinity thresholds to evaluate intrusion of brackish water into the freshwater lens. Evaluation of salinity trends can be used to monitor the impacts of groundwater exploitation and potential mismanagement of the freshwater resource and has resulted in the distinction of three zones of freshwater lens vulnerability; zone 1) low vulnerability to sea water intrusion; zone 2) high vulnerability to sea water intrusion; and zone 3) varied vulnerability in which sea water intrusion largely depends on management of abstraction well discharge. Water quality impacts resulting from sea water intrusion are a result of a combination of up-coning in areas of concentrated abstraction, coastal boundary zones affected by tidal forcing, and structural geological features where enhanced groundwater flow along long-linear discontinuities (faults, major joints) provides inland connections with the coastal zone.
The approach allows consideration of the current abstraction management schemes and the ability to improve design by instituting more realistic and science-based targets. A management instrument relative to aquifer zoning is proposed.

## Karst hydrogeology: The high-flow low-storage extreme in marble aquifers
## Kraška hidrogeologija: pojav majhnega skladiščenja v času visokih voda v marmornatem vodonosniku

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Many aquifers exhibit dual porosity, where water is stored in large volumes within their matrix and fracture porosity. In karst aquifers, these porosities increase over time, because water flow causes dissolutional enlargement. This leads to triple porosity by the creation of cave passages with high flow rates but low extra storage potential. Speleogenesis in meteoric systems in sedimentary limestones proceeds by slow carbonic acid dissolution along favourable inception horizons and fractures, accelerating to a fast-maximum dissolution rate after a breakthrough point is reached.
However, metamorphic limestones have porosities that were negligible immediately after metamorphism. Nevertheless, there are >2800 caves in such marbles in Scandinavia, Scotland and North America. Most are mainly vadose or have a simple vertical epigean morphology, suggesting they have not survived the last glaciation and have formed in the last 12,000 years, in contrast to many much older caves in sedimentary limestones in unglaciated areas. This is commonly supported by their small passages and the rarity of pre-Holocene speleothems (although some in Norway do show survival through several glaciations). These caves were initiated by phreatic water flows from ice-dammed lakes through neotectonic fractures that were commonly opened by isostatic rebound during deglaciation, many being horizontal even in vertical and angled foliations. Flow routes were short enough and fracture openings were wide enough for fast dissolutional flow rates (shown by the small sizes of wall scallops) during tectonic inception to be immediately beyond that required for chemical breakthrough. This was despite the little $CO_2$ in pure glacial meltwater and the complete absence of vegetation. In these conditions, phreatic passages enlarged at a maximum rate to ≤2m

diameter in the typical 1000 years duration of water flow during deglaciation, possibly followed by vadose entrenchment in the Holocene. The resulting marble aquifers have high flow rates and low storage capacity.

## Genesis of sediments in Muierilor Cave, Southern Carpathians, Romania; facies identification and hydrodynamics

### Nastanek sedimenta v jami Muierilor, Južni Karpati, Romunija; prepoznavanje faciesa in hidrodinamike

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Muierilor Cave (Romania, Gorj County) it is one of the representative caves from Southern Carpathians yielding unique palaeontological, morphological and mineralogical features. The sediments within the passages can provide key insights into the evolution of the cave in a regional context. The sedimentary facies and hydrodynamics conditions for sediment deposition were determined using grain size and magnetic susceptibility analyses on two profiles from the lower level of the cave (Bears Passage). The first profile (PM1, ~260 cm deep) is located in the Bears Passage being the new paleontological excavation and the second profile (PM 2, ~480 cm deep) located at the end of the Beas Passage. For grain size samples were analysed on a Horiba Partica LA-950V2 Laser Scattering Particle Size Distribution Analyzer). Anisotropy was determined using a MFK1A (Agico) coupled with a 3D rotator for automatic determination of magnetic susceptibility anisotropy (AMS). For PM1 the sediments were deposited in high energy environment able to transport both coarse sediments and large fossil remains. Even if the sediments are affected by reworking processes some parts of the channel facies has been identified. Furthermore, PM2 suggest two sedimentation facies and four stages of sedimentation. The first meter corresponds to slackwater facies where sedimentation is produced in a stagnant stationary water regime. The next 240 cm are characterized by a fast current corresponding to channel facies followed by another stage of slackwater facies in a stagnant stationary water regime for 50 cm. Overall, the results suggest that the sediments from PM1 profile were deposited during one or more hydrological episodic events in a high energy stream and for PM2, indicate the transitions from the slackwater facies to the channel facies that can be attributed to successive cave paleofloods.

## New data about the flowstone age in the side entrance of Postojna Cave, Slovenia

### Novi podatki o starosti sige pri stranskem vhodu Postojnske jame, Slovenija

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Rearrangement of the tourist trail in the side passage Biospeleološka Postaja (also known as Rov Starih Podpisov, which is a side entrance to Postojna Cave) in 2001, exposed an over four metres deep sedimentary succession. The profile consists of horizontal flowstone layers intercalated between fine-grained fluvial sediment and gravel deposits that record past environmental changes. This research was focused on determining the flowstone age since the exact chronology of the layers had not been studied yet. The time of the flowstone deposition was determined by radiocarbon and uranium-thorium dating techniques. The results point to three distinctive time periods of flowstone deposition; between 33.2 and 36.8 ka BP, around 103.2 ka BP and 153.1 ka BP. These results also indicate that flowstone deposition has not been limited solely to periods of warmer climate, which suggests that environmental conditions during glacial periods in south-western Slovenia were able to support flowstone deposition.

## Karst processes and features in Slovenia and Tennessee; a comparison with the focus on karst depressions

### Procesi in oblike v krasu v Sloveniji in Tennesseeju; primerjava s poudarkom na kraških depresijah

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Distinctive surface and subsurface karst features (e.g. dolines, collapse dolines, caves) are formed on carbonate rocks that build more than half of the territories of Slovenia and the state of Tennessee in United States of America. These are also the countries with the highest density of karst formations and caves in the world (e.g. in Slovenia there are more than 13,000 registered caves on an area of about 10,000 km$^2$, and in Tennessee more than 10,000 caves on an area of about 60,000 km$^2$). A relatively quick drainage of precipitations through the vadose zone to the karst aquifer is characteristic for karst regions in both countries. These karst aquifers are of regional importance because they collect water from several 100 km$^2$. The karst underground is also a sediment trap that is being washed into the subterranean system through numerous cracks and voids. In both countries the karst depressions are the most prominent features on the surface (i.e. dolines, collapse dolines). However, the predominantly soilless and waterless karst areas in Slovenia are characterised by solution dolines (e.g. of polygenetic origin), whereas the dolines in Tennessee are formed mostly by vertical evacuation of the top sediment covering the karst rocks (i.e. suffosion doline). Also, differences can be observed in formation of larger depressions. In Slovenia it is common that above major subterranean water channels collapse dolines form. In Tennessee on the other hand, the ground and underground beds gradually sag downwards forming subsidence depressions. Despite these differences, the karst aquifers display comparable characteristics.

## Regional and hydrogeological relations in wider catchment area of South Dalmatia (Croatia) and West Herzegovina (Bosnia and Herzegovina)

### Regionalne in hidrogeološke povezave v prostranih zaledjih Južne Dalmacije (Hrvaška) in Zahodne Hercegovine (Bosna in Hercegovina)

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Since 2013 hydrogeological investigations in South Dalmatia and West Herzegovina are ongoing. Hydrogeological terrain prospection and sampling are made in the area of Imotsko polje and valley of Tihaljina-Trebižat, through Vrgorac area all the way to the final discharge zone from Mandina mlinica, to Baćinska jezera and Prud spring. Investigated hydrogeological system is extremely complicated due to low gradients in the final discharge zone and overlapping catchment areas. One of the principal aims of hydrogeology is to propose a reasonably adequate reconstruction of the groundwater flow field, in space and in time, for a given aquifer (Kiraly 2002). For example, interpretation of the chemical and isotopic composition of groundwater, nearly always would require the knowledge of the regional and/or local groundwater flow systems (Toth 1963).
Several methodologies were applied during research. Research included field mapping, collection of water samples, site-measuring of electroconductivity, temperature and pH, laboratory analyses with accent on sulphates origin that was observed in some locations, simultaneous tracer experiment from two sites. Results of this research gave insight into recharge origin and catchment boundaries. Discretization of hydrogeological system on influential surfaces was made in order to give a description of how this hydrogeological system behaves. Results of this investigation represent a basis for determining the methodology of future research, in particular division and subdivision of catchments within complexed hydrogeological systems.

## Mahony, Tunago and Neyadalin, three neighbouring but contrasted karst hydrogeologic systems in glaciated & permafrozen low plateaus, Northwest territories of Canada: an introduction

### Mahony, Tunago in Neyadalin, trije sosednji a med seboj različni kraški hidrogeološki sistemi na ledeniško preoblikovani in trajno zmrznjeni nizki planoti v Severozahodnem teritoriju, Kanada

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Northwest of Great Bear Lake, NT (Lat. 65–66° N; 157 m a.s.l.) Precambrian Shield rocks are overlain by dolomites (Ordovician) that form a plateau dipping gently west. This experienced the last ("Wisconsinan") glaciation, being divided by a spillway during glacial recession into (i) "Mahony Dome" (south side, ~1000 km$^2$, up to 460 m a.s.l.) and (ii) "Tunago Dome" (north side, ~750 km$^2$, ≤360 m a.s.l.). Both are drained karstically, chiefly to springs in the spillway. Mean annual temperature range is -7 °C to -10 °C, precipitation is 200–350 mm. Permafrost is widespread to continuous, except beneath lakes.
Mahony Dome is a plain with a veneer of cherty till. Its centre is an impoverished muskeg (the world's most extensive *"alvar"*?) draining to sinkholes around the perimeter. Larger, glacier-scoured, depressions display a progression from (i) retaining perennial lakes with seasonal overflow, to (ii) perennial, no overflow; (iii) seasonally shrinking lakes; (iv) fully drained, with big sinkholes. The progression probably correlates with groundwater hydraulic gradients but there have been no dye traces to confirm it.
A small sector of Tunago Dome generally above ~325 m a.s.l. has similar form. Terrain below this elevation is dissected into tabular blocks (very large clints) with muskeg between. Depressions scoured against upstream corners of the clints or at narrowings now function as local sinkholes. This tabular terrain is interpreted as a 'scablands' produced by a sub-glacial mega-flood tearing up a pre-

existing karst pavement, a type noted at a few other places in northern Canada but not at the scale seen here.
Along their western edge, the dolomite plateaus are terminated by the low-angle overthrust of a Devonian *sabkha* mixture of dolomite, anhydrite and gypsum beds. Anhydrite at shallow depths has received groundwater, creating anticlinal hydration ridges up to 250 m high and 800 m wide. These obstruct the scabland drainage trends; lakes up to 300 $km^2$ have formed behind them that are drained underground for distances of 20 km or more. *Neyadalin*, a local First Nations legend, recounts two brothers exploring the longest of them by canoe, passing through giant pike and salmon *en route*!

## Contemporary decantation karren in the Kraków Upland (Poland) – preliminary results of the hydrochemical analysis

### Aktivno rastoče dekantacijske škraplje v Krakovskem višavju – prvi rezultati hidrokemijskih analiz

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The research on contemporary decantation karren is carried out in the southern part of the Kraków Upland (Poland). The karren were detected in the Kraków area and they are developed predominantly on the surface of Palaeozoic limestone (Upper Devonian and Mississippian) and occasionally on the surface of Jurassic (Oxfordian) limestone. Karren are formed on the inclined surface (50°–90°) situated directly below tree trunks, in particular: *Fagus sylvatica*, *Tilia cordata*, *Pinus sylvestris*. They are formed as a long (up to 40 cm), narrow (0.1–1 cm) channels with sharp edges and smooth interior.
The main goal of the research is to explain the origin of the karren. Formation of this type of karren has not been satisfactorily explained yet. Based on the preliminary results two alternative research hypotheses explaining the high aggressiveness of water causing dissolution of carbonate rocks were put forward. As the reasons, they indicate: (i) the impact of physiological processes of trees and (ii) concentration of atmospheric pollution on the tree bark.
To explain the origin of karren formation the hydrochemical analyses of water samples collected under natural conditions are conducted: Furthermore, in the Kraków area, a field experiment is carried out. The dissolution of specially prepared limestone plates distributed under different species of trees is analysed in an analogous way to the studies of the natural sites and the results of the analyses are analogous too. The content of $Ca^{2+}$ in the water flowing down the limestone plate (12.80 mg/L) increases significantly in relation to the content of $Ca^{2+}$ in the rainwater (4.68 mg/L) and water flowing down the tree trunk (5.92 mg/L). There is also an increase in the pH value of water flowing down the limestone plate (pH 5.38) in relation to rainwater (pH 4.80) and water flowing down the trunk (pH 4.11).

## An attempt to characterize aquifer hydrodynamics with modern analytical tools using remote sensing data and on-site monitoring (example of Mt Miroč, Serbia)

### Poskus opredelitve hidrološke dinamike vodonosnika z uporabo sodobnih analitičnih orodij, kot so daljinsko zaznavanje in meritve na terenu (primer planote Miroč, Srbija)

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Karst of Mt Miroč on a relatively small area includes surface and subsurface features and phenomena that can be considered as the most karstified and researched in Serbia. On the northern and western rim of the mountain, there are six out of ten deepest registered caves, including a 303 m deep shaft of the Rakin Ponor. Only the western rim of Mt Miroč provides opportunities to monitor and characterize the aquifer system through series of hydraulically connected caves, since little is known on hydrogeology of the rest of the aquifer. The springs are submerged in the Đerdap Lake of the Danube River, which further limits the aquifer characterization. The purpose of this work was to develop an approach to remotely assess the aquifer hydrodynamics of poorly accessible monitoring locations. The approach bases on satellite meteorological data, modern analytical tools and algorithms for hydrograph interpretation. Therefore, the study focuses on allogenic and autogenic recharge of Mt Miroč, on groundwater level in the deepest caves and caves in the immediate vicinity of the submerged springs. A network of on-site data logging devices has been established in four caves with five specific locations and at two surface locations. Monitoring includes groundwater level, electrical conductivity and temperature logging in the caves of Rakin Ponor, Buronov Ponor, Bele Vode and Pećina u Živanovom Potoku, drip water counter, water electrical conductivity and temperature monitoring of the vadose zone in the cave of Buronov Ponor, and rain gauge logging in the village of Kopana Glavica. Data of the Danube River level from the automatic hydrological station in Golubac of the Republic Hydrometeorological Service of Serbia have been collected also. Temporal resolution of the monitoring is 30 minutes. In order to spatially distribute effective infiltration, remotely sensed data of rainfall and evapotranspiration with the same temporal resolution have been collected. An analysis of big spatio-temporal data collections that represent an input-travel-output of a karst aquifer system and correlation to specific input events (rainfall) has been done using modern tools of space-time analytics, such as space-time cubes. Furthermore, machine learning algorithms have been used to determine input events that correspond to groundwater flood waves. The results will have important applications in the understanding recharge-discharge dynamics of karst aquifers with limited monitoring possibilities. Furthermore, the developed approach will mean a significant improvement in the use of remote sensing data for inference about the hydrodynamics of karst aquifers.

