

# SLOVENE CLASSICAL KARST: KRAS PLATEAU AND THE RECHARGE AREA OF LJUBLJANICA RIVER

## KLASIČNI KRAS: PLANOTA KRAS IN KRAŠKO ZALEDJE IZVIROV LJUBLJANICE

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### ABSTRACT

#### Slovene Classical karst: Kras Plateau and the Recharge Area of Ljubljanica River

The area of the Classical Karst is roughly defined by a triangle with Ljubljana, Trieste and Rijeka as its vertices. This is the area where the first scientific studies of karst phenomena were conducted. Two sub-regions that particularly attracted researchers are presented. Kras/Carso plateau with the Škocjan caves and the underground course of the Reka river. The groundwater flow of Reka-Timavo is characterised by high recharge variability of alloigenic inflow of Reka River and flow restrictions in the upper part of subterranean flow, which control regional backfloodings observed in cave systems. The recharge area of Ljubljanica Springs is known for a cascading series of poljes in intermediate cave systems. The area has been in focus of hydrological studies for over a century, but many phenomena have been resolved in the last decade based on results of continuous autonomous monitoring in the last decade.

*Key words:* Classical Karst, Kras, Škocjanske Jame, Reka-Timavo system, Ljubljanica Recharge Area, Polje.

### IZVLEČEK

#### Klasični kras: planota Kras in kraško zaledje izvirov Ljubljanice

Območje Klasičnega krasa v grobem objema trikotnik z Ljubljano, Reko in Trstom v ogliščih. Tu se je začelo znanstveno proučevanje krasa. Dve kraški območji sta tu še posebej pritegnili pozornost raziskovalcev. Prvo je planota Kras s Škocjanskimi jamami in podzemnim tokom Reke med Škocjanskimi jamami in izviri Timave. Ta tok močno zaznamuje velika spremenljivost dotoka reke Reke in lokalne zožitve v vodonosniku, ki povzročajo regionalno poplavljjanje, kot ga beležimo v jamah. Drugo je območje kraške Ljubljanice z značilnim nizom dinarskih kraških polj in jamskih sistemov, ki polja hidrološko povezujejo. Območje je že več kot stoletje predmet številnih raziskav, zvezno spremeljanje parametrov toka v kraških jamah v zadnjih desetih letih, pa je omogočilo nova spoznanja o lastnostih in mehanizmih pretakanja vode v celotnem sistemu.

*Ključne besede:* Klasični kras, Kras, Škocjanske Jame, podzemni tok reke Reke, kraško zaledje izvirov Ljubljanice, polje.

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KRAS PLATEAU AND ŠKOCJAN CAVES

## Kras Plateau

The Kras/Carso is a low, 40 km long and up to 13 km wide, NW-SE-trending limestone plateau in Slovenia and Italy, stretching between Trieste Bay, the northernmost part of the Adriatic Sea, Vipava valley in north-east, and Friuli-Venezia Giulia lowlands and river Soča in north-west (Figure 1).

The name for the area comes from genetic word *kras*; in Slovene it means rocky surface. The term gave the name to the whole plateau Kras. From this toponym the international term – karst – for such type of landscape is derived. The name and some other terms from the area like *dolina*, *polje*, and *ponor* have also entered to international scientific terminology from here.

Climate is sub-Mediterranean with warm dry summers and most of the precipitation in autumn and spring. Cold winters, with NE wind "burja" (bora = borealis) show strong influence of the continent. Average yearly precipitation on Kras varies from 1,400 to 1,650 mm, and average yearly evapotranspiration from 700 to 750 mm. Because of different land use, pasturing, in past centuries, the Kras was bare, with rocky and grassy surface. In the last decades the bushes and trees are overgrowing the landscape.

The main part of the plateau is essentially levelled, inclined slightly towards the north-west, with numerous dolines, caves and other karst features. Over 3500 caves are known on the plateau. In seven of them we can reach over 30 km of passages of the underground Reka which flows between 200 and 300 m below the surface. There is a belt of slightly higher relief in the central part of the plateau, formed by conical hills like Grmada (324 m.a.s.l.), and dissected by large depressions. The higher relief divides the Kras into two separated levelled surfaces. In the north-western part, the plateau descends to below 50 m.a.s.l. on the edge of the Friuli Plain; on its south-eastern edge altitudes are about 500 m.a.s.l. There is about 300 m of accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it.

No superficial streams occur on the Kras surface, because all rainwater immediately infiltrates to carbonate rocks. There are two dry valleys crossing the plateau and some NW-SE-trending belts of lower relief which are result of young tectonics.

The age of the karst of Kras plateau can be defined as the time when the karst rocks were uplifted out of the sea. For the most of Dinaric karst in Slovenia this occurred after the Eocene, since after that there is no

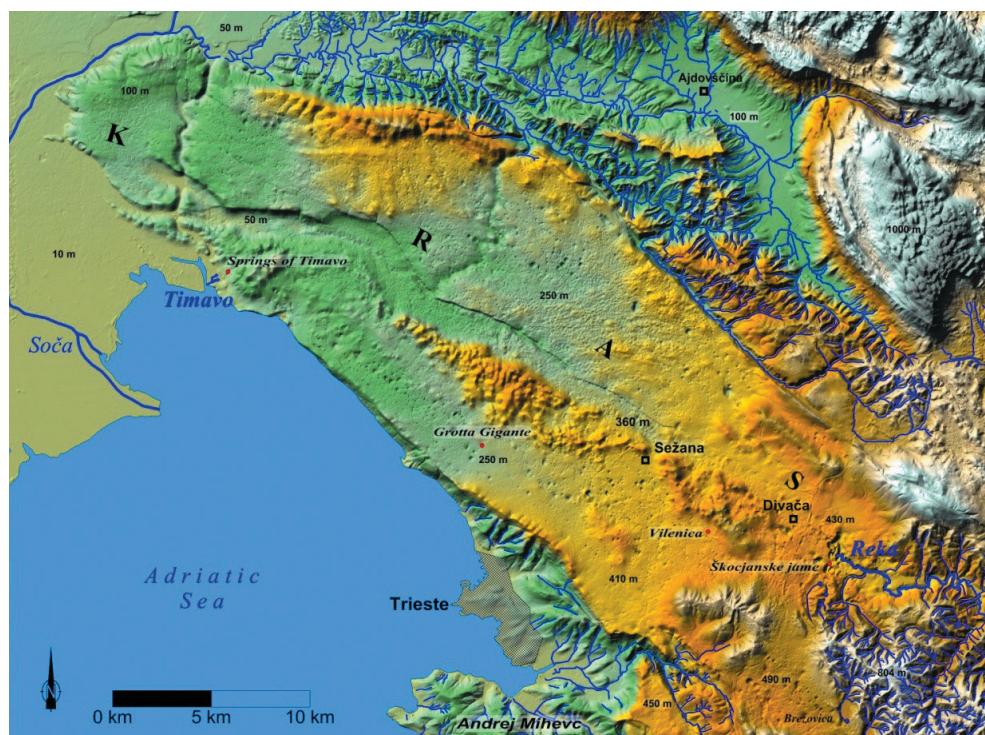


Figure 1: Digital elevation model of the Kras Plateau.

evidence of younger marine sediments. As soon as the carbonate rocks were exposed, we can expect that the karst was formed, but there are no remnants of karst features from that time. Most likely denudation has already destroyed them.

The oldest features in the karst relief are unroofed caves. They were caves that were formed by sinking rivers, bringing alloigenic sediments to caves in Kras. At the end of the morphogenetic phase all these caves were filled with fluvial sediments. This indicates the diminishing of the gradient in the whole area. Diminishing of the gradient, which ended with planation could mean tectonic phase, which ended at about 6 Ma ago. After that a new tectonic phase started. Three areas faced uplift and tilting for several hundred meters. The uplift was stronger in the SE part of the area. Karst denudation was evenly lowering the surface, so the surface remained well preserved, dissected on central parts of karst with dolines, which represent few percents of total area only. The even denudation exposed former old caves to the surface. Some of them are filled with sediments, some sediments were washed away or were never filled.

#### Geological and hydrogeological settings of the Kras Plateau

Figure 2 presents a simplified geological situation. The plateau is made up of a succession of Cretaceous to Lower Paleogene carbonates deposited on the Adriat-

ic-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 Imbricated Belt, a part of the thrust system of the External Dinarides, which furthermore underthrusts below the Southern Alps. Underthrusting also resulted in an en-echelon 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 to affect the groundwater flow (ŠEBELA 2009; ŽVAB Rožič et al. 2015). The carbonates are surrounded by flysch, which provides the input of alloigenic 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<sup>3</sup>/s are the most important.

The Reka River is the main alloigenic input to the system; ~41 % of its catchment is karstic and ~54 % is underlain by flysch. It flows ~50 km on the impermeable

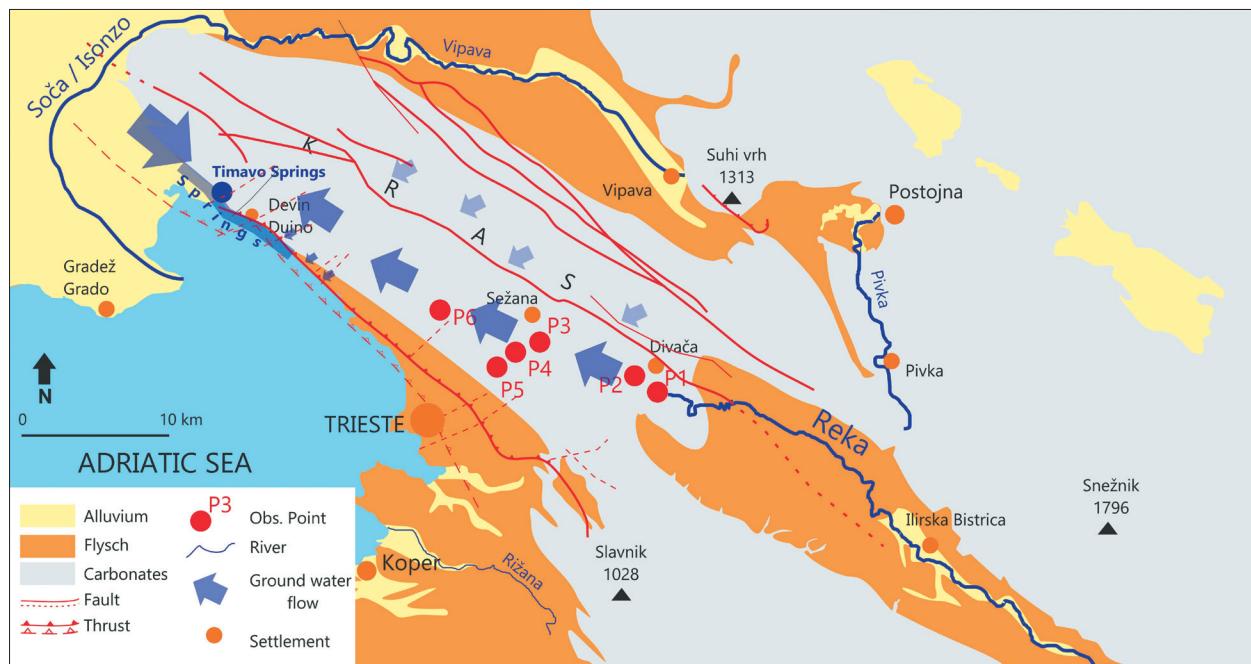


Figure 2: A simplified geology of the area with main lithological units and structural elements. P1-P6 mark the position of the caves with active groundwater flow. Blue arrows indicate the general groundwater flow direction towards the springs.

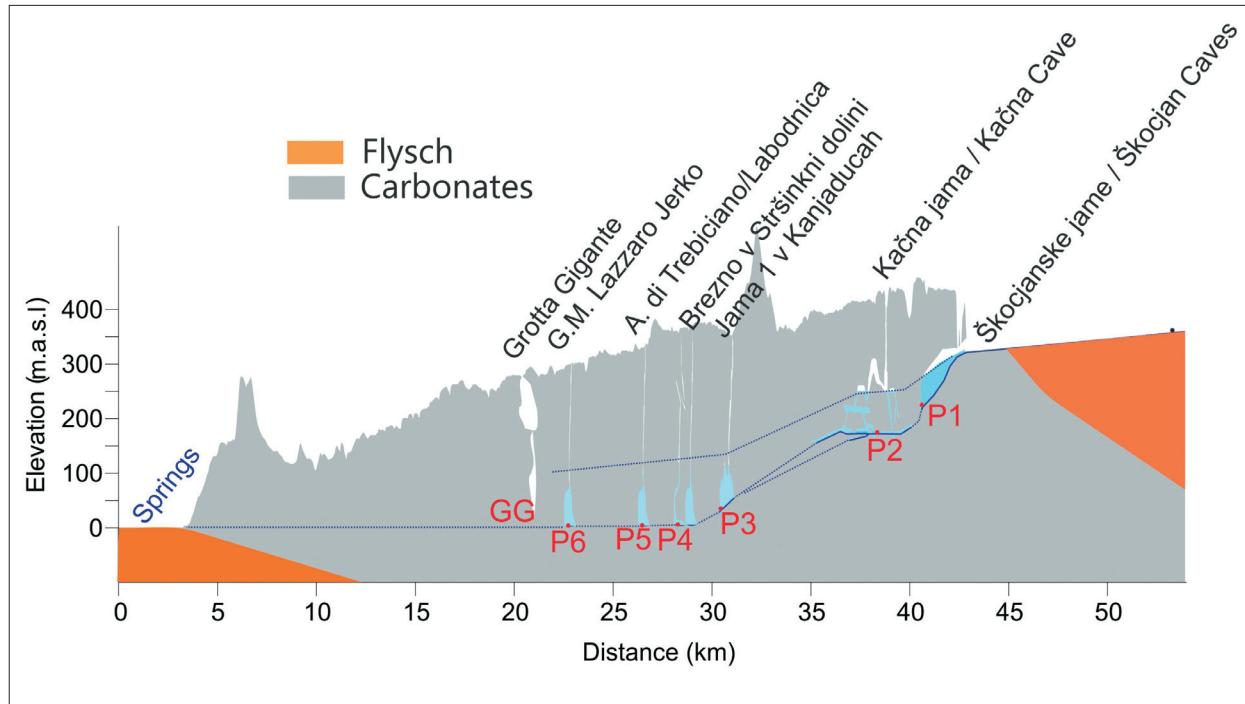


Figure 3: An idealised cross-section of the Kras Plateau between the Škocjan Caves and the springs along the NW coast of Trieste Bay. The dotted blue lines denote the position of the base flow and extreme floods. P1 to P6 indicate the positions of the observation points used in this work. Vadose parts 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.

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 (Figs. 1 & 2). 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  $7.1 \text{ m}^3/\text{s}$ , while the long-term average (1952–2013) is about  $8 \text{ m}^3/\text{s}$ . The ratio between the highest and the lowest flow rate is ~1700, with the maximum measured discharge  $305 \text{ m}^3/\text{s}$ , and the minimum  $0.18 \text{ m}^3/\text{s}$ . 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.

Yearly precipitation in the mountainous catchment of the Reka River can reach  $> 2000 \text{ mm}$ . These areas form an important orographic barrier where extreme precipitation events (e.g., 250 mm in 12 hours) have been recorded.

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

Figure 3 shows an idealised cross-section through the Kras Plateau. Several caves have been explored that cross vertically the entire vadose zone and reach the epiphreatic level with the Reka River flow. In caves P1–P6, long term monitoring of water level, temperature and electric conductivity have been monitored with autonomous instruments. The Reka starts its underground flow at Škocjanske Caves (P1 in Figs. 2 & 3), 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 2 & 3). The cave is  $>20 \text{ km}$  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  $15 \text{ m}^3/\text{s}$ , it is diverted to the sequence of large overflow galleries. More than 2 km of