## Contribution to understanding some hydrogeological relationships in Dinaric Karst

### Prispevek k razumevanju nekaterih hidrogeoloških povezav v Dinarskem krasu

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Beside lithostratigraphic and tectonic conditions, hydrogeological conditions are dominant factor in speleogenesis of all caves in Dinaric Karst. Remarkable examples of hydrogeological complexity of this area have been found in some caves. More precisely occurrences of bifurcation and high difference between groundwater levels. Many groundwater flows located in the vicinity of local river watersheds have been discovered in the Inner Karst area (Kordun). The depth of karstification in this area is estimated to be between 200 and 450 m and the deepest vertical caves explored are about -

150 m deep. „Jama pod Debelom glavom“ cave is the perfect example of this occurrence. One underground water flow of the cave belongs to Korana river catchment and the other, located just a few meters away, belongs to Glina river catchment. In the Outer Karst area, where the depth of karstification is estimated to be between 1500 and 2500 m „Jama kod Pavlinovica“ provides an information about water level fluctuation with minimum difference of 236 m. During the hydrogeological survey in 1976 speleologists have descent the cave several times to the depth of -234 m. No active groundwater flow was found. A few months later, during the rainy season, the water was pouring out from the cave and created a lake with a depth about 2 meters. The cave still hasn't been completely explored. The main reason being the owners on the land who use the cave as a sewage drain for their household located just a dozen meters from the cave. In the Middle Karst area, where the depth of karstification is estimated to be between 500 and 1200 m examples of sudden demarcations between Adriatic and Black Sea watersheds were discovered. During the construction of highway A6 (Rijeka – Zagreb) near Lokve in tunnel „Sleme“ several deep caverns belonging to Adriatic watershed were discovered. Just a few meters away in the caverns in front of north-east tunnel entrance a Black Sea watershed was discovered.
These examples show complexity of geological relationships caused by impermeable beds within the karstified limestones. Tectonics caused sudden changes of permeability which caused the changes in underground water flows.

## Improving pumping test interpretation in karst aquifer by diagnostic plot method
## Izboljšana interpretacija črpalnih poskusov v kraškem vodonosniku z metodo diagnostičnega grafikona

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Study of groundwater resources using pumping test started with Theis solution. It allows estimating the hydraulic parameters of porous aquifers such as transmissivity and storage coefficient from the water drawdown. Various methods exist to interpret well-test for different boundary conditions in porous or fractured aquifers. Assumptions are still needed to apply the Theis solution and its derivatives to karst aquifers. The diagnostic plot method is a method to assist hydrogeologist to interpret the pumping test. It appears to be useful to identify flow regime and discriminate conduit and matrix flows in karstic aquifers.
This study aims to carry out pumping test and apply diagnostic plot method in two geological settings to improve the hydrogeological understanding of karst aquifer. We also discuss how the diagnostic plot method enhances the classical pumping test interpretation.
This study concerns the carbonate aquifer of the Huveaune watershed near Marseille city in southern France, including the recharge area of the main regional spring Port-Miou. We use a database of pumping tests performed in two geological contexts: an alluvial confined aquifer with channels and a carbonate aquifer located in the surrounding of a large polje showing the karst evolution of the local environment. Results will open perspectives for groundwater management for water supply in this Mediterranean region.

## The Châtaigniers cave (Ardèche, France): an indicator of Pleistocene variations and Combe d'Arc meander shortcut

### Jama Châtaigniers (Ardèche, Francija): pokazatelj nihanj v pleistocenu, ki se odraža kot bližnjica meandra Combe d'Arc

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The Pont d'Arc, is a natural bridge that crosses the Ardèche River about 30 meters above the water and shortcuts an abandoned meander: The Combe d'Arc meander. It is one of the main geomorphological objects of the Ardèche canyon. The processes that have led to the Pont d'Arc shortcut are still poorly constrained. A new approach is proposed here by the studying of the caves next to the Arch and the abandoned meander as environmental archives that may have registered the Pont d'Arc formation. How did the river and the endokarst interacted during the river incision and the shortcutting process? The Châtaigniers cave is located inside the abandoned meander. Both the cave and the Pont d'Arc shortcut develop between 70 and 100 m a.s.l. The study of the morphologies and the deposits inside the Châtaigniers cave can bring new information on the meander shortcut. A 3D model containing the Châtaigniers cave, the Pont d'Arc shortcut and the abandoned meander was created for the purpose of an accurate geomorphological mapping. That cartographic process was supplied by high resolution topographic model in order to better understand the links between the Ardèche River base level morphologies (limestone water tables, alluvial shingle deposits) and the endokarstic morphologies (which are visible inside the Châtaigniers cave and also in the Pont d'Arc shortcut itself).

## Modelling groundwater-surface water interactions in lowland karst (Ireland)

### Modeliranje interakcije podzemne in površinske vode v nizkem krasu (Irska)

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A distinctive feature of lowland karst groundwater catchments located in the west of Ireland is the considerable degree of interaction between surface and groundwater; streams frequently disappear underground and then reappear again in surface reaches or as ephemeral lakes within glacially formed depressions, known locally as "turloughs". The associated seasonal inundation cycles has led to the development of unique habitat and linked ecology within the turloughs. However, in recent years there has also been some extreme groundwater flooding events following exceptional periods of rainfall, where inundation has reached levels way beyond the more usual upper seasonal boundaries, causing considerable damage and disruption. This paper describes two different approaches to modelling such groundwater-surface water interactions: a semi-distributed 1D/2D pipe network model; and a simpler transfer function model.
The modelling has been focussed on a 500 km$^2$ catchment which receives allogenic recharge via rivers from adjacent mountains and autogenic recharge directly onto the limestone, all draining to an intertidal spring. In the semi-distributed 1D/2D pipe network modelling approach, karst conduits are represented as pipes with links to a 2D mesh generated from high accuracy LiDAR data. The model was calibrated using historical stage data from several turloughs, as well as aerial photography from recent flood events. The model is being used to assess different groundwater flood mitigation options to protect properties and minimise disruption, whilst minimising impacts on the catchment ecohydrology.

The computationally simpler transfer function modelling approach links the main input (rainfall) and boundary conditions (tidal movement) to net surface flood volumes. Promising results have been made using machine learning techniques such as Support Vector Regression and Artificial Neural Networks to simulate the rainfall/flooding behaviour of the systems. This model is being developed to act as an early warning system of flooding in the catchment linked to real-time telemetric data.

## A potential of user related data in development of integral approach towards flood related spatial planning

### Potencial uporabniških podatkov pri razvoju integralnega pristopa pri prostorskem načrtovanju na poplavnem območju

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The paper addresses the notion of user-related issues in the context of flood sustainable spatial planning. It considers the co-evolution of natural and social systems, where understanding changes in one requires understanding of changes in the other, rather than treating them separately. This is reflected in the development of the conceptual model for integral system of flood sustainable planning and represents a powerful base and determination for setting up user-centred module as one of the components of the model. To understand environmental problems and help design effective policies, it is essential to understand the underlying human drivers. By introducing daily routine analysis of the selected user-profile, backgrounded by the method of behaviour mapping it addresses small – but important – data in the context of usually big-data related analysis of high-water modelling, and by this aims to bring the dynamics of everyday living into the system of flood sustainable planning. This user-centred module is developed and tested in the studied area of Planinsko Polje, typical karst overflow polje that is frequently flooded. This novel approach addressing people's life and their interactions with space opens new perspectives on floods related issues and can act as an alternative or complement to standards and conditions in spatial planning measures and processes.
The research was conducted in the framework of the projects J5-7178 Integral system of flood sustainable spatial planning financially supported by the Slovenian Research Agency.

## A retrospective look at the first dye tracing study for karst-related forest management purposes in British Columbia (Canada)

### Vpogled v prvi sledilni poskus, ki je bil opravljen za potrebe upravljanja z gozdom na kraškem območju Britanske Kolumbije, Kanada

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Northern Vancouver Island's Glory 'Ole Cave/Karst Management Area (GCMA) contains coastal temperate rainforest karst resources of high relative value. Two caves in the 432-ha management area were Canada's fifth and sixth deepest and one sixth longest in 1986. Today, one cave is the fourth deepest and tenth longest. The mapped length of the known hydrogeologically connected caves in the GCMA now surpasses 20 km, making the aggregate cave system among the longest documented in Canada. Many of the karst resource values were legally established for protection from forestry activities in 2007.
The significance of the karst resources in the GCMA prompted the Province to commission a dye tracing study for the GCMA in 1998. The results were intended to support the development of

strategies to meet government's karst management goals and objectives at the catchment level. No similar comprehensive dye tracing studies have ever been conducted anywhere in British Columbia.
In retrospect, the results of the GCMA dye tracing study were apparently never used as intended to inform landscape-level planning for karst. Instead, the GCMA continued to be subjected to forestry activities (mostly roadbuilding and timber harvesting). Today, only 3.91 % of the GCMA and 24.1 % of the contributing allogenic catchment areas remain undisturbed. These amounts contract to 0.69 % and 9.11 % respectively when an 80-m spatial buffer is applied to account for harvest-related edge effects such as tree windthrow.
Landscape-level protocols with an emphasis on allogenic catchment areas and potential karst system impacts must be developed and integrated into the BC government monitoring program for effectiveness and cumulative effects for karst at the cutblock scale, which has been under development since 2003. The program should be adequately funded, aim to identify the causal factors for the failures to implement total catchment karst management, and directly involve karst specialists in its design.

## Impossible karstification: the Bärenschacht saga (continued)
## Nemogoče zakrasevanje: primer jame Bärenschacht (nadaljevanje sage)

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Bärenschacht (Bear's shaft) is the downstream link between the famous Reseau Siebenhengste-Hohgant and the spring area at Lake Thun (BE, Switzerland). Observations in Bärenschacht, today with almost 83 km (-946 m) one of the large cave systems in Europe, led to a new speleogenetic model (Häuselmann *et al*. 2003) and to the insight that cave systems may cross marly layers. Actual speleological research (February 2019) permitted to cross a fault with a displacement of around 1 km and to enter marnocalcareous schists which are considered impermeable. The passage found presents a small river, which flows below the catchment area of the neighbouring St. Beatus cave. The presentation indicates possible catchment areas of that river and discusses problems in mapping superimposed catchment areas.

## Geomorphologic presentation of Iraquara karstic basin - Municipio de Iraquara Bahia - Brasil
## Geomorfološka predstavitev kraške uravnave Iraquara - Municipio de Iraquara Bahia - Brazilija

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The Iraquara karst is located in the centre of the Bahia state, in South Sertão. This semi-arid area is covered with a catinga type of vegetation and can be defined as a karstic basin which is lined with quartzite and arenite massifs. The precambrian limestone in the region which is studied, constitutes a subhorizontal area with altitudes going from 650 to 750 m a.s.l.. The surface we are dealing with is about 800 km$^2$, and part of it is covered with clayey detritic rock. In some areas we can see lapiaz tables which have often collapsed. The position of the karstic phenomenon on the surface (closed valleys, sinkhole lapies) as well as endokarstic phenomena show a conditioning directly in connection with the litho-structural context of the Irece synclinal. A large concentration of sink holes (several hundreds) and three closed valleys make a remarkable complex of karstic depression. In the downstream part these last ones are ended by large cavities like the Lapa Doce system (look at the poster) set by the Agua de Rega closed valleys. These valleys have temporarily slid in a semi-arid

climatic context for some 15,000 years. They have created numerous subhorizontal underground complexes which re-emerge at different places as far as several kilometres south east of the Rio Santo Antonio hydrographic basin. A digging, an aggradation and an incision have been noticed in the paleo drainage. This has happened for a long time according to the dimensions of the galleries and the power of the alluvial deposits which have been noticed.
The organisation and the morphology of the galleries can be interpreted according to the structural and lithologic context, allowing the morphogenesis of labyrinths, the morphogenesis of auto-captures and of fracture intensity, and the morphogenesis of all kinds of galleries you can imagine. The vast and deep flooded karst in the Iraquara basin expands around 60–120 m in relation with the epikarst level. This karstic aquifer is an important water reserve in South Sertão.

## Natural archives of the Iraquara karst: A wide variety of indicators for karstology
### Naravni arhiv krasa Iraquara: velika raznolikost indikatorjev zakrasevanja

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For a scientist, natural archives which are trapped in karstic areas represent the memory bank of the construction stages of underground networks as well as the memory of the evolution of a valley directly related to its karst. In order to be able to rely on these precious indicators, they have to be there and on the other hand they have to be in excellent condition. The Iraquara karst which is located in the Bahia state in Brazil, combines both conditions. Actually a wide variety of natural archives, which are in exceptional condition, can be seen in this area. These have registered the mega pipe morphogenic evolution for over 2 million years, with the alluvial deposit aggradation which has been observed and studied in the Lapa Doce system. The impressive size of the galleries does not match the hydrographic regime which feeds the karst now. The recent climatic evolution (approximately 15,000 years) corresponds to a semi-arid climate with long dry spells. This climatic change was confirm by the extinct biological indicators such as the soft water bivalves seen in the Lapa Doce network alluvium, as well as the numerous giant sloth skeletons found in the different cavities in the area. According to the specialists these two species must have lived during a colder and rainy time. The visible flow in these networks is now caused by the sparse rain which seeps into the karst. Lastly, several dozens of collapsing sink holes, which can be hectometric, make the opening to underground galleries. Nowadays these spectacular collapses maintain gravity deposits as well as erosion morphologies which allow us to date these phenomena. In a way this indicates the beginning of the endokarst destruction, as well as a primary stage which goes from the karst to the paleokarst. This poster tries to describe these main natural archives which evidently represents a potential for scientific research: a treasure for this region.

## Karstic features analysis in virtual reality environment
### Analiza kraških značilnosti v okolju navidezne resničnosti

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The use of remote sensing techniques in geomorphology, such as the Shuttle Radar Topography Mission (SRTM), has changed the way we used to obtained elevation models in the past. Nowadays,

is the use of Unmanned Aerial Vehicles (UAVs) that has been increasing due to the use of photogrammetric techniques that are changing how we acquire 3D and elevation models. This digital approach combined with the new computational systems developed by both universities and private companies (e.g., VRGS, Polyworks, Lime) to handle outcrop collected data, have improved the way earth scientists analyse Virtual Field Environments (VFE) in a desktop setting. As these earlier systems are not available for use outside its respective institution and the commercial versions are expensive for academic purposes, Vizlab's research group has been developing MOSIS, a Virtual Reality (VR) outcrop visualization and interpretation software capable of recreating fieldwork experiences previously only possible while in the field. It allows geoscientists to immersively study digital karstic features in a VR environment and integrate data and analysis. With an extensive interpretation and measurement toolset, it allows the study between fracture systems, sedimentary bedding, and fluvial processes in different karst land formations. It also enables the measurement of karst carbonate fractures enlarged by dissolution, as vertical fluid conduits, dissolution along horizontal layers, and path-ways of water/oil flow. The enlargement of conduits contributes to the collapse of blocks into sink-holes and expansion of caves during different degrees of karstification. That can be easily measured by changing the virtual field scale of work in VR at any time using teleportation and scale tools. Besides of bringing users to the notion of being physically present in the field, it is a powerful and low-cost solution based on a disruptive technology designed to handle the Virtual Outcrop Models (VOM) in an immersive VR setup.

## Rock comets and karstic mushrooms, Patagonia archipelago, Chile
### "Skalni kometi" in "kraške gobe" na otočju Patagonije, Čile

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Rock comets and karstic mushrooms are singular forms that develop in karren landforms. These were discovered during the Ultima Patagonia expeditions on Madre de Dios Archipelago, Chile. The formation of these specific forms begins with the deposition of allogenous decimetric to metric erratic blocks during the last glacial retreat. These impervious blocks preserved the underlying limestones from dissolution leading to the erection of these spectacular features. This process is made possible due to the extreme subpolar oceanic weather conditions (annual rainfall: 8–10 m/year, prevailing westerly winds, no frost). As these features are specific to this environment, "rock comets" refers to block protecting a limestone tail, and "karstic mushrooms" refers often to a larger block remaining on a pedestal.

In order to study these spectacular features, several 3D photogrammetric surveys were conducted (drone and camera) and anemometers were installed on the field during the Ultima Patagonia 2019 expedition. The aim of these surveys and monitoring is to analyse and to reproduce the control of climatic conditions (mainly rainfalls and winds) on the genesis and on the morphology of these features by applying 3D simulations. The final aim of this work is to better understand the karst of Patagonia by providing one of the scientific aspects background to promote the island of Madre de Dios as a potential site for the UNESCO World Heritage list.

## Quantitative analysis of the hydrogeological research for engineering practice in karst environment

### Kvantitativna analiza hidroloških raziskav za inženirska dela v kraškem okolju

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Karst hydrogeological system (KHS) is characterized by high heterogeneity and spatial variability of hydrogeological parameters. Therefore, researchers are often faced with numerous uncertainties regarding the internal structure as well boundary conditions of the system, whether the researches are dealing with water-supply problems or with constructions (dam and tunnels) built in karst. Understanding of relations between the flow systems (through channels and rock matrix, deep and shallow, epikarstic and saturated zone), represents a key factor for the characterization of the system, establishing the conceptual model and eventually the application of the proper technical solution. The quantitative analysis of the results obtained by hydrogeological exploration has been presented on several examples on the Serbian karst.

Initial analysis for water-supply represents is very important, when extensively research has not yet begun. In such circumstances, the regime analysis of the karst spring and the boreholes represents the only window through is possible to obtain insight into the functioning and elements of the KHS. By establishing the recharge-discharge model in the natural (undisturbed) condition it is possible to analyse further scenarios of active groundwater management and facilitate the research focus towards to groundwater tapping structure. Equally, as in the initial research, this analysis should also be applied in later stages of research and monitoring of the exploitation process.

With respect to constructions such as dams built in karst, researches are mostly focused on the functioning of the hydraulic barrier, and water losses determination. Various research methods are applied, along with the detailed monitoring program. Analysis of the long-term data of the water table can give a general insight about status of the hydraulic barrier, but detailed and short-term data enables to focus on water losses from the specific zones of the hydraulic barrier.

Regarding hydrogeological research of the water-conveyance tunnel in karst terrain, this not only concerns the waterproofing of the tunnel, but also the loading on tunnel lining. The operation of a pressure tunnel is closely related to the rock mass and state of the groundwater and therefore the quantitative analysis is essential. Specificity of this research and quantitative analysis are related to the operational function of the pressure tunnels. During the period of the fully operated tunnel, researches are mainly focused on the water table monitoring at the piezometers nearby tunnel axis and the water control gate. During the period of tunnel inspection, researches are more detailed and focused on the internal tunnel zone enabling to point out hydraulically critical points inside the tunnel.

## Interpretation and modelling of karst groundwater quality

### Interpretacija in modeliranje kakovosti podzemne vode

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In this study, the factor analysis techniques are applied to KARST areas groundwater quality data sets obtained from the different sites. The data obtained were standardized and subjected to Factor extraction to simplifying its interpretation and to define the parameters responsible for the main variability in water quality. The objective is to evaluate the mutual correlations among the various water quality parameters to reveal the primary factors that affect reservoir water quality, and the differences among the various water quality parameters. The factor analysis resulted in three factors explaining more than 60 % of the total variation in groundwater quality data set. The first factor indicates the variation in water quality is due to anthropogenic sources and second factor shows

variation in water quality due to organic sources that are taking place in the system. Finally, the results of factor analysis reflect a good look on the water quality monitoring and interpretation of the groundwater. Multivariate statistical techniques are potential tools and provide greater precision for identifying contaminant parameters linkages with groundwater chemistry in the area.

## Hydrological monitoring in an Alpine vadose shaft to estimate the storage capacity of the epikarst, Hochschwab (Austria)

### Hidrološki monitoring alpskega vadoznega brezna za izračun skladiščene kapacitete v epikrasu, Hochschwab (Avstrija)

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The Hochschwab karst massif is located 80 km southwest of Vienna in the northeast of Styria. The Kläfferspring as the largest spring in the north of the Hochschwab massif is an important source of drinking water for the city Vienna. Therefore the knowledge and research of the properties and vulnerability of the karstic aquifer is of importance. The study area is the Furtowischaft, which is located in the west of the catchment area of the Kläffersprings. The cave opens at 1785 m a.s.l. in the Polsterkar in a steep slope that partly shows a grassy soil cover. Predominantly hydrological active vadose canyon shaft series are explored down to -712 m and cave exploration is still in progress. The lithology is Middle Triassic Wetterstein limestone and the cave is mainly fault controlled. In order to quantify the water storage in the epikarst, a weir (Thomson-weir) was installed in a small canyon at 100 m below the entrance. Since 2016, electrical conductivity (EC), temperature (T) and the water level have been logged every 10 minutes. The mean discharge at the weir is 0.3 l/s with a variation between 0.003 l/s and 17 l/s. The mean T is 2.6 °C and the mean EC is 158 µS/cm. So far, two observations could be interpreted with a water storage in the epikarst: (1) Reactions of T and EC after the increase of discharge vary between 10 min and 5 h. (2) During summer rain events, EC increases (after a short decrease) and remains at an elevated level for longer time. Salt tracer experiments, hydrograph analysis, and numerical modelling shall describe water flow and storage in the unsaturated vadose zone.

## Environment evolutions and anthropic impact records in deposits and forms in the Hautecourt Cave (Ain, France)

### Informacije o razvoju okolja in antropogenih vplivih v jamskih oblikah in sedimentih v jami Hautecourt (Ain, Francija)

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Speleothem records are relevant tools to follow past and late evolutions of karstic systems. The Hautecourt Cave (Ain, France) and its Nature Reserve are studied here because of their dual interest: historical data (from the 19$^{th}$ century to nowadays) provide information about touristic occurrences onto the cave and landscape changes above the cave. This knowledge allows us to test the relevance of stalagmitic data by comparing the two results (natural and historic). The first purpose of this study is to determine different steps of the formation of the subterranean karst volume by studying three-dimensional geomorphology through lasergrammetric analysis. This step brings essential knowledge for understanding the speleogenic history of the cave and sampling speleothems for datations

(U/Th), laminar analysis and trace elements determination. Two active concretions shows dark laminaes which could correspond to touristic occurrences onto the cave during the 19th and the 20th century. This current research aims at distinguishing what is relevant to the ancient tourist practices from what is relevant to the land use changes above. And so, by combining the geomorphological study and the speleothem analysis, this research brings new knowledge for understanding the sensibility and the resilience of karstic environments to human behaviours and land use evolutions.

## Hydraulic conductivity and effective porosity of karst, measurements along new railway line Divača-Koper

### Hidravlična povezanost in efektivna poroznost v krasu; meritve vzdolž odseka novega odseka železnice Divača-Koper

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Large scale construction projects very often demand exact understanding of hydrogeological conditions. In karst terrains however the prediction of hydrodynamic conditions is very challenging due to variable nature of hydraulic properties. Karstic rocks formations are known by their high spatial variability of hydraulic conductivity and porosity, both on local and regional scale. Values of hydraulic conductivity coefficients for karstic rocks in literature varies within the range of $1 \times 10^{-8}$ m/s to $5 \times 10^{-2}$ m/s (Struckmeier *et al.* 1995) while Freeze and Cherry (1979) indicated hydraulic conductivity for karst limestone higher than $2 \times 10^{-6}$ m/s and for non-karstic limestone to minimum 7 x 10-10 m/s. Still it should be noted that hydraulic conductivity represents a lumped parameter which describes all porosity types in karstic aquifers, including conduits and karst channel. Brenčič (1996) published reviewed literature data concerning effective porosity of karst and carbonate rocks and found out that the values ranging between 0.1 to 25 %. Since the values of hydraulic properties varies almost along all the variable range an intensive effort must be taken into account in order to properly define spatially relevant values, considering underestimations or overestimations can have drastic influence on feasibility of construction or even more, the environmental impacts.
In Slovenia a new railway line is planned and will connect mainland to the coast. Track line which is currently at the design stage will run over the Karst Plateau (Classical Karst), thought two tunnels each of length up to 6.4 km and depth up to 0.37 km. An important part of design stage was focused on geological, hydrogeological, karstological and geotechnical investigations. Hydrogeological investigations included mapping, drilling, slug tests, borehole logging, piezometric level, spring measurements and geophysics (seismic and georadar).
Effective porosity was 0.3 % (Prestor *et al.* 2003) and regardless video logging open cave along line are in the range up to 2 m wide. Hydraulic conductivity values for karstic carbonate strata along the railway line were interpreted within the range of $1.8 \times 10^{-7}$ m/s to $3 \times 10^{-6}$ m/s, while for fault zones significantly higher values were considered, that is $3 \times 10^{-3}$ m/s. Interpreted length of fault zone was 25 m and average distance between zones was approximately 800 m. In cases of values below $1 \times 10^{-8}$ m/s performance and interpretation was more difficult, since slug tests represents robust field method. Moreover, the results showed that from regional scale view the investigated karstic massive can be interpreted with medium hydraulic permeability or even semi-permeable formations and low porosity rocks that leads to low or medium productive aquifers with high vulnerability and are significantly affected by precipitation. However, also cavernous and highly fractured zones with concentrated permanent groundwater flow must be taken into account, because they have high production potential and might represent drainage zones, which are important for water supply and have also high vulnerability.

## Impact of soil hydrology on the hydrological recharge of karst regions – A model approach

### Vpliv hidroloških značilnosti tal na hidrološko napajanje kraških območij – analiza z modeliranjem

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Precipitation is a major natural control on the amount of karst groundwater resources. However, not all amount of precipitation in karst regions results in aquifer recharge, since evapotranspiration uses significant hydrological resources. We have developed a soil model that quantifies the recharge at different sites in Slovenia and Croatia. To characterize the regional climate variability, the selected locations have different thermal regimes and hydrological balances across the Dinarides. The implemented model assumes that actual evapotranspiration results from the potential evapotranspiration and the available soil water content. The same hydrological soil characteristics were assumed for all studied locations to isolate the impact of climate on the hydrological recharge. The input data to run the model at each site are the monthly values of precipitation and temperature, and the values of the field capacity and initial soil water content have to be specified. For each site, the model was run for a period of 15 years, from 1975 to 1989, when the global warming had still limited impact on the region. The model quantifies the amount of rain water that finally reaches the aquifer. In sites with a clear positive hydrological balance more than 50 % of precipitation turns into hydrological recharge. However, in sites with a clear negative water balance only between 20 and 25 % of precipitation turns into hydrological recharge. The model highlights how vulnerable are the groundwater resources in most Mediterranean karst regions to drought or rise in temperatures. In the context of the ongoing climate change, the model shows that a warming of 2ºC results in higher actual evapotranspiration rates and decreases on the hydrological recharge by 15–20 % in Mediterranean sites and by 30 % in sites with a continental climate. This model also forecasts the karst groundwater hydrological recharge as a result of different scenarios of climate change.

## Decreasing the unpredictability of karst aquifers – preliminary results of speleological and hydrological research in the Učka cave system, Croatia

### Zmanjševanje nepredvidljivosti kraških vodonosnikov – prvi rezultati speleoloških in hidroloških raziskav v jamskem sistemu Učka, Hrvaška

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Comprehensive knowledge about the structure and functioning of a particular karst aquifer requires multiple research approaches. Herein we report preliminary results of a hydrological monitoring of the cave stream that has been exploited as a water supply for almost 40 years, but where recent speleological explorations revealed a vast extension of the cave spaces and opened possibilities for finding additional water sources.

During the construction of a 5 km long "Učka Tunnel" in 1977, a cave was breached releasing high quantities of flowing groundwater. Conclusions of the first geological investigations were unambiguous: the cave is formed at the contact of highly fractured limestone rocks that overthrust younger impermeable flysch deposits, thus forming a dammed aquifer above 500 m a.s.l. fed only by autogenic recharge. Soon after, a water catchment facility inside the tunnel was built, which today comprises an invaluable water source for the city of Opatija and wider area, especially during summer high season. More than 30 years later, curiosity led speleologists to follow the cave airflow

on the surface above the tunnel through very narrow vadose zone eventually reaching vast cave chambers where a new water stream was found. Dye tracing proved a connection to the known tunnel cave downstream. Finally, in 2018 cave divers connected both of the caves into a single cave system "Kaverna u tunelu Učka – Zračak nade 2".
Under the scope of a 2018–2019 project, a hydrological and microclimate monitoring was established by setting water pressure/temperature, SEC and air temperature data loggers throughout the cave system. Combined speleological and hydrological studies so far yielded significant results: (1) Učka cave system with 4.1 km in length and 427 m depth is currently the longest and the deepest cave in the Kvarner region, (2) water monitoring showed high variation of discharge (16–538 L/s), first estimates for water balance and dynamic air/water temperature profiles giving clue about microclimate conditions in this ventilated cave system.