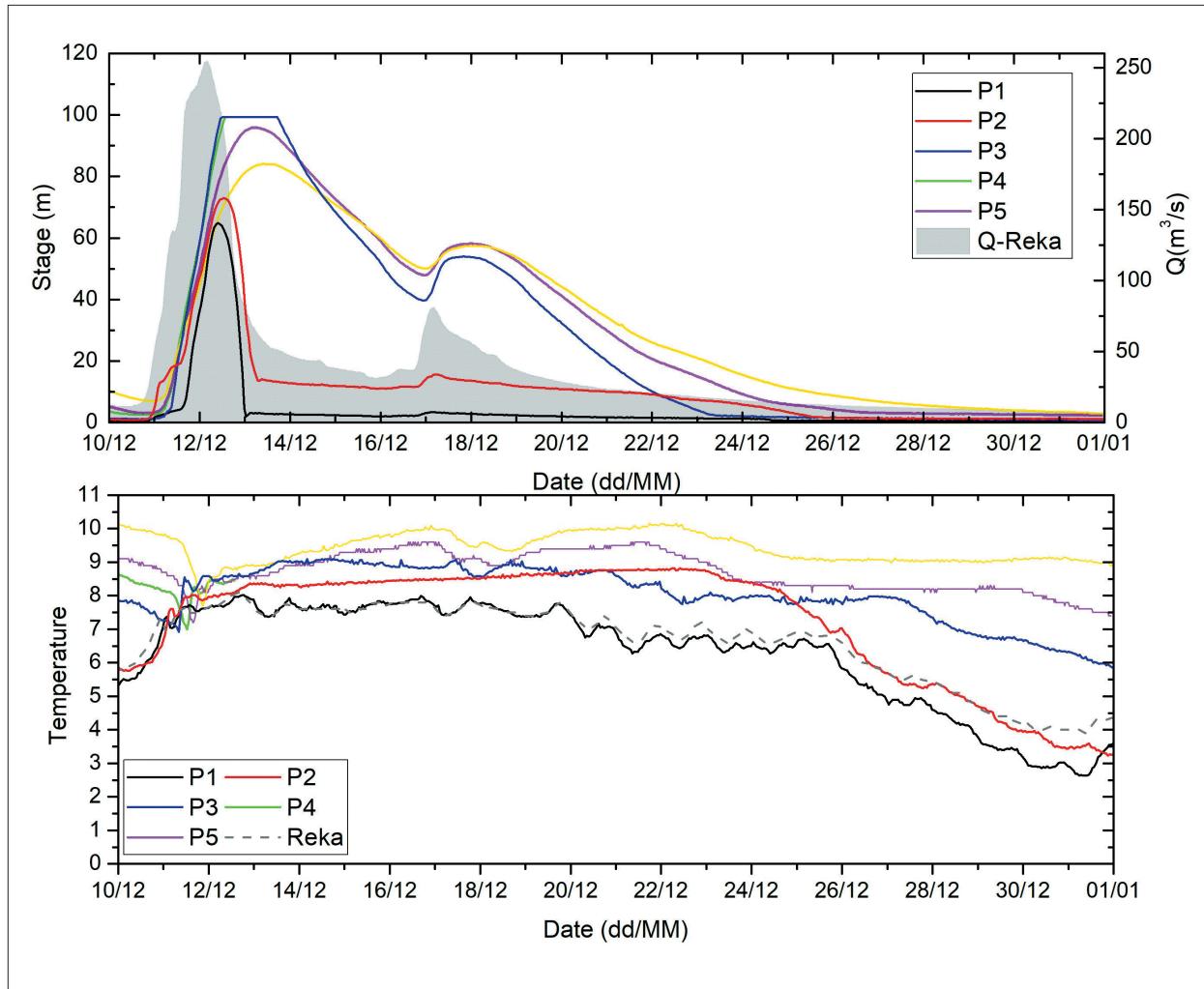


Figure 4: Level and temperature hydrographs recorded in caves of the Reka-Timavo system during major flood in December 2008.

the overflow channels, interrupted by perched sumps, have been explored. The underground flow can be observed in several other caves (observed caves are P3 to P6), where typically a series of rather narrow shafts lead to large chamber or passage with groundwater flow.

Characteristics of flood propagation through the Reka-Timavo system

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  $15 \text{ m}^3/\text{s}$ . When this is surpassed, the flow is diverted along higher positioned overflow galleries. This can drain efficiently flow rates up to  $130-150 \text{ m}^3/\text{s}$ . 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  $10 \text{ m/h}$ .

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.

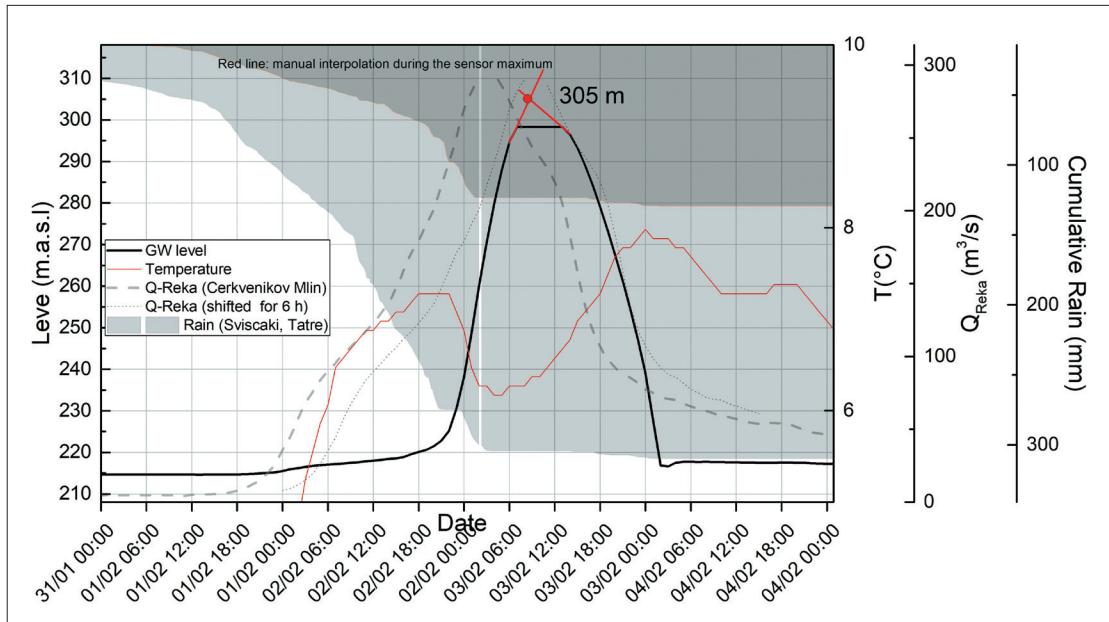


Figure 5: The flood event of 2019: Cumulative rain at two stations, discharge of Reka and level and temperature in Martel's chamber. Dotted grey line shows discharge shifted for six hours, an estimated travel time from gaging station to Martel's chamber.



Figure 6: The water rose for over 90 m during flood 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, ESA Sentinel). Below: rough cross-sectional schematic view of water level during the 2019 flood.

### The flood event in February 2019

Between January 27<sup>th</sup> and February 4<sup>th</sup> 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<sup>3</sup>/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 (Figs. 5 & 6). 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 6).

### 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. 2021). 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<sup>6</sup> 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).

### A brief speleological review of Škocjanske jame

Škocjanske Jame (Škocjan Caves) are 5.8 km long cave (Figure 7) 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 19<sup>th</sup> century raised the water table level by 132 m. The largest chambers are Martelova Dvorana, with a volume of 2.6 x 10<sup>6</sup> m<sup>3</sup>, and Šumeča Jama with

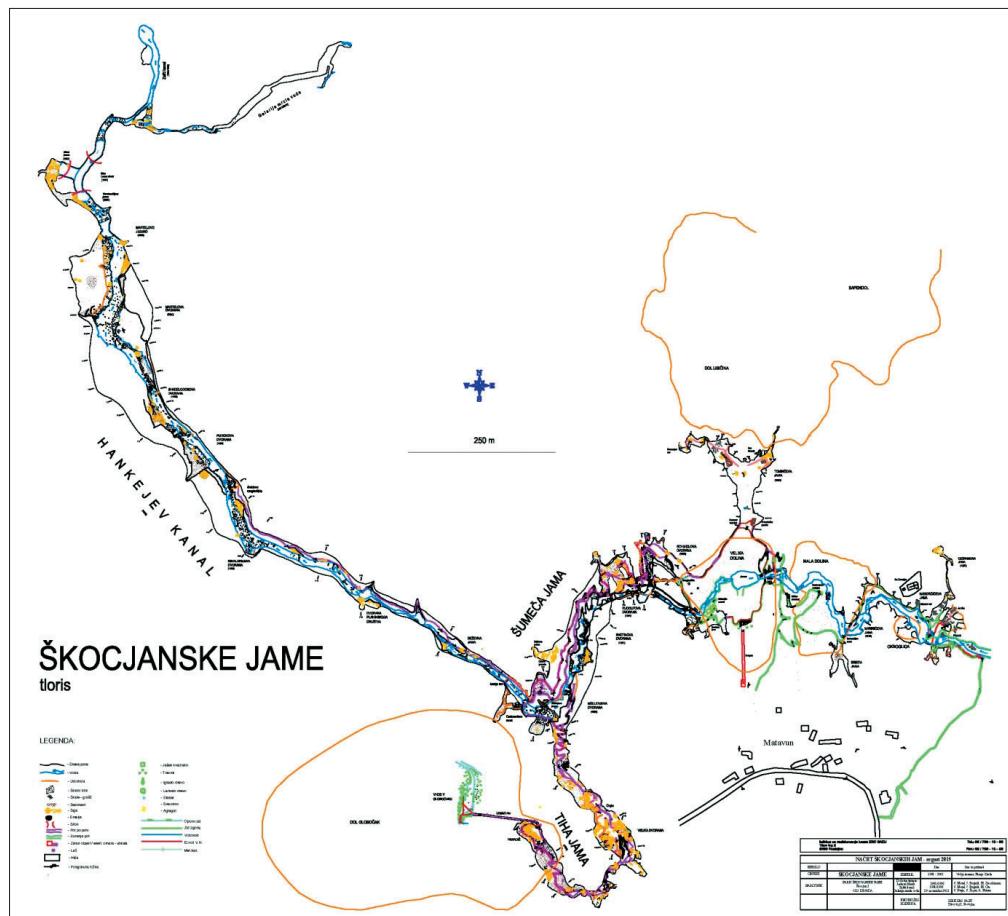


Figure 7: Map of Škocjanske Jame (Cave Register 2019).