## The global warming and its impact on hydrology of Glijun, the main Kanin karst spring

### Spremembe hidrološkega režima Glijuna, glavnega kaninskega izvira, v znamenju vplivov segrevanja ozračja

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The Kanin Glaciokarstic Plateau measures almost 60 km$^2$ and is characterized by numerous abysses, continuing to large interconnected cave systems. The mountain is drained by several karst springs, most important of them being the Glijun and the Boka Springs in the south, the Možnica Spring in the east and the Goriuda Spring in the north. According to few dozen years of observations of the responses of the Glijun Spring to specific weather situations, including occasional and seasonal measurements show the effects of global warming. This is marked by a shift in the outbreak of spring snow melting time from the middle of April to the beginning of the month or earlier, which is due the shortening of the highland winter time. The increasing of temperatures in late winter, at the time of the lowest water level, can be attributed to global warming, too. Summer minimal water temperatures stay more or less the same, however, in late July and August we observe the second minimum, as a result of increasing summer temperatures and faster snow meltdown. Global warming also affects the karst underground cryosphere. Its reduction can be demonstrated with the present easier accessibility of entrances to several abysses, in opposition to sixties, when snow and ice caps were often observed in their upper parts even in August. The most convincing proof of global warming on the southern, Slovenian side of Kanin is the retreat of ice in the G2 Ice Cave. The same applies to the snowfields even in the highest parts of the Kanin Plateau. All this has a decisive influence on karst hydrology, including the availability and quality of water. Water quality depends not only on the changing water source from snow to rain precipitation, but also on the influence of man. Since the 1930s, the Glijun karst spring has been used for hydropower station. Today, it is influenced by tourist activity on the highland karst plateau which is to be extended. The spring is therefore not used for water supply although it has some potential.

## Investigating the role of karst on the spatial variability of catchment water balance and its impact on flood processes

### Vloga krasa pri prostorski spremenljivosti vodne balance v zaledju in njenega vpliva na poplavljanje

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Our study investigates the links between karst hydrogeology and surface hydrology. The aim is to assess to which extend karst can affect water balance, and which hydrological processes are affected. The used methodology is based on catchments water balance at their outlet, including precipitations P, evapotranspiration E, runoff Q, baseflow separation and intercatchment groundwater flows (IGF), combined to a geomorphological characterisation. Geomorphological parameters are drainage density, endorheism intensity and IDPR (Index of Development and Persistency of River networks, quantifying the terrains connectivity to hydrographic network). Annual components of the water balance are calculated from multi-annual time series at a daily time step for medium-sized catchments (from 50 to 500 km²). For each outlet global and intermediate catchments are differentiated (defined as the draining area that feeds a river reach located between two gauging stations). The whole study site (25,000 km²) includes 3 karst zones of various geological settings in France (Cévennes Mountains, Jura Mountains, Normandy) equipped with 120 gauging stations. First, results show that many catchments are "non conservative" (i.e. Q > P or $Q_{upstream} > Q_{downstream}$), and that this behaviour can be linked to supposed karstification associated to carbonate layers. Results also show that such karstification affects both quick and slow flow components, as well as the IGFs. In a second step, we find correlations between those hydrological characteristics and geomorphology, relatively strong depending on the study sites. Weakness in correlations for the karst Jura Mountains could be related to the importance of IGFs, as shown by local artificial tracing tests. Finally, our results highlight the control of catchment hydrology by karst and the specific role of groundwater flows in karst areas during floods. The high percentage of karst basins in the world gives interesting perspectives for hydrological flood indicators mapping linked to karstification.

## Overview of the Bükk karst water monitoring system (NE Hungary)

### Pregled vzpostavljenega sistema za spremljanje kraške vode v hribovju Bükk (SZ Madžarska)

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As a major source for water supply of Miskolc (NE Hungary), the karst aquifers of the Bükk Mountains deserve particular attention. The Bükk Karst Water Monitoring System was established to satisfy this need. This complex monitoring system passed its 25th anniversary two years ago and a vast amount of data and experience have been gathered through its operation. Measured quantities are mainly the precipitation, water levels (heads) and electric conductivity, water, air and soil temperatures. Measurement locations include springs (captured and uncaptured), caves, observation wells, thermal wells.
The karst aquifer system is composed of an upper, cold water regime, and a lower thermal water regime with a larger extent. Karstified limestones outcrops over 200 km², while the surface catchment area of the open karst extends over 230 km². The thermal karst aquifer extends over 4000 km². The water supply of the city and surrounding settlements rely on the upper, more vulnerable

system. Nonetheless the thermal karst water is also used for energetic (district heating) and for bathing purposes or even for residential water supply. Due to the interaction between the two regimes the whole system requires an integrated management.
The initiation of a complex monitoring system was triggered by the increasing demand for water supply during the 1980s. Meanwhile the water demand decreased (at the moment it is around 40,000 $m^3$/day, supplying roughly 75,000 homes), but the importance of a monitoring system is still acknowledged. New challenges exposed by climate change and extreme precipitations are expected to justify its operation in the future.

## Water-rock interaction in Postojna Cave: can we use stable oxygen isotopes as palaeothermometer?

### Interakcija med vodo in skalo v Postojnski jami: uporaba stabilnega izotopa kisika za izračun preteklih temperatur

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Stable oxygen isotopes of carbonate cement such as speleothems and calcrete have been used extensively as palaeothermometers. They have served as a reliable proxy in various occasions, however, each region and geographical setting impose a unique challenge whether their value can truly be incorporated into studies of palaeotemperatures.
The extensive Postojna Cave System is situated at the edge of the town of Postojna in southwestern part of Slovenia at the contact of Mediterranean and continental climate. Despite an apparent temperature variations and air circulation in open passages, the Postojna Cave has a number of more isolated passages such as Pisani Rov with very low ventilation and with a stable temperature of around 8.4 °C where degree of equilibrium conditions during speleothem growth should be at maximum. Previous studies of calibration of a speleothem $\delta^{18}O$ record from Pisani Rov with the regional record of $\delta^{18}O$ composition of precipitation during the last decades demonstrated that the speleothem accurately recorded the variability of the $\delta^{18}O$ values of regional precipitation filtered by the aquifer; they showed that the recorded $\delta^{18}O$ signal of two speleothems is not seasonally biased, and they discarded the existence of kinetic fractionation related to evaporation. The stable isotope laboratory at the University of Melbourne, Australia, was used to analyse stalagmite samples within our study to interpret palaeoclimatic conditions throughout the speleothem-growth timeline within the Postojna Cave. However, the Mediterranean precipitation in Slovenia (Portorož) and continental precipitation in Slovenia (Ljubljana) have a temperature gradient of round 0.19 ‰/°C and 0.29 ‰/°C, respectively (Postojna Cave is situated in the middle of these two stations) – applying the difference in rainfall during a temperature change, and the calcite/water fractionation at the mean annual temperature of the cave (~-0.25‰/°C) illustrates that there could be a net positive as well as a net negative shift of oxygen isotopes of calcite, and in ideal circumstances, the shift would be non-existent and as the temperature gradients of the precipitation and calcite/water fractionation even each other up. The stable oxygen isotopes can therefore not be used as palaeothermometers, instead, their fluctuating values rather reflect moisture variations.

## Collapse dolines in Stockyard Gully National Park, Australia
### Udornice v narodnem parku Stockyard Gully, Avstralija

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Collapse dolines are one of the most prominent surface features in karst landscape and can occur in various types of rocks. The Stockyard Gully Cave System in the southwest part of Western Australia offers an excellent insight into a formation of collapse dolines in cemented Quaternary calcareous dunes which have been subjected to multiphase breakdown sequence. These dunes are termed Tamala Limestone and defined as aeolianite, stretching for more than 1000 km along the southwest Western Australian coast.
The Stockyard Gully Cave System is a fragment of a former uniform cave channel, now separated by collapse dolines and an unroofed cave. There are six major apparent collapse dolines which follow the main course of the subsurface discharge in the southeast to northwest direction towards the Indian Ocean and are clustered at the beginning of the allogenic inflow from siliceous sand plain into the karst aquifer of the Tamala Limestone. All collapse dolines in the research area are strongly influenced by the calcrete layer capping the aeolianites. When the final collapse of the surface calcrete layer occurs, the calcrete layer remains overhung in regards to the underlying rock strata. This is the main difference to other collapse dolines where overhangs are the exceptions. Due to the lithology, mainly expressed as weakly cemented aeolianite on one side and well cemented calcrete layer on the other that influenced the collapse dolines' morphology, we present a 4-stage multiple breakdown sequence of their formation: cave dome, calcrete caprock dome, young collapse doline, and mature collapse doline. The known age of different aeolianite members and cave sediments enabled us to constrain the genesis of mature collapsed dolines between 100 ka and 3 ka, which contrasts with much longer time of collapse doline genesis on classic karst.

## Typology of karst aquifers and recommendations for their management – GeoERA RESOURCE project, CHAKA work package
### Tipologija kraških vodonosnikov in predlogi za upravljanje z njimi – project GeoERA RESOURCE in delovni paket CHAKA

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Karst aquifers represent a widespread groundwater resource in Europe. Classically, due to their high degree of heterogeneity, the understanding of karst aquifers hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterize the karst as a whole entity. Until now, the proposed approach has focused on discharge time series analysis using several types of tools (spectral analysis, recession curve analysis…). During the last decades additional parameters are being monitored (temperature, turbidity, electrical conductivity, etc). They provide promising information about the karst hydrodynamics and vulnerability that should be used in order to propose a new and more complete typology of karst aquifers.

"Resources of groundwater harmonized at cross-border and pan- European scale" (RESOURCE) project is a part of GeoERA (Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe) research programme, which is established and run by a group of 33 national and 15 regional geological survey organisations from Europe. The main objective of the CHAKA (CHAlk and KArst) work package, which is part of the RESOURCE project (http://geoera.eu/projects/resource9/), is to develop a joint methodological framework for characterizing karst aquifer resources with the aim of solving water management issues (quantity and quality).
The approach will be constructed, tested and validated in various geological environments (limestone, chalk, dolomite, covered/barren karst systems) and different hydrogeological datasets (measurements from springs or wells/piezometers, frequent vs. scarce measurement frequency) based on a selection of case studies from the project partnership. The specific objective is to achieve a joint classification typology that should be applicable to a large spectrum of karstic environments, and to associate it to recommendations regarding aquifer management (aquifer protection, monitoring strategies, and exploitation).

## Visual KARSYS – a web service for modelling karst aquifers
### Visual KARSYS – spletno orodje za moderiranje kraških vodonosnikov

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Visual KARSYS is a web service under development and currently available at visualkarsys.isska.ch. Visual KARSYS addresses modellers (hydrogeologists, geologists, private companies, etc.) and end-users (administrations, NGOs, etc.) working for the documentation and/or the management of geology and groundwater resources in karst areas. It makes possible for modellers to setup projects, to entry geological and hydrogeological data and to design geological 3D model via the use of GmLib (developed by BRGM, see Lopez *et al.* 2018) in order to subsequently apply the KARSYS approach (see Jeannin *et al*. 2013). On one side, Visual KARSYS offers an intuitive interface in which modellers are guided through the steps of the approach. On the other side, Visual KARSYS offers a dedicated output page for end-users which displays formatted data and resulting models built by modellers. Editing and reading permissions can be allotted by the project administrator to different users (both modellers and end-users). End users can arrange data and results as they want (form, layout, views, etc.) and different analysis tools are at their disposal (slicer, drawing tool, etc.). They can export different data or print maps. Main developments on Visual KARSYS will end in June 2019. At that time the web service will be available for everyone. Perspectives for potential extensions to Visual KARSYS do exist in the field of karst hydrology (karst conduits generating, flows modelling, etc.) but also in a broader geological field (for instance: volcanic areas, glaciology, etc.).

## Microbiological characterization of moonmilk speleothems from Snežna jama na Raduhi and Košelevka Cave, Slovenia

### Mikrobiološka analiza speleotemov iz jamskega mleka v Snežni jami na Raduhi in Košelevki, Slovenija

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Moonmilk is a collective term for cave deposits characterized by a very porous texture and distinct soft consistency, composed of aggregates of fibrous microcrystalline calcite (FMC). The genesis of FMC remains controversial: some authors attributed its origin to purely physicochemical processes but most research suggests that microbes play an active role in FMC precipitation. However, the role of microorganisms and the mechanism of calcite precipitation remain uncertain, particularly regarding what factors control the fibrous habit of calcite, which is the main intrinsic characteristic of moonmilk. Our study aims to evaluate the possible passive role of organic matter in moonmilk precipitation. We hypothesise that microbial exopolymeric substances (EPS) can influence crystal morphology and composition of distinctive, non-equilibrium crystal forms of FMC.

To evaluate the potential role of microbial communities in EPS production we have performed microbiological analysis of a variety of moonmilk speleothems from two karst caves: Snežna jama na Raduhi and Košelevka. Using sterile syringes we collected 10 cm long cores from veils and moonmilk stalactites to compare microbial activities in the inner and outer parts of the deposits.

Moonmilk was aerobically cultivated at 10 °C and 20 °C on different media. Samples from Košelevka from the outer core layer of moonmilk exhibited the highest biomass, both in terms of total adenosine triphosphate (ATP) concentration, cultivable microbial biomass (6.98×104 Colony-Forming Unit per gram of dry weight (CFU/g DW)), and electron transport system (ETS) activity (0.30 µlO2/ gWW h). Similar trend was in core samples from Snežna jama where higher cultivable biomass from the outer core section (~104 CFU/g DW) was accompanied with higher nitrate concentrations (up to 225 mg/l). A fluffy cottonball macromorphological type of moonmilk in a pool exhibited the highest nitrate (750 mg/l), and cultivable microbial biomass (~105 CFU/g DW). A positive correlation ($p<0.05$) between nitrate and concentration of biomass estimated from cultivation at 10 °C and 20 °C on different media was observed. In Snežna jama the ETS values among samples differed, but still, the outer core section exhibited higher ETS activity. Moonmilk appears to be metabolically active, rich in microbial biomass and nutrients, particularly at the outer layers where calcite deposition actively develops.

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## Remote sensing for monitoring and mapping karst groundwater flooding in the Republic of Ireland
### Uporaba daljinskega zaznavanja za spremljanje in kartiranje poplavljanja podzemne vode na Irskem

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Karst related groundwater flooding represents a significant hazard in many rural communities in Ireland. A series of unprecedented flood events in recent years have reinforced the need to improve our ability to quantify the location and likelihood of flood occurrence. Geological Survey Ireland, in collaboration with Trinity College Dublin and Carlow Institute of Technology, has established a collaborative project to investigate groundwater flooding specifically related to seasonal lakes known as turloughs. There are over 400 recorded turloughs across Ireland, the majority of which located on limestone lowlands. Turloughs can completely dry during summer months but extend to hundreds of hectares during the winter flood season. The practical limitations of establishing and maintaining a network of over 400 turloughs supported the use of remote sensing and GIS techniques to delineate flood extents using passive satellite imagery such as of the ESA Copernicus programme. Measurements at 50 sites for over 18 months were used to calibrate and validate results from satellite data. With limited recorded groundwater flood data, the use of remote sensing data provides historical archives of images to look at past flood conditions to optimise the detection of groundwater and delineate maximum groundwater flood maps. These new data will improve the fundamental hydrological understanding of groundwater flooding in Ireland, enabling key stakeholders to develop appropriate flood mitigation measures and allow for informed flood assessments to be made in future.