$0.87 \times 10^6 \text{ m}^3$  (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 (ŠEBELE 2009). The passages were initially formed in phreatic conditions along tectonized bedding-planes, and later modified by paragenesis or gravitational entrenchments and collapses.

### Exploration and tourism in Škocjanske Jame

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 cav-

ers 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.

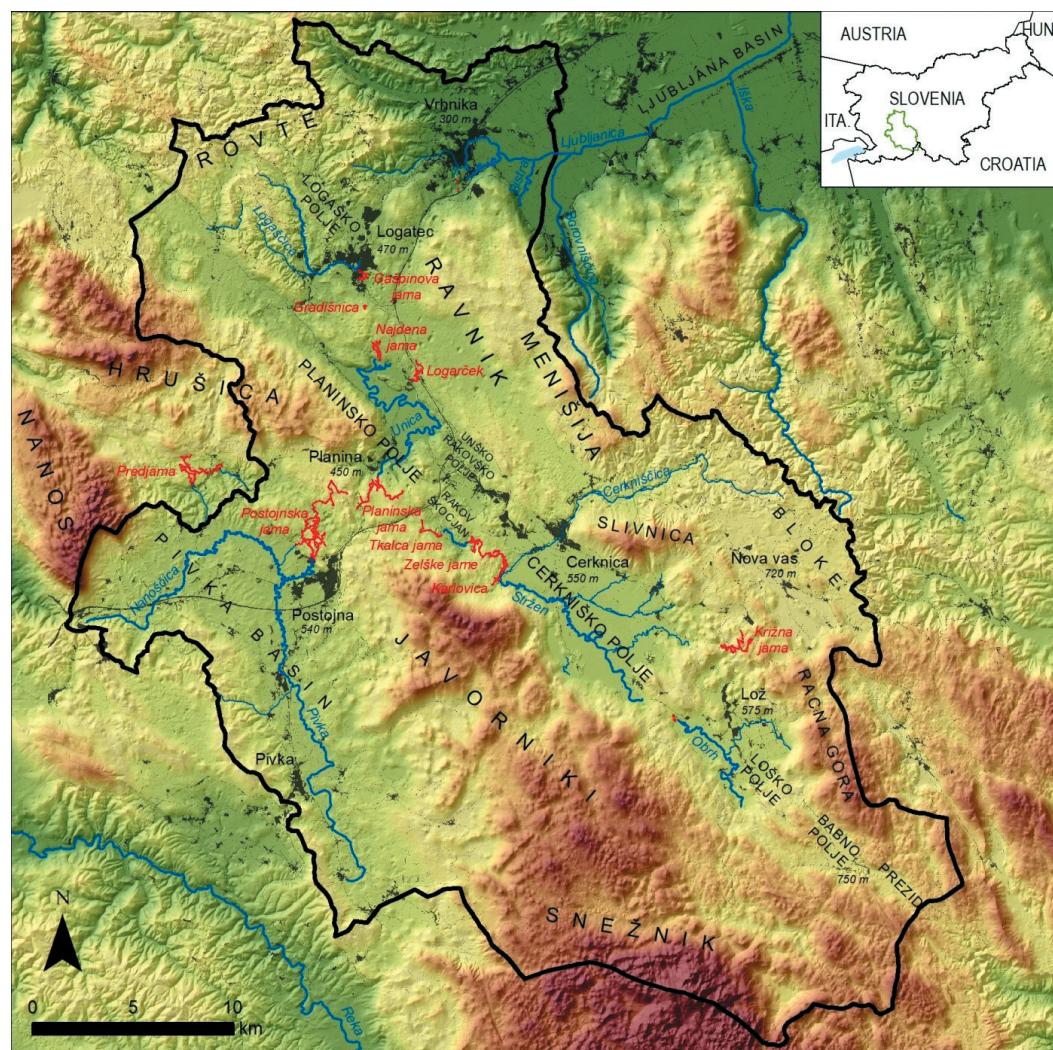


Figure 8: The Ljubljanica River recharge area with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.

## THE LJUBLJANICA RIVER RECHARGE AREA

The central part of the Slovenian Dinaric Karst drains to the springs of the Ljubljanica River, located on the southern edge of the Ljubljana Basin (Figure 8). Although the area is about 26 km of straight-line distance close to the Adriatic Sea, intense tectonic activity has triggered drainage into the Sava-Danube river basin, which flows to the Black Sea. The estimated total size of the Ljubljanica recharge area is almost 1800 km<sup>2</sup>, of

which about 1100 km<sup>2</sup> are karstified. The karst catchment area was delineated during an extensive tracing campaign in the 1970s (GOSPODARIČ & HABIČ 1976).

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

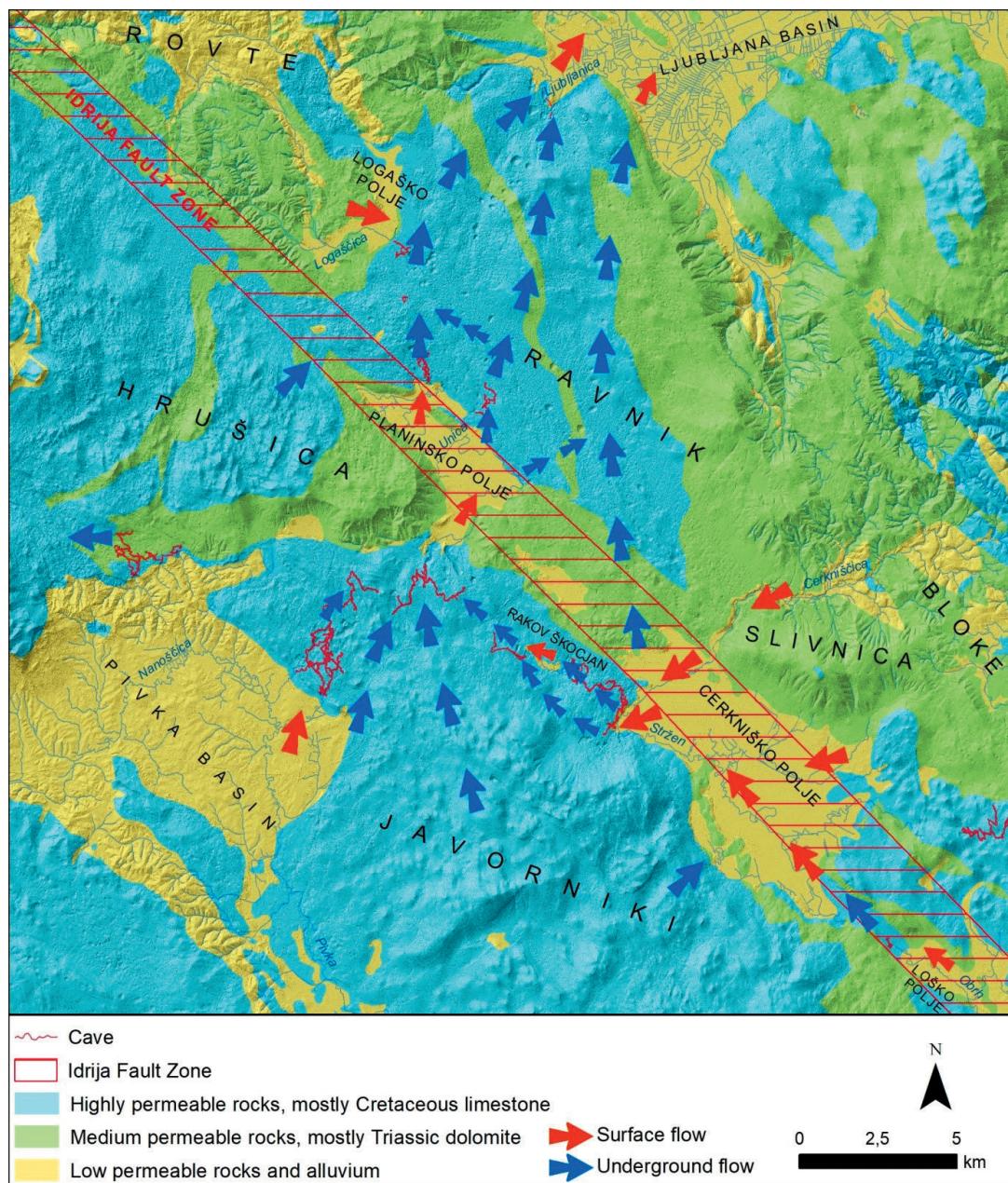


Figure 9: Hydrogeological map of the Ljubljanica recharge area (adapted from Krivc et al. 1976).

erally with less than 5%, locally even only 0.1%, insoluble residues. The total thickness of the carbonate sequence is almost 7 km.