## Fluorescent tracers in karst hydrogeology: limitations, new challenges
### Fluorescentna sledila v kraški hidrogeologiji: omejitve, novi izzivi

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Thanks to their powerful color, fluorescent dyes were used very early to trace hydraulic connections in karst media. Their instrumental detection came much later. Fluorometry not only lowered the limits of detection in tracing but also made possible the quantitative approach. By the way, a greater variety of fluorescent tracers could be used (i.e. UV colorless tracers). The detection of fluorescent tracers at exceptionally high levels of dilution is now reached thanks to a combined use of specific spectral dimension gained from samples and high frequency in-situ measurements using automatic field fluorometers. This combined approach has become one of the main criteria to guarantee a reliable identification of breakthroughs at very low concentrations (by opposite to some false positives that could be found earlier).
Today, besides their importance as a fundamental research tool, tracer tests can be mainly applied in three fields: resource characterization at catchment scale, source protection (mainly for drinking water), and pollution assessments. Many other applications are now demanding like mine and quarry dewatering, industrial risks, wastewater treatment etc.
This study makes a review of some advances, limitations, needs and challenges emerging for fluorescent tracers in particular.
These limitations include some unknown behaviours of the tracers, the need to discriminate background, the lack of analytical standardization, or the toxicological and environmental risks due to

the use of these tracers. Training and education is also necessary for young hydrogeologists to make them take right methodological choices in increasingly complex situations.
The main concern of the discussion will however be about how far fluorescent tracing techniques can bring us new insights in some recurrent topics in karst hydrogeology. For instance how far artificial tracers can fill the gap between what we know from the structural approach of karst and what we infer from the monitoring of natural tracers.

## Distribution of dolines in Slovenia defined by LIDAR data sets and machine learning

### Razporeditev vrtač v Sloveniji, analiziranih z uporabo lidarskih podatkov in strojnega učenja

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Dolines are small centric enclosed karst depressions and are the most numerous karst feature Slovenia. Recently LIDAR scanning made the study of doline distribution and morphology possible on the level of whole county.
To catalogue dolines we manually label dolines on a fraction of digital elevation model of Slovenia with a binary mask. We then train 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 DEM of Slovenia. We convert the resulting mask into ESRI Shapefile and manually verify the results. We note that the training and inference is error prone on types of relief that were less common in the training set (e.g. the relatively uncommon collapse dolines). We believe manual verification mitigates most of these errors, so the resulting map is a good basis for the doline study.
Algorithm marked 471,192 dolines. They are present on most of 7,400 km$^2$ of karst areas except the Alps where they were eroded by glaciers or covered by glacial till. Distribution pattern, size and shape of dolines reflect mostly geomorphology and evolution of karst terrains. From the data set some metric properties of basic genetic types of dolines can be extracted.
Most abundant, 470,325 are solution dolines. Average doline is 9 m deep, has a diameter of 42 m and volume of 14,000 m$^3$. Density of dolines on levelled surfaces can be higher than 400 per km$^2$.
We have designated 314 dolines to be of collapse origin. Mean depth of collapse dolines is 49 m, and 20 of them is deeper than 100 m. Mean volume of collapse doline is 1.2 Mm$^3$, with the largest having volume 11.6 Mm$^3$.
Suffosion dolines are forming in alluvial sediments that were deposited on karst, mostly in blind valleys or on poljes. 553 such dolines were located.

## Inland cockpit notch morphology in Kinta Valley, Malaysia and its significance to surface water behaviour

### Oblikovanost celinskih zajed v kokpitih v dolini Kinta, Malezija, in njihov vpliv na obnašanje površinske vode

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Notches in inland vertical limestone surfaces are caused by the sideways dissolution of carbonates by acidic surface water, and are seen as an indicator of surface water levels in the past. In the study area in Gunung Rapat, located in the Kinta Valley, Perak, notches with multiple levels of roofs and floors with heights of up to 24.7 m are preserved on three vertical faces. These notches are believed to have been formed sub-aerially in the cockpit of a remnant karst hill complex that was filled with

ponded water. An episode of deposition has also filled the area with thick tin-bearing alluvial deposits, which were later excavated by miners, leaving an uneven floor throughout the cockpit. Between 49.5 to 60 m from mean sea level, distinct levels with different horizontal depths of the notches reflect different base levels. Slanted roofs indicate a progressive lowering of water level, while abrupt decreases in base levels are marked by sub-horizontal floors. Changes in base level are related to cycles of fluctuation of the supply of water into the cockpit. The distinct morphology of these notches may reflect the lowering of the local base level throughout the long history of their formation, subsequently preserving a long record of local base levels.

## Structural control on water circulation in the Bossea karst system (S Piedmont, Italy)
### Vloga strukture pri toku vode v kraškem sistemu Bossea (J Piedmont, Italija)

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The Bossea cave is in the Ligurian Alps of Southern Piedmont (Italy). It is the only outlet of the Bossea karst system, whose drainage area comprises the middle sections of Corsaglia and Maudagna valleys. Its water feeds Torrente Corsaglia, one of Tanaro River main tributaries. The cave is nearly a kilometre long and can be subdivided in two portions: an upper and a lower one. In the upper portion, the main underground river flows along a canyon carved in a Mesozoic marbles sequence. The lower portion developed along the contact between the Mesozoic meta-carbonate sequence and the underlying Permian meta-volcanic sequence. Large halls and massive gravitational collapses characterize this segment of the cave.
Geological surveys, structural and thin section analyses helped to unravel the speleogenesis and water circulation in the vadose zone above the cave. The surveys within the cave and in the surrounding surface outcrops revealed a complex structural setting caused by the coupling of lithological-mechanical heterogeneities with two major regional left-lateral ESE-WNW strike-slip faults. This led to a disharmonic deformation, accommodated by a detachment surface, between the meta-volcanics and the isoclinally-folded-marbles sequence lying on top of them. Low-angle shear zones, recumbent or drag folds, and small stacks of duplexes localized in the proximity of this detachment. The ductile structures probably formed during the main Alpine deformation phases (Early Oligocene) while secondary brittle structures developed during late deformation events (Pliocene-Pleistocene). The Bossea karst system developed by taking advantage of this setting. The structural surveys revealed also that the preferential pathways for water circulation inside the vadose zone are the folded bedding interfaces in the marbles sequence. Fracture clusters at slipping bed terminations, on the other hand, may provide through-sequence connectivity. Once speleogenesis reached the cataclastic and highly deformed meta-volcanics of the detachment core and damage zones, erosion started, removing large volumes of rocks. The downward erosion of the Permian basement rocks caused gravitational instability and subsequent roof collapses aided by structural control in the damage zone above the detachment surface (slip surfaces in between duplexes or drag folds). This gravitational instability ultimately led to the formation of the giant halls that are characteristic of the Bossea cave.

## Hydrogeochemistry of a complex karst system: the Bossea cave example
### Hidrogeokemija kompleksnega kraškega sistema: primer jame Bossea

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Bossea karst system is located in Southern Piedmont (Italy). Its catchment is comprised between 800 m a.s.l. and 1700 m a.s.l. and drains water from Corsaglia and Maudagna valleys. Infiltrating waters feed an underground river, called Torrente Mora, that flows along the Bossea show cave for more than 1 km, then water resurfaces in the Corsaglia River. The downstream segment of the cave develops along the contact between the underlying low permeability Permian meta-volcanics and the above Mesozoic meta-carbonate sequence. Torrente Mora is also fed by several secondary tributaries that drain the vadose zone. These tributaries can be divided into two types, depending on their discharge: high discharge tributaries (called "polle") representing fracture flow, and low discharge dripsites.
Several secondary tributaries and the main underground river were equipped with monitoring devices that measure water level, electrical conductivity and water temperature. Seasonal water sampling was carried out for analysis of major elements and lanthanides. The chemical analyses of all water samples were performed in the Polytechnic of Turin (DIATI).
High spatial variability and relatively low temporal variability emerged from the chemical analyses of the major components in the secondary tributaries and Torrente Mora. The predominant hydrochemical facies is the Ca-$HCO_3$ one, but each secondary inflow shows a characteristic chemistry, as highlighted by the Mg/Ca, $HCO_3/SO_4$ and (Na+K)/Cl ratios. The vadose inflows that are fed by the fracture network partially developed in the meta-volcanics show the highest alkali to chloride ratio. Calcite and dolomite saturation indexes are well correlated for each sampling site but such correspondence disappears comparing different inflows. Lanthanides contents are also highly variable both spatially and temporally. The REE abundance normalized to the PAAS helped to recognize different flowpaths in relation to the hydrodynamic conditions.

## Research Infrastructures and karst science
### Raziskovalne infrastrukture in krasoslovje

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Data management planning in research became a key practice in today' science. While open science is a growing trend, encouraging scientific research data to be freely accessible, the reliability of such data depends also on the capacity of researchers to conduct a responsible data management of their scientific work.
Recent challenges in environmental research related with climate change effects, biodiversity loss, assessment of geo-resources, and management of geo-hazards need to be assessed in order to measure their current and future trends. The European Research Area started such assessment through activities of Research Infrastructures (RIs) that include major scientific equipment, data resources, e-infrastructures, and communication networks. RIs perform a precise evaluation of the current state of the environment through long-term measurement data in a multidisciplinary framework, and they provide efficient solutions to overcome the above mentioned challenges, respecting FAIR data principles (Findable, Accessible, Interoperable and Reusable).
Karst Research Institute at ZRC SAZU has joined three of the European environmental RIs (EPOS ERIC, LifeWatch ERIC and eLTER) through its national consortia of 14 research institutions.

The institute, as a full partner at the three European environmental RIs has now the opportunity to develop a standardized digital database for karstological data as well as for specific data of the partners in the three consortia, following a careful data management plan. The institute commitment in the European RIs will help the karst science to step forward in current international research requirements.

## Developing karst groundwater flood maps for Ireland
### Izdelava zemljevidov kraških poplav na Irskem

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Identifying and mapping areas vulnerable to flooding is a key step in the management of flood risks. However, the nature of groundwater flooding on the lowland karst limestone plains of Ireland pose significant technical challenges in this respect. These areas are susceptible to groundwater flooding due to the combination of low soil and aquifer storage, high diffusivity and limited surface drainage. Unprecedented flooding during 2015/2016 reinforced the need for a greater understanding of groundwater flooding as a geohazard and improving our ability to quantify the location and likelihood of flood occurrence.
A novel approach was developed to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive. A monitoring network of over 50 sites was established during the winter of 2016/2017 to improve our understanding of groundwater flood regimes and provide baseline model calibration data. A methodology for delineating flood extents and water elevations from multi-temporal Synthetic Aperture Radar (SAR) imagery was developed to provide flood data from the 2015/2016 extreme flood event at gauged and ungauged sites. Maximum flood extents derived from SAR imagery from this event were combined with limited field observations to produce historic groundwater flood maps.
Hydrological models capable of reproducing groundwater flooding time series from antecedent rainfall and soil moisture conditions were developed. Models for viable groundwater flooding locations were calibrated on a combination of observed and SAR hydrographs. Using long-term observational and stochastic meteorological series as input, the models have been used to construct long-term hydrological series suitable for extreme value analysis and the generation of predictive groundwater flood extents and maps.

## Quantification of frost weathering and its influence on cave development
### Količinska opredelitev zmrzalnega preperevanja in njegovega vpliva na razvoj jam

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Although frost weathering caves are rather small they are abundant in Lower Austria: 32 % of all registered caves (6191 by 2018) can be predominantly dedicated to that type. Most of these caves are developed in altitudes between 600 and 900 m a.s.l. A previous field study in two caves showed a strong correlation between frost periods and the amount of breakdown material due to weathering. In winter in both caves, two orders of magnitude more rock mass could be collected than in summer (Oberender & Plan 2015). The rock moisture, which has a major impact on the efficiency of frost weathering, was not measured at that time. To follow up these observations, three caves that developed in different lithologies and altitudes were chosen. Since autumn 2018, in these caves, temperatures of air, soil, and rock are monitored and the amount of break down material is

recorded. Additionally, the rock moisture is indirectly measured by geophysical methods: 1) The electrical resistivity tomography is a direct current technique based on measurements between four electrodes (at two current is injected and at two others the resulting voltage is measured), in order to produce a tomography of the subsurface. 2) The induced polarity method provides information on the conductivity (energy loss) and capacitive (energy storage) properties in the underground. 3) With electromagnetics the conductivity of the substrate is determined. For this measurement, no current is injected, but it is generated contactless by induction. Conductivity as well as capacity varies due to the amount of air, water, and ice filling the rock pores. To set the frame conditions the porosity of the different lithology was measured in the laboratory. The aim of the study is a more detailed understanding of the frost weathering processes: is microgelivation or ice segregation the dominant process of cave development in a certain cave?

## Applicability of automatic recession extraction methods to a large number of karst spring hydrographs

### Uporabnost samodejne ekstracije recesijskih krivulj v primeru velikega števila hidrogramov izvirov

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A large portion of the world's population as well as agriculture and other water-dependent activities depends on groundwater from karst aquifers. The groundwater flow in karst aquifers is characterized by a complex interplay of fast and slow flow processes. Automatic recession analyses on large datasets of hydrographs have been of great value to understand hydrological process variability across different catchments, scales and regions. Event-based recession analysis of karst hydrographs has been used to characterize karst aquifers for a long time but, to our best knowledge, automatic recession analysis has yet not been applied for karst spring characterization. In this study, we evaluate the applicability of automatic recession extraction procedures for analysing the recession characteristics of a large number of karst spring discharge hydrographs. We use an automatic routine that recognizes changes in the semi-logarithmic slopes of the recession to separate conduit and matrix contributions. That way, we fit the already available karst-specific recession models to calculate the master recession coefficients of the conduit and matrix system. We evaluate the performance of the extraction techniques and the fitted karst-specific recession models by comparing the variability among recession coefficients calculated by different models. The outcome will be used to: (1) provide guidelines for automatic recession analysis of karst systems using adapted extraction methods and karst-specific recession models; and (2) infer the comparative importance of conduit and matrix drainage in different catchments.

## Interaction of air and water dynamics in deep caves of Mt. Velebit, Dinaric karst, Croatia

### Interakcija dinamike vode in zraka v globokih jamah Velebita, Dinarski kras, Hrvaška

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Air and water dynamics observed in the deep caves of Northern Velebit Mt. present example of coupling effect of various processes in karst environment. Cave exploration provides unique opportunity to separately observe and study various processes and their interaction directly in the karst underground (in situ). Simplified model of cave air circulation and temperature profile/gradient modified by circulation characteristics is presented. Inward air circulation during cold weather and

absence of significant circulation during hot weather produce significant imbalance in the cave T and surface mean annual T. Lower cave T is manifested by snow and ice accumulation in the parts of the cave affected by chimney effect. Ice melting and accumulating absorbs or releases significant flow of energy. Therefore, ice accumulation acts as an efficient thermal buffer which preserves cave T in the zone of accumulation at 0 °C. In that way cave acts as a cold air trap due to its specific morphology, producing negative thermal anomaly in karst massif. Specific cave climate characteristics can also alter karst groundwater temperature and dynamics. Air dynamics which effectively cools cave atmosphere and produces ice accumulation also cools water flowing through the cave and recharging karst aquifer system. It is possible that cumulative effect of cold air trapping induced by caves morphology has substantial effect on lowering T within karst massifs. Water at karst springs is usually considered to reflect average annual T of its watershed. Presented mechanism can effectively lower groundwater T in comparison to surface T, as can be seen on vadose water flows in the Lukina jama-Trojama cave. Results of the presented study show that air and water circulation characteristics in karst underground can be significantly altered by morphological characteristics of caves.