Structurally, the entire Ljubljanica catchment belongs to the Adriatic Plate. The area consists of several nappes that were overthrust during the peak of the Alpine orogeny in the Oligocene in a NE to SW direction (PLACER 2008; PLACER et al. 2010). A later change in the direction of plate movement led to the formation of the Idrija Fault Zone, a dextral strike-slip fault that crosses the area in the direction of NW-SE (Figure 9) (VRABEC 1994). The Idrija Fault Zone largely determines the direction of regional flow (Figure 9). In general, the steepest hydraulic gradient is oriented northwards, from the Notranjska region towards the Ljubljana Basin, which represents a regional base level. However, the fault zone acts as a barrier to groundwater flow and forces the water to surface in the poljes. At the same time, it diverts the flow in the Dinaric direction (SE-NW) (ŠUŠTERŠIČ 2006).

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

In general, the water follows the SE-NW direction with surface flow on the poljes and groundwater flow in-between (Figure 10). Additional water enters the flow system at numerous springs draining the areas of the Snežnik and Javorniki mountains in the south of the Idrija Fault Zone. Several sinking rivers draining dolomite or flysch areas also contribute to this system (GAMS 2004). The altitude of the poljes drops from about 750 m to 450 m (Figure 10). The streams that flow through them have different names: Trbušovica, Obrh, Stržen, Rak, Pivka and Unica. Apart from a relatively small amount of water flowing directly from Cerkniško

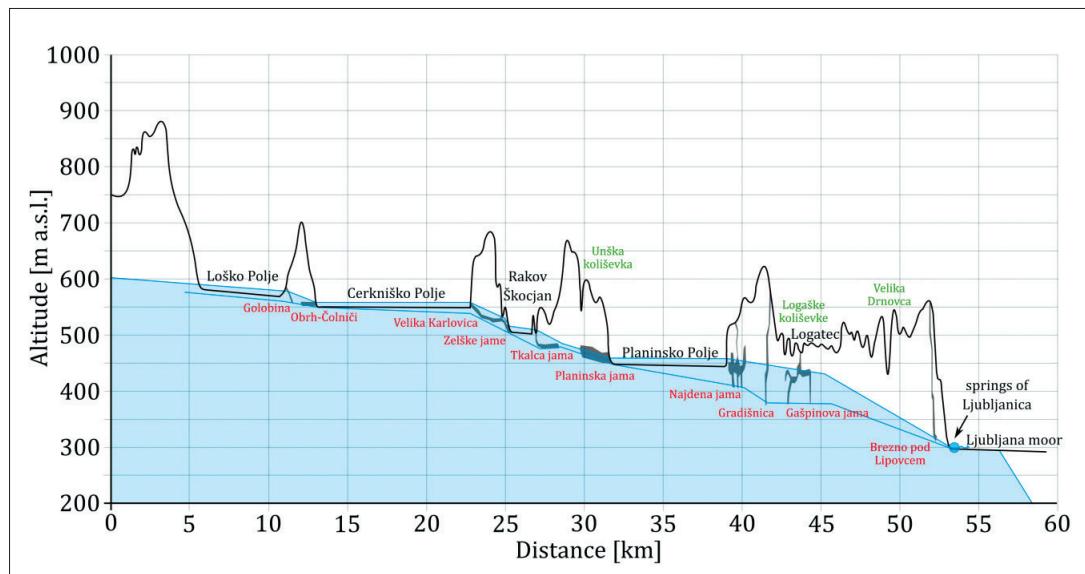


Figure 10: Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnik. The major caves are indicated in red, large collapse dolines in green.

Polje to the springs of Ljubljanica, most of the water comes to the surface along the southern edge of Planinsko Polje. Along its eastern and northern edges, the water sinks back underground and flows northwards to several large and many small springs aligned along the southern edge of the Ljubljana Basin, which is connected to the gradual tectonic subsidence of the area (KRIVIĆ et al. 1976; GAMS 2004). The average annual

discharge of the Ljubljanica springs is 38.6 m<sup>3</sup>. An additional amount of water drains from the low- to medium-permeable Rovte plateau and contributes to the Ljubljanica springs by sinking into the ponors of Logaško Polje (MIHEVC et al. 2010).

There are over 1600 known caves in the recharge area of the Ljubljanica River (CAVE REGISTER 2019). Most of them are accessible fragments of a fossil un-



Figure 11: (a) Flooded Cerkniško Jezero (Spring 2013) (Photo: C. Mayaud). (b) Ponors of Rešeta during low flow conditions (Summer 2017) (Photo: M. Blatnik).

derground 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.

### Cerkniško Polje

Cerkniško Polje is the largest karst polje in Slovenia (GAMS 1978, 2004). It is often called Cerkniško Jezero (Lake of Cerknica) because of its regular floods (Figure 11a). When full, the intermittent lake covers up to 26 km<sup>2</sup> out of 38 km<sup>2</sup> of the polje's total area. The bottom

of the lake is at an altitude of 550 m. Its intermittency has attracted many scholars since the beginning of the New age including the polihistorian Valvasor, who published his famous study of the Cerkniško Jezero in 1689 (SHAW & ČUK 2015). The main part of the polje is underlain by Upper Triassic dolomite at its N, E and SE borders. The areas to the W and NW, on the other hand, are mainly underlain by Cretaceous limestone (Figure 9).

The polje is regularly flooded for several months, mostly in autumn, winter and spring (KOVAČIČ & RAVBAR 2010). On average, about ten days a year the water is above the level of 550.3 m, which corresponds to a flooded area of 21.84 km<sup>2</sup> (RAVBAR et al. 2021). The main in-

flows into the polje come from a series of karst springs called Žerovniščica, Šteberščica and Stržen, located on its eastern and southern borders. The springs on the SW side (e.g. Suhadolca, Vranja jama) contribute substantial amount of water during floods. In addition, an important allogeic component comes from the Cerkniščica River, which drains a dolomitic area of about 44 km<sup>2</sup> in the east (GAMS 2004). Finally, several estavelles (e.g., Vodonos) also contribute to the inflow into the polje.

In addition to the estavelles, several ponor zones located in the inner part of the polje drain a certain amount of water directly to the springs of Ljubljanica (KRIVIĆ et al. 1976) (Figure 11b), while the main ponors are aligned along the W side of the polje, with Velika and Mala Karlovica being the most prominent. Both

caves extend for over 8.5 km between Cerkniško Polje and the Rakov Škocjan karst valley. So far, only a small section between Velika Karlovica and Zelške Jame (located in Rakov Škocjan) is unexplored as an important collapse zone is located there. Recent studies have shown that at low to medium water levels (GABROVŠEK et al. 2010; RAVBAR et al. 2012; KOGOVŠEK 2022), a large part of the water sinking into the ponor of Mala Karlovica reaches the Kotliči springs in the middle of Rakov Škocjan and a smaller part reaches Zelške Jame, which would be the most logical direction.

In the last centuries, several attempts were made to change the hydrological behaviour of the polje, but none was completed or successful. In the 1960s, a plan to transform the Cerkniško Jezero into a permanent

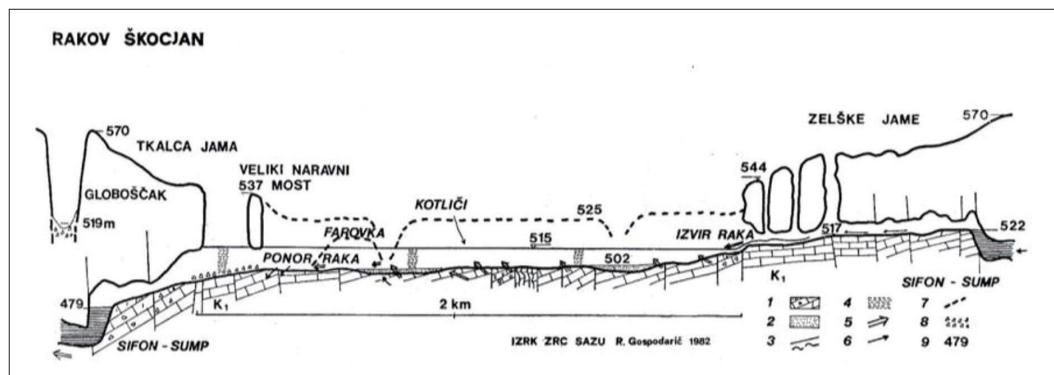


Figure 12: Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring; 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.

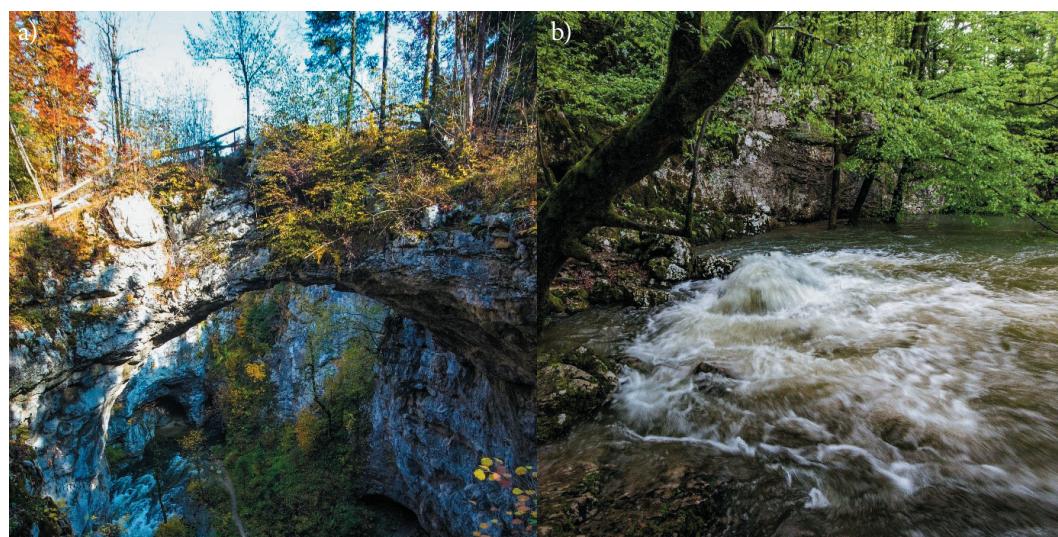


Figure 13: Rakov Škocjan karst valley. a) The arch of Mali Naravni Most. b) Kotliči spring at the beginning of a hydrological event (Photos: M. Blatnik).

lake was initiated. The entrances to the caves Velika and Mala Karlovica were closed with concrete walls and a 30 m tunnel was built to connect Karlovica to the surface. However, it had a minor impact on water retention during dry periods (SHAW & ČUK 2015).

### Rakov Škocjan karst window

Between Cerkniško and Planinsko Polje, the water surfaces in an about 1.5 km long and 200 m wide karst valley (karst window) Rakov Škocjan (Figure 12). On the upstream side (SE) the water emerges as the Rak River from the cave Zelške Jame. Zelške Jame is about 5 km long. The breakdown below the collapse doline of Ve-

lika Šujca prevents cavers to connect the cave to Karlovica cave system, which drains water from Cerkniško Polje. The entrance area of Zelške Jame is a fragmented system of channels and collapse dolines. The most prominent feature is Mali Naravni Most (Small Natural Bridge; Figure 13a), where an impressive narrow arch, which was part of the former cave ceiling, crosses the collapse doline (GAMS 2004).

Downstream, the valley widens and several springs (Figure 13b) located along the SW side of the valley (e.g. Kotliči, Prunkovec) form perennial or intermittent tributaries of the Rak River. The valley narrows an impressive natural bridge called Veliki Naravni Most (Big Natural Bridge; Figure 14). The rocky arch is made of thick-bedded and anticline-folded Lower Cretaceous limestone.



Figure 14: a) Flooded Rakov Škocjan Karst Valley in October 2020, b) Veliki Naravni Most (Big Natural Bridge) during dry period in summer; and c) during high water event in winter (Photos: M. Blatnik; RI-SI-LifeWatch)

After Veliki Naravni Most, the channel opens into a 150 m long canyon that ends at the entrance to Tkalca Jama, an almost 3 km long cave that drains the water towards Planinsko Polje. The connections of the Rak with the water from Cerkniško Polje and with the Unica springs at Planinsko Polje have been proven by several tracer tests under different hydrological conditions (GABROVŠEK et al. 2010; RAVBAR et al. 2012). A narrow passage in Tkalca Jama acts as a flow constriction that causes regular floodings of Rakov Škocjan. The floods can reach a height of 19 m above the cave entrance (located at 496 m a.s.l.), bringing large part of the Rakov Škocjan under water (DROLE 2015; Figure 14a). Before World War 1, Rakov Škocjan was a private park owned by the Windischgrätz family, while between the First

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

### Planinsko Polje and Planinska Jama

Planinsko Polje is one of the finest examples of an overflow structural polje (GAMS 1978; ŠUŠTERŠIČ 1996). The springs located on the southern side recharge the Unica River that sinks in two major outflow zones located along the eastern and northern borders of polje (Figure 15). The polje surface is slightly undulating and about 10 km<sup>2</sup> large, with a bottom elevation between 444.5 m and 450 m a.s.l (BLATNIK et al. 2017). Apart

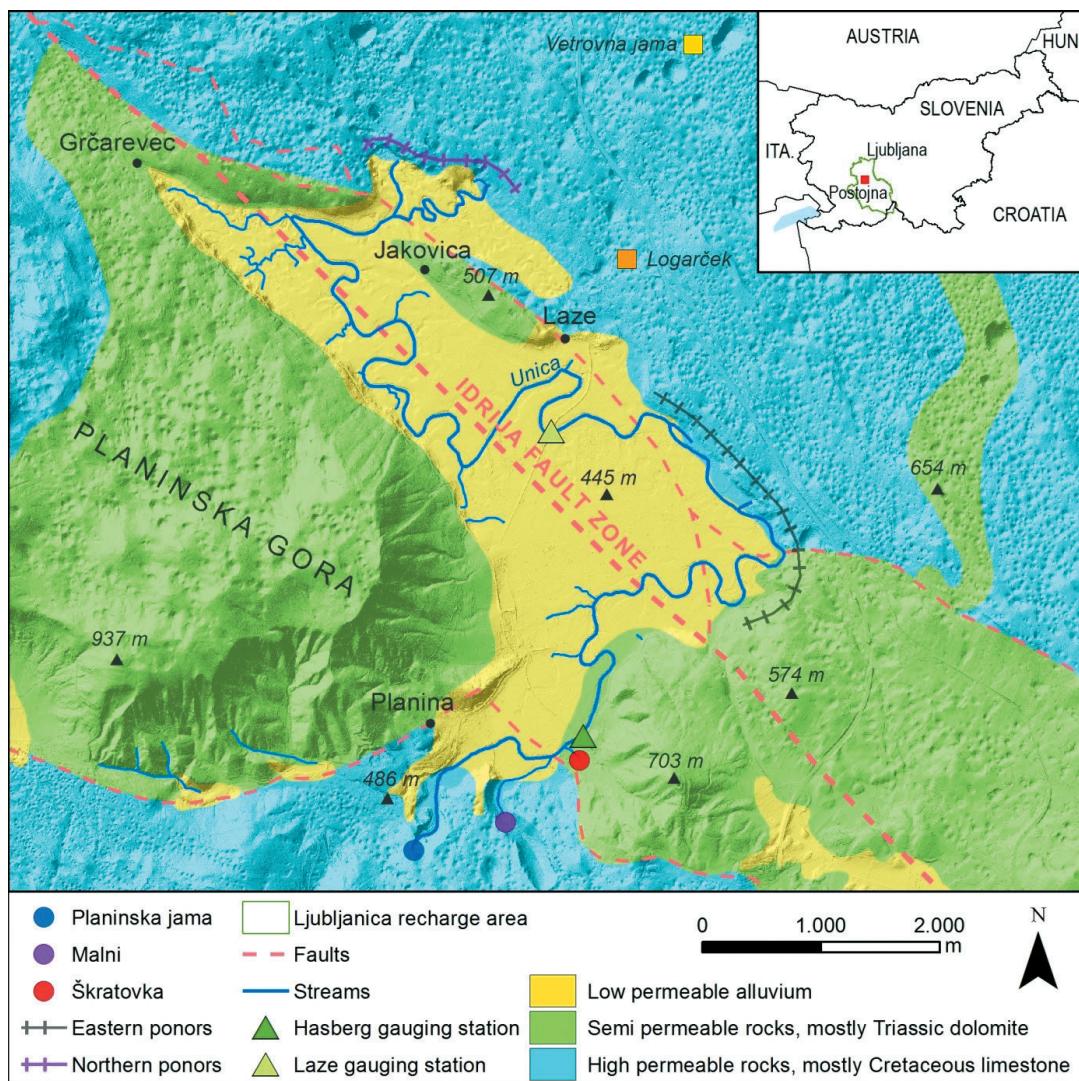


Figure 15: Planinsko Polje and its surrounding area with the position of caves, springs, ponor zones and main gauging stations. The upper right insert shows the regional position of the area in Slovenia.