## Development of an IT platform for flood prevention and mitigation of harmful environmental impact - GDi ensemble FloodSmart

### Razvoj IT platforme za preprečevanje poplav in omilitev škodljivih okoljskih vplivov – GDi napovedovalni model FloodSmart

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GDi d.o.o. and Croatian Geological Survey as a Partner are working on the project implementation – „Development of an IT Platform for Flood Prevention and Mitigation of Harmful Environmental Impact - GDi Ensemble FloodSmart“ (October 2017–March 2020). This project aims to develop a unique system based on Esri ArcGIS platform, whose program solutions will consolidate all relevant decision-making segments in flood risk management and its harmful effects on the environment. The GDi solution developed within this project will integrate Flood Risk Prediction and Flood Protection activities before and after the flood events through a single system, where up-to-date information will be available to all decision makers in real time. European Environment Agency (EEA) reported Europe suffered over 213 major damaging floods between 1998 and 2009 which have caused around 1126 deaths, the displacement of about half a million people and at least €52 billion in insured economic losses. Consequently, the EU Flood Directive has been in force since November 2007 which main purpose is to establish a framework for flood risk assessment and management to reduce the negative consequences of floods on human health, economic activity, cultural heritage and the environment. The outcome of the project will be GIS application organized in modules that combines tools for preparing and acquiring the required data, spatial analysis tools, tools for final design and management of results, and Web Portal with hierarchically organized information, alarm system, and display of results in the form of web GIS operational dashboards and viewers. All modules are integrated into the unique GDi Ensemble FloodSmart platform that will be soon ready for use in the real environment.

## Natural attenuation of pollution in karst – a geochemical, chemical and microbial investigation in the Carpathian Mts., Romania

### Naravno pojemanje onesnaženja na krasu – geokemična, kemična in mikrobiološka raziskava v Karpatih, Romunija

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The nature of host rock and flow characteristics result in a low natural attenuation of pollution along rivers crossing karst terrains. However, more recent studies have suggested that, apart from mechanical and chemical processes, degradation resulting from microbial activity could lead to an overall reduction of pollution. To test this hypothesis, we have investigated five hydrokarst systems (HKS) in NW Romania, by collecting monthly samples of water for three years and analysing their physical, chemical and microbial characteristics. The stable isotopes of oxygen and hydrogen in water were used to assess the sources of water feeding the five HKS and the transfer times from input (ponors) to outflow (caves and springs). Chemical data indicated a slight decrease of pollution from input to outflow. The overall diversity of microorganisms seemed to decrease while the water passes the HKS. Microorganisms are retained underground by filtration through limestone pores, they may adhere to sediment particles, or they may form biofilms on various substrates in the subsurface. Retaining of microbes in subsurface HKS can be of importance for natural attenuation of pollution. On one hand, the water emerging back to surface in springs contains less microorganisms then that that entered underground upstream in ponors. On another hand, the microorganisms retained underground may contribute to biodegradation of pollution, so that the water flowing out of HKS is cleaner.

## Use of Arduino in speleology – development and application of ultrasonic level data logger

### Uporaba Arduina v speleologiji – izdelava in praktična uporaba ultrazvočnega avtomatskega registratorja nivoja

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After testing different Arduino boards for speleological purposes presented at 26th IKS and data logger prototyping in the mid-2018, two equal relatively simple battery-powered non-commercial ultrasonic-based (non-contact) pocket-sized data loggers that measure and record distance were developed. Special emphasis was put on simple construction and code, low energy consumption, low costs, reliability of measurement (precision), and water resistance in humid (100 %) underground environment. Total costs of material that included Arduino Pro Mini 3.3 V microcontroller, HC-SR04+ ultrasonic sensor, Micro SD card module with SD card, DS3231 Real Time Clock, Li-ion 18650 battery (3,000 mAh), protection (plastic case), and jumper wires were calculated to be 15 EUR. Without advanced power efficient software (sleep modes) and extra hardware (EEPROM, MOSFET switch), on average several tens of mA of energy consumption was achieved with Arduino Pro Mini at 3.3 V that is good enough for several days of operation when short sampling interval is preferred (<1 min).
In November 2018, applicability of developed data loggers was tested underground during 3-days-long water injection and 4-days-long dye tracing experiments to confirm hydraulic and actual connection between two different injection points (one of them also location of sewage treatment plant) and stream inside the Kovačeva jama (Blacksmith's Cave). Since stream as well as injected water discharge is small (0.5 L/s) small, mm-scale changes of water level were expected and

frequently used commercial data loggers with pressure sensors were expected and later confirmed to be useless. To get insight into and to increase precision of measurements, vertical distance between water level and sensor was recorded as a sequence of 5 measurements separated by 2 sec each minute. During water injection tests, average standard deviation of 1.4 mm was achieved after minimum and maximum among 5 measured values were omitted (a measure of repeatability); this was good enough to clearly detect 1.3 cm high water rises that confirmed hydraulic connectivity between both injection sites and the stream inside the cave. Even more, due to daily oscillation of drinking water consumption, morning and afternoon 4 mm high peaks from sewage treatment plant were detected. During dye tracing experiment, average standard deviation among 5 measured values without maximum and minimum value was even better (0.77 mm). Again, daily oscillation of water level for about 4 mm was clearly detected. Together with salt dilution discharge measurement and determination of dye concentration, oscillation of water level registered by ultrasonic data logger was used to establish rating (height-discharge) curve and dye recovery rate.
Simple non-commercial cost-effective ultrasonic distance data logger that was adapted to specific needs met requirement of mm-scale measurements of water level oscillation. Similar data logger can be applied elsewhere where similar precision of measured distance between 2 and 400 cm is needed. However, to achieve at least longer lifetime and µA-scale energy consumption, further work has been put into optimisation of the existing device.

## HiddenRisk – a project to understand the impact of human activities on subterranean biodiversity
## HiddenRisk – projekt, posvečen ugotavljanju vpliva človekove dejavnosti na biotsko raznovrstnost v podzemlju

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Subterranean ecosystems are rich in endemic biodiversity with different morpho-physiological adaptations and constitute one of the most poorly known and unprotected natural resources of our planet.
While numerous species live deep in the underground, surprisingly little is known about how subterranean ecosystems are affected by human activities.
Infiltration of contaminants to the subterranean ecosystems is fast, making them excessively vulnerable to impacts of pollution. Despite worldwide recognition of the importance of subterranean ecosystems as the most important sources of freshwater for human consumption and also recognized as critically endangered, initiatives like the EU Water Framework Directive or the Groundwater Directive, stress the need to achieve a good physicochemical status of groundwater, neglecting its endemic biodiversity.
Animal species richness below the ground plays a key role in regulating the whole suite of ecosystem functions directly related to groundwater dependent ecosystems, as springs and rivers. A complete evaluation of the condition of subterranean ecosystems should consider not only abiotic parameters but also their biological components.
Furthermore, the fact that terrestrial subterranean ecosystems are intimately linked with the groundwater cycle is also neglected and scientific information concerning the effect of pollution in these ecosystems is needed for their protection.
The project HiddenRisk aims to understand the impact of anthropogenic activities in subterranean ecosystems, generating a framework for their future ecological and ensuring its sustainability. As far as the subterranean species may be more sensitive to chemical pollutants than surface species, ecological quality criteria based on responses of surface organisms may be insufficient to protect subterranean ecosystems. This project generates valuable information on the sensitiveness of subterranean species from habitats strategically selected to be representative of different climatic,

geographical and impacted conditions, thus contributing to estimate the impacts of pollution on these hidden ecosystems.

## Karst hydrogeology: who, what, why, where, when, & how
### Kraška hidrogeologija: kdo, kaj, zakaj, kje, kdaj in kako

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Karst hydrogeology is the study of the storage and movement of water within the shallow Earth crust in regions composed of carbonate or other soluble rocks. Such study seeks to answer many questions of who, what, why, where, when, & how. The drivers of these systems are gravity, topographic relief, and chemical gradients. The latter two result from tectonic and climatic conditions/pre-conditions, and encompass also biological factors, especially with regard to the generation of acids needed to promote dissolution of pathways through the bedrock. The main differences between karst systems and the more common porous medium (Darcian) groundwater flow systems are the presence of triple permeability (matrix, fracture, and conduit) flow pathways, and the likelihood of very rapid flow paths. Pragmatic (applied) reasons for the study of present-day karst hydrogeology, include apportionment of water rights, evaluation of water quantity, and pollution protection. These are commonly accomplished by tracing (typically via dyes) for groundwater basin delineation, flow path identification, flow velocity determination, as well as groundwater flow modelling. There are also more purely academic reasons to study both present-day and paleo karst hydrogeology, such as understanding the genesis of cave systems, determining rates of landscape evolution, and deciphering past climate conditions. Techniques such as morphological analysis, speleothem/clastic sediment dating, and genetic (reactive) modelling are employed for this. Scientific study of karst flow systems began in the late 1800's including pioneering works by Jovan Cvijić and others in the circum-Adriatic region. Evolution of dye tracing techniques from qualitative to quantitative, along with the development of automated sampling systems and low-detection limit fluorometry, have provided nuanced understanding of thousands of settings across the globe. In-situ sensors with dataloggers and improved modelling, along with increased human exploration of flooded systems by SCUBA provide the next steps in the field.

## ESA CAVES program: astronaut training, testing and operations using speleology as an analogue to space exploration
### Program ESA CAVES: astronavtsko usposabljanje, testiranje in upravljanje s pomočjo speleologije kot ekvivalentom za raziskave vesolja

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Speleology shares several analogies with space exploration and complex operations on other planetary bodies. For the human being, caves are in some way alien and extreme environments compared to the surface. Cave systems can provide many space-relevant conditions such as isolation, deep sense of distance from the surface, stable environment (high $CO_2$ levels, T), lack of diurnal cycles, confinement, minimal privacy, technical challenges, limited equipment and supplies.
Since 2008 the European Space Agency (ESA) has started to study the possibility to use underground environments as a natural platform for astronaut training, investigating all the analogies with space, starting from the International Space Station (ISS) missions. With this purpose in 2011 a new ESA

training program named CAVES “Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills”, was launched, and involved astronauts from Partner Space Agencies.
The main aim of the CAVES program is to create a multidisciplinary and multicultural team exploration mission in a natural underground setting. Location, environment and course content specifically designed by an international team of speleologists and with the support of caving organizations and schools make CAVES a safe space analogue experience, with useful and real outcomes not only for the astronauts but also for the speleological community. These training events recreate situations that are spaceflight analogue in terms of perception of risk, crew composition, isolation, and confinement, but also experience spaceflight-like operations, science, equipment testing, and exploration, in preparation of future planetary endeavours.
The ESA CAVES training course has been recognised by all participant astronauts as a very realistic spaceflight analogue, providing unique multicultural operational team training opportunities, in one of the best space analogue environments available on Earth. In addition, biological and microbiological sampling carried out by astronauts allowed to find three new cave-dwelling species of the genus *Alpioniscus Racovita*, and to discriminate the impact of human beings on cave microbiology.

## Monitoring of environmental parameters in a tourist cave - case study of Upper Barać cave near Rakovica (Dinaric karst, Croatia)

### Spremljanje okoljskih parametrov v turistični jami – primer iz Gornje Baraćeve špilje pri Rakovici (Dinarski kras, Hrvaška)

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With its uniqueness cave tourism attracts wide audience. In order to be able to manage such a system, it is necessary to know its characteristics and to monitor the basic environmental parameters especially when it comes to a location that is so close to the well-known attractions as the Plitvice Lakes National Park.
Upper Barać cave is a tourist cave in Rakovica municipality, about 18 km from the Plitvice Lakes National Park. It is part of a complex of four caves, one of which function as a spring called Baraćevac. The microclimatic parameters observed in Upper Barać cave were air temperature, relative humidity and carbon dioxide concentrations. The results of air temperature and relative humidity show very stable values with no oscillation. Carbon dioxide concentrations have recorded changes associated with the distance from the entrance and the vegetation season. In addition to microclimatic conditions, the following physicochemical parameters of drip water and spring water are monitored: temperature, pH, alkalinity, dissolved oxygen concentration, nitrate and orthophosphate concentration. The results show the impact of the limestone substrate and correspond to stable microclimatic conditions but biogenic and anthropogenic influences. In order to collect additional information from lampenflora samples, 24 diatom species (*Bacillariophyceae*) were determined. Dominant species are aerophilic and cosmopolites. The most frequent is *Diadesmis contenta*. In order to estimate the ecological status of the Baraćevac spring, 29 diatom species were determined. The dominant species were *Achnanthidium minutissimum* and *Cocconeis placentula*. The ecological status was estimated by using Saprobic Index (SIHRIS) and Trophic Diatom Index (TIDRH). Ecological status was estimated as high (oligotrophic to oligo-mesotrophic) in April and as moderate (mesotrophic to meso-eutrophic) in July.

## Tufa deposits sheltered by inland notches as indicators of Quaternary denudation rates
### Lehnjak ohranjen v celinskih zajedah kot kazalnik hitrosti denudacije v kvartarju

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Inland notches are elongated concave-shape indentations that develop on the carbonate rocky cliffs of mountainous zones, down to the desert fringe. These unique features formed as a result of the interaction between specific lithological and climatic controls, emphasizing the importance of environment upon rock decay. Inland notches form because of slight differences (1–15 %) in the porosity of the visor and cavity bed: the cavity bed is more porous, so more likely to erode by exfoliation and dissolution. Thus, the cavity bed retreats at a faster rate compared to the slower subaerial dissolution of the visor bed, until a critical point is reached where the visor collapses. In Israel, inland notches inhabit the same lithostratigraphic units as do large caves. Notches are most common in semi-arid and in Mediterranean climates but mainly in areas with annual rainfall of between 400 mm and 850 mm. In more humid areas (> 900 mm/y) notches are negligible or completely absent, due to the rapid rate of chemical dissolution of carbonate rocks. In the desert fringe (200–300 mm/y), mechanical decay is accelerated and notches exhibit disintegration processes, visor collapse, and rock falls. In the desert area (< 200 mm/y), salt decay replaces the chemical decay, encouraging tafoni formation.
In the Mediterranean zone, tufa stalactites and stalagmites occasionally grow within the cavity of the notch. The Carmel tufa deposits that grew under the notches visors and on the cavity back-wall were dated by U-Th chronology at the Geological Survey of Israel using ion exchange column chemistry and MC-ICP-MS techniques. Six layers from four tufa samples were dated giving ages spanning from 13,636 ± 834 ky to 37,562 ± 2,397 ky, implying that the these notches were formed during the last glacial period, or during the last deglaciation.