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).

Besides Planinska Jama, the most important recharge input is the spring of Malni (Malenščica River,  $Q_{\min} = 1.1 \text{ m}^3/\text{s}$ ,  $Q_{\text{mean}} = 6.7 \text{ m}^3/\text{s}$ ,  $Q_{\max} = 9.9 \text{ m}^3/\text{s}$ ; 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



Figure 16: Two of the many ponors draining Planinsko Polje. Left: Velike Loke located at the eastern border. Right: So-called Putickova štirna located at the terminal outflow zone at the northern border (Photos: M. Blatnik).

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 (Figure 16). 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  $18 \text{ m}^3/\text{s}$  and individual outflow ranging between  $1.0$  and  $5.6 \text{ m}^3/\text{s}$  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  $60 \text{ m}^3/\text{s}$  (ŠUŠTERŠIČ 2002).

Similar 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. 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  $10.3 \text{ km}^2$  and more than forty 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. 2021). The longest periods the polje has been overflowed 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. 2021). To prevent extreme flooding in Planinsko Polje, different measures have been undertaken in the beginning of 20<sup>th</sup> 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 (Figure 16).

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 meters lower than the flood of February 2014. The only explanation is that all ponor zones have been cleaned in between (MAYAUD et al. 2019).

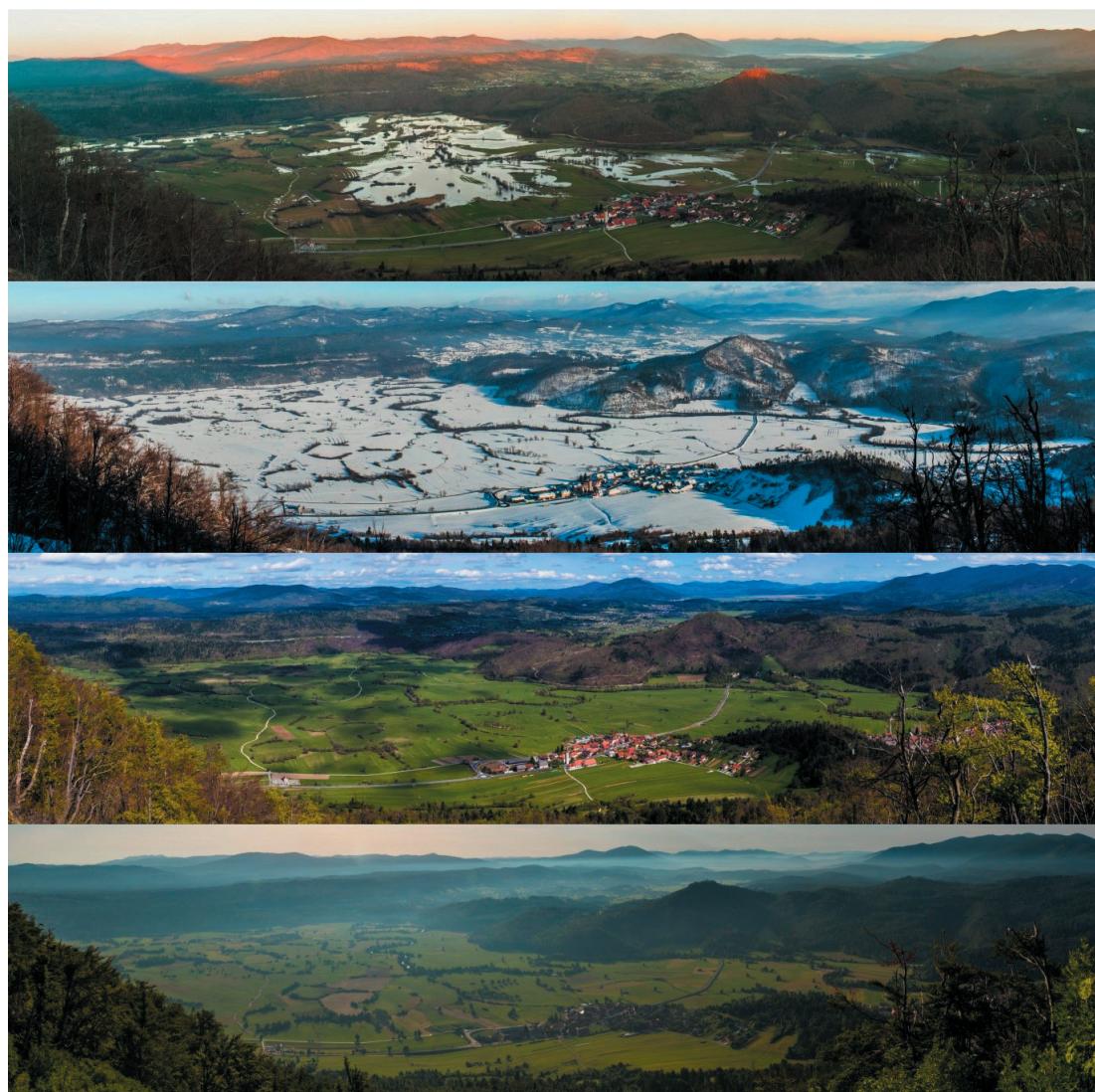


Figure 17: Planinsko Polje in different hydrological situations (Photos: M. Blatnik).

Planinska Jama (Planina Cave) is a large spring cave located on the southern edge of Planinsko Polje (Figs. 18 & 19). The cave is about 6.6 km long and consists mostly of large active river passages with cross-sections larger than 100 m<sup>2</sup>.

The cave entrance is 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. The Pivka Branch and the Rudolfov Rov (passage south of the Rak Branch), on the other hand, are

formed in Upper Cretaceous massive limestone and breccia with Caprinidae and Chondrodontae (HABIČ 1984). Both parts of the cave end with siphons that have been dived but do not yet have a connection to the upstream systems. However, the recent dives in the final siphon of the Pivka Branch give justified hope that a connection to the Postojnska jama cave system could be established in the near future.

The cave is known to be the confluence of two important regional rivers (Figs 18, 19): the Pivka River, which drains a large allochthonous catchment through the