## From monitoring to management of karst groundwater resources
### Od spremljanja kraških vodnih virov do njihovega upravljanja

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The characteristics of karst groundwater systems result in specific requirements regarding tools and approaches employed for their monitoring and management. Following a holistic concept, this includes investigations from a quantitative, qualitative, and ecological perspective. The spatial heterogeneity and temporal variability of karst hydrogeology makes the assessment and interpretation of representative basic data a challenging issue. Diverse methodological procedures have been developed so far and are still progressing to tackle these challenges. An overview is given of recent approaches and their application in Switzerland. In this context, the consideration of dynamic water storage in the different karst sub-systems appears one of the bullet points, with respect to both short-term protection and long-term usage. The quantitative availability of karst groundwater resources, in terms of volume and safe yield depending on recharge pattern and storage capacity, is particularly under pressure in periods of dryness and related to expected climate change. Similarly, monitored karst groundwater composition and quality is the result of differing residence time components, and the occurrence of individual substances at karst springs provide distinct information on pollutant sources as well as aquifer characteristics and its natural attenuation potential. The major concern in the management of drinking water supply is the hygienic quality of the resource. Monitoring upon microbiological parameters, and microbial source tracking techniques

respectively, not only serve as indicating fecal pollutions, but may also provide information on the hydrogeological framework. Furthermore, the microbial community forms part of the natural biocenosis, as well as does the stygofauna. Novel parameters are increasingly complementing the conventional monitoring spectrum. The main objective of the management of karst groundwater resources consists of their appropriate protection. Given the system heterogeneity, vulnerability assessment has become state-of-the-art for groundwater protection in karst environments. However, some questions are still under discussion, i.e., how to define and validate vulnerability in a quantitative manner, or how to address differing impact scenarios. Traditional tools, such as tracing tests, may be adapted to these requirements. Despite the awareness of the particularities in the context of groundwater quantity, quality, and ecology, karst features are still not yet routinely implemented in environmental management. A thorough data assessment and deepened understanding of karst hydrogeology and related processes is the prerequisite for further progress in this direction.

## A 'Field Lab' on the forested karst of Quadra Island, British Columbia, Canada

### Terenski laboratorij v gozdnatem krasu otoka Quadra, Britanska Kolumbija, Kanada

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A permanent water monitoring station has recently been installed at a series of karst springs on Quadra Island that are used by a household for domestic water and micro-hydroelectric power generation. Vancouver Island University students have been using the site to gain practical experience in karst and to complete research projects. Geological mapping during yearly field schools along with dye tracing has increased the understanding of the recharge areas of karst aquifers in the region, where forestry activities are ongoing. Three subsurface drainage paths with associated springs have been identified with relatively shallow subsurface drainage paths that are defined at the surface by dry valleys with dolines and windows, along with reappearing and disappearing stream segments. Continuous monitoring of spring flow, conductivity and temperature indicates that one spring is dominated by allogenic flow from non-karst areas upslope, while the other is more related to autogenic recharge. Continuous measurement of turbidity is also being used to more fully understand sediment transport in the area, where considerable glacial materials are present. A new study is investigating benthic invertebrate communities and comparing karst-influenced streams to nearby non-karst streams. Preliminary results suggest a higher abundance of invertebrates along with significantly increased species diversity in the karst streams. It is anticipated that students from Vancouver Island University will continue using this karst area for field studies, possibly uncovering other aspects of interest in the future.

## Investigation of the flow system of the Molnár János cave

### Proučevanje pretakanja vode v jami Molnár János

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The Molnár János Cave is a hypogenic cave situated under a densely populated area of Budapest, the capital of Hungary. The cave is the youngest member of the Buda Thermal Karst System. Its passages extending several kilometres under the Rose Hill are almost completely submerged. Mixing corrosion

is still active in the passages that are filled with waters originating partly from regional, partly from local/intermediate flow systems.
The cave passages - evolved along tectonic fractures - form a multi-level maze, the cross section of the passages range from near impassable restrictions to tunnels large enough to pass for subway lines. Determining the flow directions and velocities is essential in order to find the different inflows, the possible connections to the nearby caves or to determine the propagation of urban pollution reaching the cave. This is an enormous task, since all measurements must be carried out by cave divers, sometimes far from the exit point and at considerable depth.
The large cross-sections and the existence several alternative routes between any two points in the cave result in small flow velocities preventing the use of propeller flow meters. Furthermore, the lack of suspended material makes the use of ADCP-s practically impossible. In the last few years our group improved water sampling methods for scuba divers, and developed novel instruments for underwater use.
With the combination of tracking the changes in the physico-chemical properties and chemical composition along the different sections of the cave, and using “micro” tracing techniques to determine flow parameters we have identified sites where water from the surface enters the cave, and determined major flow directions in the main passages.

## Anthropogenic pollution in the Molnár János Cave
### Antropogeno onesnaženje v jami Molnár János

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The Molnár János Cave is a hypogenic cave situated under a densely populated area of Budapest, the capital of Hungary. The cave is the youngest member of the Buda Thermal Karst System. Its passages, extending several kilometres under the Rose Hill are almost completely submerged. The cave is part of the aquifer that stretches under the Transdanubian Mountains. Although the very long flow path of the majority of waters entering the cave ensures that the water quality is excellent, close to the entrance of the cave drip waters carrying anthropogenic pollution reach the upper passages. The chemistry of these drip waters shows high spatial variation, however, a common characteristic is high nitrate content, well above drinking water standards. Although the drip rates at the different sites also display significant variation over time, earlier attempts to correlate drip rates with precipitation events on the surface failed, indicating long infiltration times, and the complicating effects of the epikarst.
In this work water chemistry, drip rate and precipitation time series are collated at 4 different drip sites in the entrance tunnel, the entrance hall (Kessler hall) and two side passages. Cave diving techniques were also used to search for further drip sites deeper in the cave. Theories were developed about the origin of the drip waters and the effects of the epikarst were also observed.

## Stratigrapic profile of the Slovačka pit (Northern Velebit, Croatia)

### Stratigrafski profil Slovačke jame (severni Velebit, Hrvaška)

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Caves are generally a good source of geological data, especially deep pits where we can precisely monitor structural elements and stratigraphy succession. This was a motivation for making a stratigraphic profile of Slovačka pit on Northern Velebit. Slovačka pit is the second deepest pit in Croatia located in Strict Reserve "Hajdučki and Rožanski kukovi". It is 1324 m deep and has one fossil phreatic channel on -350 m and one active on the bottom. Besides that, pit is predominantly vertical, which makes it suitable for creating a vertical stratigraphic profile. The samples of rock were taken at irregular intervals in accordance with safety measures. They were processed in laboratory and analysed under the microscope. Stratigraphical division is based on micropaleontological and microfacial observations. Generally, profile is divided in two parts: underlying Jurassic carbonates and overlying Velebit (Jelar) breccias from Oligocene epoch. In addition, Jurassic carbonates are also chronostratigraphically divided. Some structural elements (strike and dip) were also measured.
The aim of this research was determining the depth of erosion contact between Velebit breccias and Jurassic carbonates which was confirmed through finished profile. Stratigraphic profile of the Slovačka pit in combination with measured structural elements gives us a better insight in complex geologic structure of Rožanski kukovi on Northern Velebit.

## Use of isotopes in the assessment of water resources in the city of Bandundu in Democratic republic of Congo

### Uporaba izotopov za vrednotenje vodnih virov v mestu Bandundnu v Demokratični Republiki Kongo

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The city of Bandundu with its 300,000 inhabitants, located at the confluence of rivers Kwango and Kwilu has large surface water reserves and quality groundwater. Currently, the city is serviced from two drill points located in the eastern part. The entire network serves just 29 % of the city's population and covers 18 out of the 20 neighbourhoods in the city, with over 70 % of the population without access to drinking water. The drinking water distribution network has not followed the anarchic extension of the city in a row a population explosion that plagued a large proportion of the rural population and that of the provinces in conflict to set up in the city of Bandundu occupying periurban areas unserved by drinking water in precarious conditions.
Thus, characterization of the resources likely to present a certain hydrogeological potential thanks to the isotopic tool and to the classical hydro geological techniques, will allow the managers and decisions makers to diversify the sources of drinking water supply and to ensure a proximity distribution by the exploitation of resources of economic interest.
This research provides policymakers, researchers and funders with scientific information on the characteristics of rivers Kwango and Kwilu because, to, date there is a lack of database and addition to lack of human resources to cope with management difficulties in water resources in Democratic Republic of the Congo.
Scientific results:
- Physico-chemical parameters (pH, temperature, electrical conductivity) are measured;
- The major ions (anions and cations) were dosed;
- The turbidity measured.

## Groundwater geochemistry of the hypogene karst systems in Mariovo, Macedonia

### Geokemija podzemne vode v hipogenem kraškem sistemu Mariovo, Makedonija

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Previous studies of the Mariovo hypogene karst systems, based on cave morphology and deposits, have shown that hydrothermal speleogenesis is the main cave forming mechanism, locally converging with other processes, such as sulfuric acid speleogenesis and ghost-rock weathering. We conducted a geochemical study of three hypo-thermal and two sub-thermal springs associated with these karst systems and one cold spring, in order to further understand the processes controlling hypogene karst development. We have determined the concentrations of major ions and trace elements, as well as the isotopic composition of water, dissolved sulfate and carbonate. Groundwater mean residence time was determined based on radiocarbon, tritium and noble gasses concentrations. Radiocarbon concentrations indicate long mean residence time. High dissolved content and more positive carbon stable isotope composition indicate longer interaction with the carbonate rocks. Higher concentrations of trace elements that are associated with the Neogene and Quaternary volcanic rocks of Mariovo (e.g. arsenic) indicate also water-rock interaction with the volcanic rocks at depth. Presence of tritium in all of the studied springs shows that a young groundwater component is also present. The relationship of radiocarbon and tritium concentrations with spring temperatures indicates mixing of two components: an older thermal groundwater and a younger cold groundwater, with higher contribution of the younger cold waters at the springs with lower temperature. This is also supported by the total dissolved content and stable isotope compositions. The long mean residence time, as well as the dissolved content, stable isotope composition and trace element concentrations of the studied groundwaters confirm the previous assumptions of a deep groundwater flow in these hypogene karst systems, with the increased geothermal gradient connected to the volcanism.

## Age determination of cave and glacial sediments in the Central Balkan Peninsula using in situ produced cosmogenic nuclides

### Določanje starosti jamskih in ledeniških sedomentov v osrednjem delu Balkanskega polotoka z uporabo in situ nastalih kozmogenih nuklidov

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The “Geochronology using Cosmogenic nuclides in Macedonia” (GeCosMa) project aims to provide a better understanding of the Quaternary geomorphological evolution and climate change in the Central Balkan Peninsula. Despite its position between continental and Mediterranean Europe and its tectonic setting within the South Balkan extension zone, the study area was not in the main focus of geochronological studies so far.

Burial age dating of cave sediments using the in situ produced cosmogenic nuclide pair of 26Al and 10Be will be applied for the first time in this region. Caves from karst areas in the drainage of the

Vardar River are used to date two main events: (1) Base level lowering due to valley incision connected to the Early to Middle Pleistocene uplift and draining of the lacustrine basins; (2) Base level rise due to Pliocene-Early Pleistocene fill-up of basins that followed a previous phase of incision, presumed to be related to the Messinian Salinity Crisis.
For the reconstruction of the former glaciations, three mountain ranges have been selected: Jablanica Mt, Jakupica Mt and Šar Mts. Glacial geomorphological mapping has been finished at Jablanica and Jakupica Mts, and a glacial geochronological framework is about to follow by exposure age dating using cosmogenic 10Be. Preliminary results from Jablanica and Jakupica Mts (Temovski *et al.* 2018, 2019) suggest that the oldest preserved moraines belong to the MIS 6, thus for the first time confirming the presence of glacial remnants from a glaciation older than the MIS 2 in this part of the Balkan Peninsula.
This research was supported by the NKFIH FK124807 and GINOP-2.3.2-15-2016-00009 projects.

## Basin-scale conceptual groundwater flow model for carbonate regions
## Konceptualni model vodnega toka na ravni porečja na karbonatnih območjih

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The hydrogeology of thick and deep carbonate regions is challenging not only theoretically but also from a practical point of view. Well-established basic concepts are needed to interpret basin-scale hydrogeology, including thick carbonate systems, in a coherent way. The applicability of the gravity-driven regional groundwater flow (GDRGF) concept for such ranges was justified based on the principle of hydraulic continuity. Thus, the concept of GDRGF can be used as a working tool for understanding basinal hydraulics and flowing groundwater as a geologic agent in thick carbonate ranges. Groundwater flow is responsible for advective heat transport and related basinal chemical pattern.
The simplified modelling scenarios demonstrated that basin geometry, water-table pattern and regional hydrostratigraphy are the focal issues on the basin-scale flow, even in a carbonate basin. The dominant groundwater flow direction is lateral in the unconfined flow domain, with undeveloped hierarchy of flow systems due to smoothened water-table differences. Furthermore, the water has basically meteoric origin accompanied by low water temperature.
In a deep basin and an associated confined subbasin, a complex flow pattern evolves. The position of the intense discharge place at the boundary of the unconfined and confined basin is determined by the minimum topographic elevation of the water table. The asymmetric flow pattern is the consequence of the more intense meteoric infiltration in the unconfined part compared to the confined one. Along the evolved interface between freshwater and basinal fluids, porosity enlargement due to mixing corrosion (hypogenic karstification) can be supposed due to significant chemical differences between freshwater and basinal fluids. Plus, the convergence zones of groundwater flow are suitable places for heat accumulation and deep geothermal energy investment. Application and validity of the generalized flow pattern and related processes were revealed in e.g. Hungary, China and Spain. This study is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 810980.

## Comprehensive educational programmes as a part of project "Center of excellence – Cerovac caves; sustainable management of natural heritage and karst underground"

### Obsežni izobraževalni programi v sklopu projekta "Center odličnosti – Cerovačke špilje; trajnostno upravljanje z naravno dediščino in kraškim podzemljem"

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Environmental education plays important role in the sustainable management of natural heritage. Therefore one of the goals of project "Center of excellence - Cerovac caves; sustainable management of natural heritage and karst underground" that started its implementation in April 2018 is to offer practical learning to all-age groups through interactive experience in nature. The educational programmes of the project offers specialized training and non-formal education, and thus evolving more active engagement in nature preservation. They target all learning stakeholders (children, students, teachers, environmental experts, volunteers, adventurers, etc.) by offering optimal solutions for recreation or professional development. Programs like Little caving school, Educational-tours in Cerovac caves and Cave Adventure tours on Crnopac massif offer learning opportunities on field, allowing people to relate with karst underground and its particularities. All programs focus on providing new experience using specialized skills that enable reconnecting with nature, create personal responsibility for nature preservation and improve behavioural patterns and social cohesion. Trans-national branding of these programmes along with the other project activities will help to improve connections across regions and hopefully become an interface between science, education and nature preservation.

## Long-term trends for seasonal and interannual variations of stream water chemical composition, $pCO_2$, carbonate equilibrium and hydroclimatic parameters (discharge and temperature) in a mountainous karstic catchment (Pyrenees, France)

### Dolgoročni trendi pri sezonskem in letnem nihanju kemijskih ($pCO_2$, karbonatno ravnovesje) in fizikalnih (pretok in temperatura) lastnosti vodotoka s hribovitim kraškim zaledjem (Pireneji, Francija)

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The carbonate dissolution plays a major role in the atmospheric $CO_2$ sink and in the riverine transfer of dissolved inorganic carbon from the atmosphere to the soils/rocks and to the oceans. The Baget watershed (13.25 $km^2$, altitude 950 m) which drains a karstic area in the Pyrenees Mountains has been monitored since more than 40 years for better understanding of the impact of global changes on carbonate dissolution and stream waters chemistry. It is an experimental catchment which belongs to the French Karst Network and to the French (OZCAR) and European (LTER) Research Infrastructures.
The annual precipitation is more than 1500 mm and the average annual temperature is 12 °C. The predominant lithology is calcareous (around 2/3 of the catchment area) which is dominated by calcite. The Baget is essentially forested and poorly exposed to local anthropogenic pollution.
In this work, we present the results obtained since 1978 with a focus on carbonate dissolution, stream water chemistry (mainly pH, Ca, Mg and alkalinity), $pCO_2$ and calcite and dolomite saturation index (SI) in relation with temperature (T) and river discharge (Q). We analysed the long-term trends

of the instantaneous values but also the interannual fluctuations of mean annual and monthly values.
Globally, this study shows that when Q decreases, the $pCO_2$ increases and the SI decreases, but there is no trend during the 40 years and no significant $pCO_2$-Q and SI-Q relationship. Anyway, the mean annual values show significant relationships, positive for $pCO_2$-Q and negative for $pCO_2$-SI. On the contrary, for the mean monthly values, the $pCO_2$-Q and $pCO_2$-SI relationships are both negative, showing high $pCO_2$ during the low water period and low SI values.
The $pCO_2$-T relationship exhibits a well-shaped anti-clockwise hysteresis with higher $pCO_2$ in autumn (September-November) than in spring (March-May) for the same T.

## Microplastic pollution in karst environment
### Onesnaženje kraškega območja z mikroplastiko

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The presented results are the first study conducted in karst environment in Europe that focused on water and sediment pollution with microplastics. Sampling was done in two sinking rivers – Pivka and Reka – and their catchment area, where we sampled surface and underground streams, rimstone pools and puddles filled with percolating water near tourist paths, karst springs Malni and Timavo, rainfall water, and sediment. We performed polymer analysis of potential microplastic particles, using IR-ATR method. Further, we tried to determine primary or secondary origin of microplastics using low vacuum setup on SEM microscope. Results showed that microplastic was found in 31 samples out of 87 and indicate 35.6 % of pollution. Majority of microplastic was found in water samples, mostly from rimstone pools or other shallow pools of water next to tourist paths in Postojna and Škocjan caves, which indicates fast water discharge through the karst underground system and potential accumulation of microplastic pollution in karst sources of drinking water. With these preliminary results we found out that contamination with microplastics became a serious problem also in karst aquifer.

## Paleoclimate reconstruction based on speleothems from Ecuadorian caves
### Rekonstrukcija paleoklime na podlagi speleotemov v jamah Ekvadorja

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Paleoclimate has become the keystone for understanding our past environment and fine-tuning the current climate models. Among the terrestrial archives, speleothems have emerged to become a robust terrestrial archive for paleoclimate applications, especially in the Northern Hemisphere.
Despite this ongoing progress, there is still a lack of terrestrial paleoclimate archives in South America, especially from speleothems. In fact, most of the paleoclimate research has focused on tree rings, paleofire, paleolimnology and ice cores.
Ecuador is one of the most biodiverse countries in the world, which biota is highly sensitive to climate fluctuations due to the direct influence of ENSO, ITCZ and the high solar irradiance. However, the short duration of continuous instrumental and sparse paleoclimate data make the comprehension of the past environment very limited.
With this regard, a project for broadening the paleoclimate record of the country has started by sampling speleothems from several caves in the Amazonian and the Pacific karst areas of Ecuador. In addition, a monitoring program for future calibration of speleothem records has been initiated.

The aim of this project is to expand our understanding of the past climate and observe the patterns and interactions on both sides of the Ecuadorian Andes.
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## Pleistocene paleohydrological changes recorded by speleothemes of the Szemlő-hegy Cave (Buda Thermal Karst, Hungary)

### Paleohidrološke spremembe v pleistocenu rekonstruirane iz sigove tvorbe v jami Szemlő-hegy (termalni kras Bude, Madžarska)

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Hypogenic caves of the Buda Thermal Karst developed in Pleistocene times as a result of interaction Eocene limestones with thermal waters rising along pre-existent fractures and discharging at the local base level of erosion. Because of subsequent tectonically controlled uplift, most caves are now dry and far above the actual thermal-water level. This study is an attempt to reconstruct the story of the shift of the cave from the hypogenic (phreatic) to the epigenic (vadose) zone.
Positions (incl. altitude) of the collected speleothems were measured by means of classical geodetics, and plotted on cave maps. Samples were studied petrographically and classified using Frisia's terminology (Frisia *et al.* 2000, Frisia 2015). Five major groups (mammillary crusts, cave rafts, cave-coralloids/popcorns, dripstones) were identified and their paragenetic order recorded at each sampling point. Mammillary crusts were considered as phreatic precipitates, cave-rafts as water-table indicators, whereas cave-coralloids/popcorns and dripstones as vadose zone features. Morphology, mineralogy (XRD, SEM) and stable C and O isotopes were studied and age-datings were carried out by the U/Th series method.
It turned out that the speleothems may facilitate, indeed, the reconstruction of changes of both the water-table and temperature. Cave rafts now found at 179 m a.s.l., proved to have been precipitated 500 kyr BP, at 37 °C on the surface of smaller or larger thermal-ponds separated by dams in NE-SW oriented straight passages. Cave rafts settled down to the bottom of those ponds became subject to overgrowth 390 to 410 kyrs BP. Gradual uplift of the Buda Hills and concomitant incision of the Danube resulted in gradual decrease of the water-table thus the level of formation of calcite rafts and mammillary crusts also shifted downwards. At the same time, some of the previously formed calcite rafts became overgrown by vadose-zone speleothems (eg. cave coralloids. Age datings show that 290 to 300 kyr BP the thermal water table (by then only of 27 to 28 °C) dropped by about 8 m (its related rafts and mammillary crusts are found now at 172 m a.s.l.) and most passages became partially air-filled (=vadose zone). 280 kyr BP the thermal water-table rose again (this time by about 5 to 6 meters) and the rise was accompanied by a temperature-increase (related speleothems are now at 174 to 175 m a.s.l. and their temperature of precipitation was calculated as 47 to 49 °C). At about 186 kyr BP, right before having left the cave finally empty, the temperature of the thermal water decreased already to 21 to 25 °C (related speleothems are found now at 168 m a.s.l.). The last thermal-water speleothems were precipitated at 160 kyr BP from luke-warm waters of 20 to 23 °C and the cave has been dry ever since then. The swift cooling of the water during the last stages of the uplift of the Buda Hills was most probably the result of mixing with increased amounts of infiltrating meteoric waters from the eroding surface.

## Geomorphology, hydrology, and distribution of Gypsum karst in Lower Austria
### Geomorfologija, hidrologija ter razporeditev krasa v sadri v Spodnji Avstriji

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In the Eastern Alps, gypsum occurs in a number of tectonic units but is only distributed locally, in rather small patches. The most important evaporitic units in Lower Austria lie within the Northern Calcareous Alps (NCA; part of the Upper Austroalpine) in the Upper Permian Haselgebirge Formation, the Lower Triassic Werfen Fm. However, in detail (i) the spatial distribution, (ii) the surface morphology and (iii) the consequences for society are poorly known. This comprehensive study aims to shed light on these aspects. Based on geological maps, the mining register, and field studies including morphologic mapping occurrences of gypsum are located. In addition, water analysis concerning enhanced electric conductivity (0.6 to 2.7 mS/cm) and sulphate content (up to 1.3 g/l $SO_4$) are utilised to testify dissolved gypsum.
Due to the stratigraphic position and the fact that the comparatively soft gypsum and associated silt- and sandstones are prone to erosion, most gypsum occurs on slopes and in valleys. The most common landforms of gypsum karst in Lower Austria are dolines. Most of them are particularly round and funnel shaped, develop on steep slopes, and can reach diameters of several tens of metres. Due to the location on steep slopes and the high solubility, subsurface gypsum bodies are often associated with landslides and it is often hard to distinguish the dominant process for the development of depressions (i.e. dissolution or landslide). Natural outcrops of gypsum are rare but in most cases, at least small karren features were detected. Among ca. 4000 registered caves in Lower Austria, only five are related to gypsum dissolution. They are relatively small, unstable and change their shape quite rapidly.
Despite its high importance as a natural resource, gypsum can cause hazards to infrastructure. The constant and rapid dissolution by natural or human induced water can cause fast-developing cavities and subsequently collapse features.

## Improving groundwater vulnerability and risk assessments within karst aquifers using GPR
### Izboljšanje ocene tveganja in ranljivosti podzemne vode v kraškem vodonosniku z uporabo georadarja

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As a transboundary aquifer, the Classical Karst Region represents an important water source for both Slovenia and Italy. However, due to extremely heterogenic subsurface settings and specific hydrogeological conditions of karst environments, the aquifer remains insufficiently protected (Turpaud *et al.* 2018).
As agricultural activity represents one of the major sources of groundwater pollution in Slovenia (MOP 2015), accurate groundwater vulnerability and risk assessments in agricultural environments is vital for a sustainable food production, especially in karst areas (Ravbar 2007). By using the non-invasive ground penetrating radar (GPR) method, it is possible to both track the top soil thickness in a continuous way across the field (Kirsch 2009) as well as detect the presence of karst features, which can contribute to the hydrogeological dynamics of the aquifer.
A GPR survey was carried out on an agricultural field with reduced crop growth within the Classical Karst aquifer. In order to avoid additional irrigation and fertilization that could lead to a potential increase of pollutants reaching the groundwater, the presence of subsurface discontinuities and karst

features as well as the top soil thickness were investigated using GPR. The results gave important information regarding the conditions within the shallow subsurface. In addition to tracking the top soil thickness, we were able to detect the lower boundary of the weathered limestone as well as identify discontinuities representing limestone bedding, solutionally enlarged fractures and karst features (e.g. channels, cavities, as seen in Zajc *et al.* 2015).
The results provided information on both lateral and vertical variations of the subsurface features, therefore this method could also be applied for defining the most representative positions of soil moisture tracking probes within agricultural fields used for irrigation optimization purposes in precision agriculture. The use of GPR could therefore contribute to more accurate groundwater vulnerability assessments as well as a more sustainable food production.

## Importance of methodological approach for karst aquifers evaluation: an example of study of Učja Valley aquifer, NW Slovenia

## Pomen metodološkega pristopa pri proučevanju kraškega vodonosnika: primer vodonosnika doline Učje, SZ Slovenija

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Due to increasing needs, the overexploitation of water resources and changes of climatic conditions, an increasing problem of the water scarcity occurs. In order to ensure enough quantities of quality drinking water in the future, it is necessary to define reserve water resources. While lowlands aquifers are often been studied and used, represent less accessible aquifers great potential both for exploration as well as for the exploitation. A great part of Slovenia is covered with carbonate rocks in which karstic and fractured aquifers occur. Such systems are often vast reservoirs of high quality water and thus important sources of drinking water in the future. Because these systems are complex, both detailed geological and hydrogeological studies of aquifers in these regions are quite rare, and in the future represent an important area of research also with the perspective to determine potential water resources for drinking water supply.
Through the presented study the comprehensive survey of Učja Valley aquifer was elaborated with the aim to understand and evaluate its potential as drinking water resource. Applied research methods have enabled to design the conceptual model of the observed aquifer and to assess the current condition of the water resource. In such approach, where the analyses combine various parameters and factors, the systematic use of research methods is crucial. The results showed that the basic geological investigations, such us lithological and structural mapping, are necessary and basic for further planning of analyses (hydrogeochemistry, trace experiments etc.) and final interpretations. Furthermore, with the right methodological approach we can avoid unnecessary additional analyses at a certain investigation stage, which in themselves would not provide enough data for interpretation.

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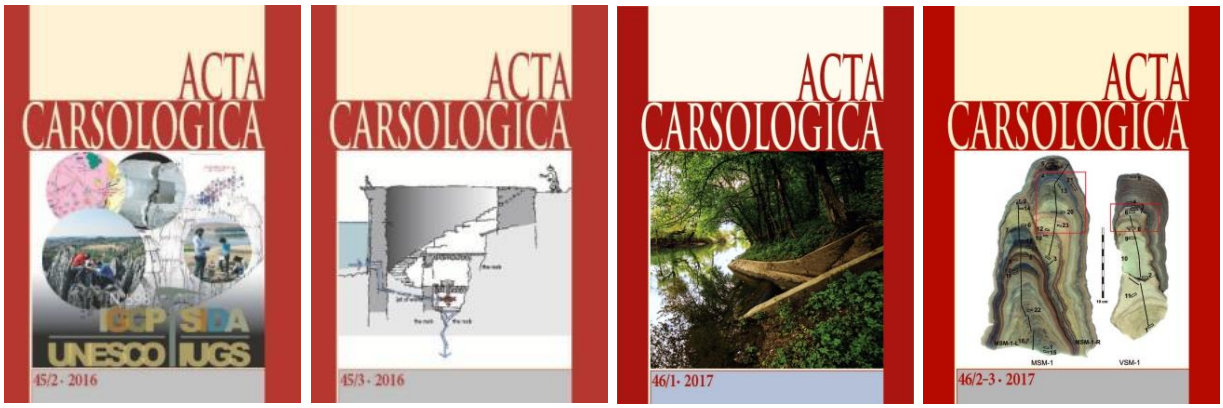


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# Welcome to Karstology doctoral study

The Karstology doctoral study programme is a world-wide unique programme which provides a comprehensive study of karst science, combining the study of the karst landscape, karst caves, karst hydrogeology, biology and ecology of karst in one course of study. It was designed for students who wish to gain deeper insight of this broadly integrated system of karst sciences. The fundamental objective of the programme is to produce two types of karstologists. The first is the karstologist-researcher who can conduct independent research on karst and karst phenomena from multiple aspects.The second type is the karstologist- manager who can apply the full knowledge of karst conveyed by narrowly specialized experts for different applications (economy, education, protection).

The programme was developed with researchers of the Karst Research Institute at Research Centre of the Slovene Academy of Sciences and Arts (ZRC SAZU) and is carried out by professors and researchers from Karst Research Institute and invited foreign professors, and is coordinated and managed by the University of Nova Gorica. Lectures and research take place in the premises of the Karst Research Institute in Postojna where students are provided all necessary professional and scientific support for their own research work. Successful functioning of doctoral study programme Karstology resulted in naming it in 2014 as the **UNESCO Chair on Karst Education**.

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