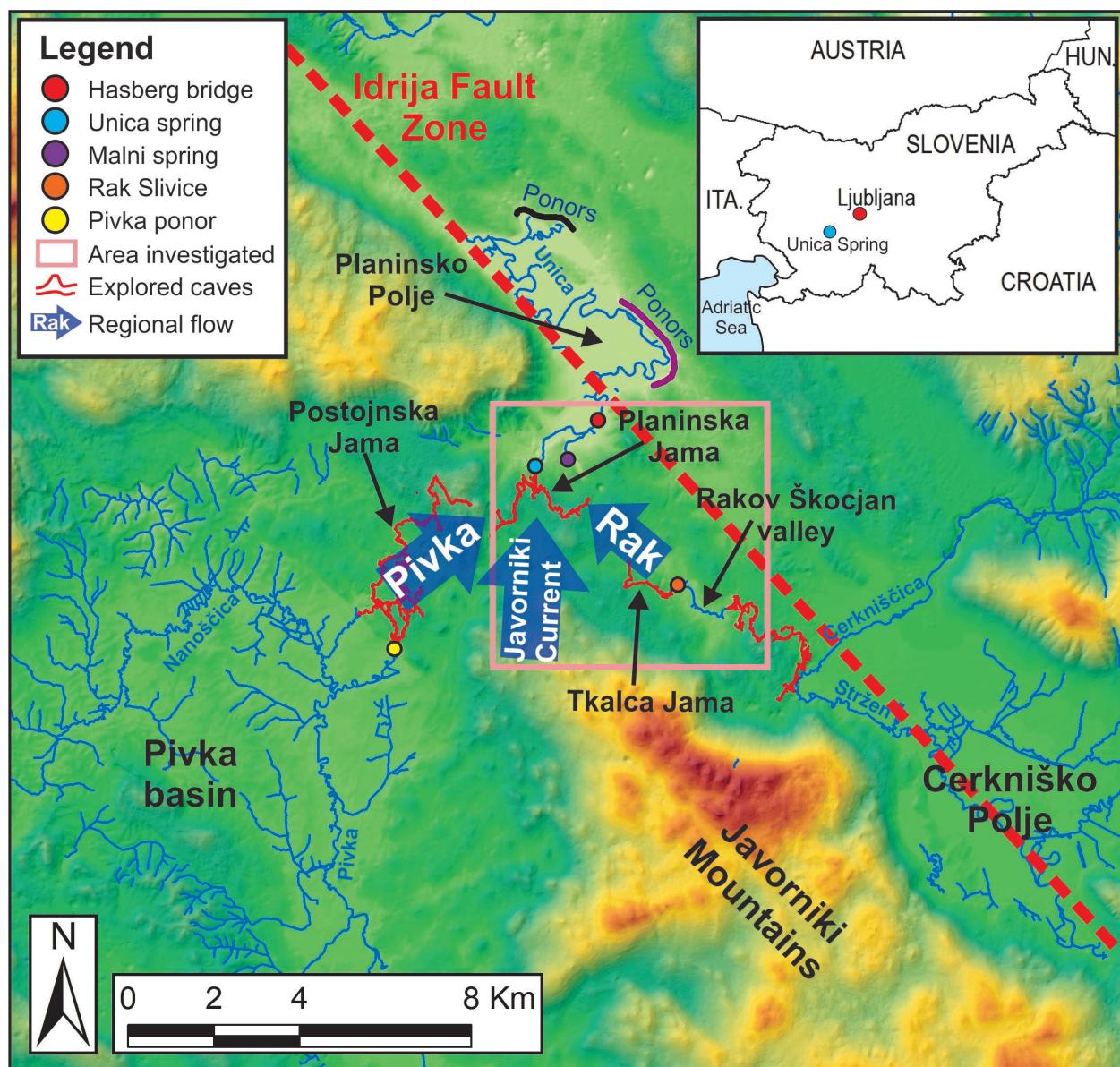


Figure 18: Map of the Unica catchment with explored cave systems, main springs and ponors, and assumed flow directions. The pink frame delineates approximately the area that is further investigated. Inset: location of the Unica Spring in Slovenia.

Postojnska Jama (GABROVŠEK et al. 2010; KAUFMANN et al. 2016; KOGOVŠEK 2022) and reaches the confluence with the cave via the Pivka Branch, and the Rak River, which carries water from Rakov Škocjan and Cerkniško Polje via the Rak Branch. Finally, a large amount of water also flows into the Rak Branch via the siphon of the Javornik Current, which is located below the Mysterious Lake (Figure 21) (KAUFMANN et al. 2020). The water exits the cave under the common name Unica River with a discharge between 0.2 and 90 m<sup>3</sup>/s (KOGOVŠEK 2022).

The different parts of the aquifer that feed the Unica spring show considerable differences in water contribution (SAVNIK 1960, KOGOVŠEK 2022). During high water conditions, there is a groundwater divide in the Javorniki Mountains. The water discharges through the western, eastern and northern edges of the massif. Then the nearby Malni Spring (Figure 18), which is mainly fed by the autogenic Javorniki water and allogeic water from the Rakov Škocjan reaches a maximum discharge of 9-10 m<sup>3</sup>/s (KOGOVŠEK 1999; KOVACIĆ 2010, 2011). As the spring is damped, the Rak Branch is activated and acts

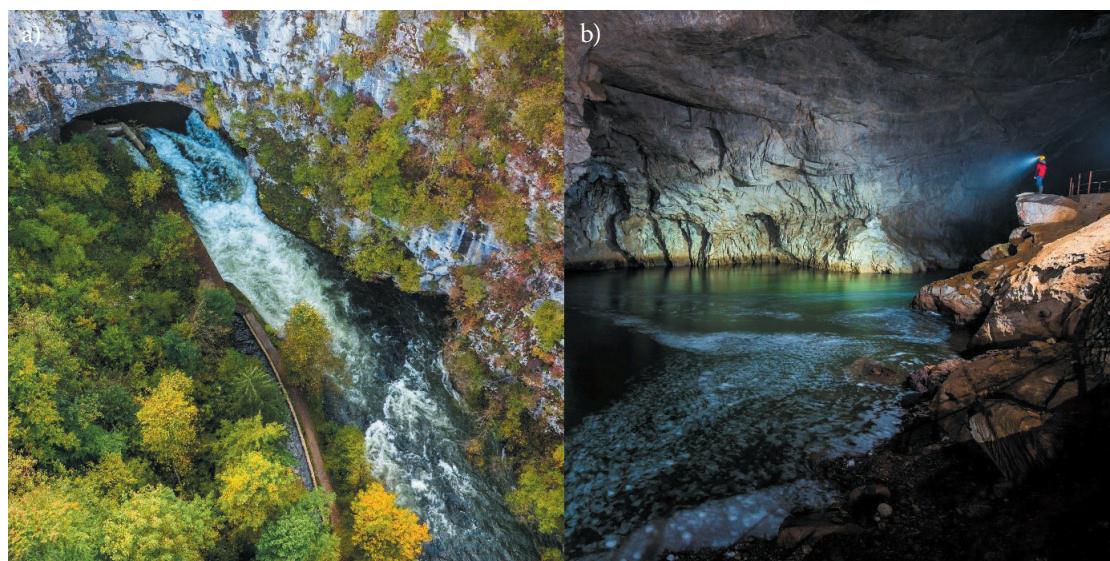


Figure 19: Planinska Jama. a) Cave entrance. b) Confluence of the Pivka and Rak Branches (Photos: M. Blatnik; RI-SI-EPOS).

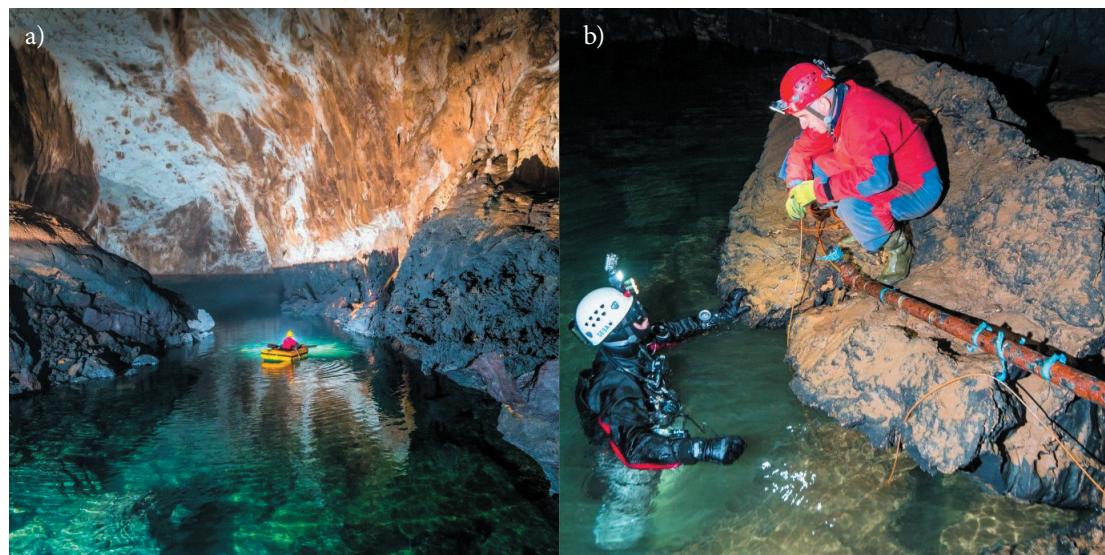


Figure 20: Planinska Jama. a) example of typical large cave passage in the Rak Branch. b) recent diving exploration in the Mysterious Lake and Javornik Current (Photos: M. Blatnik).

as an overflow, while the Unica spring also receives water from the Pivka Branch. At low-flow, after the Cerkniško Jezero is drained, the outflow is solely directed towards the Malenščica spring, while the Unica spring is fed exclusively by the Pivka Branch (KAUFMANN et al. 2020, Kogovšek 2022). The inversion of the flow direction between the Mysterious Lake and the

Malenščica spring was numerically simulated with a pipe flow model (KAUFMANN et al. 2020).

There are also differences in flow velocities between low and high flow conditions (PETRIČ et al. 2018). In general, the apparent dominant flow velocities in the karst aquifer are five times higher during high water (between 20 and 25 m/h) than during low water condi-

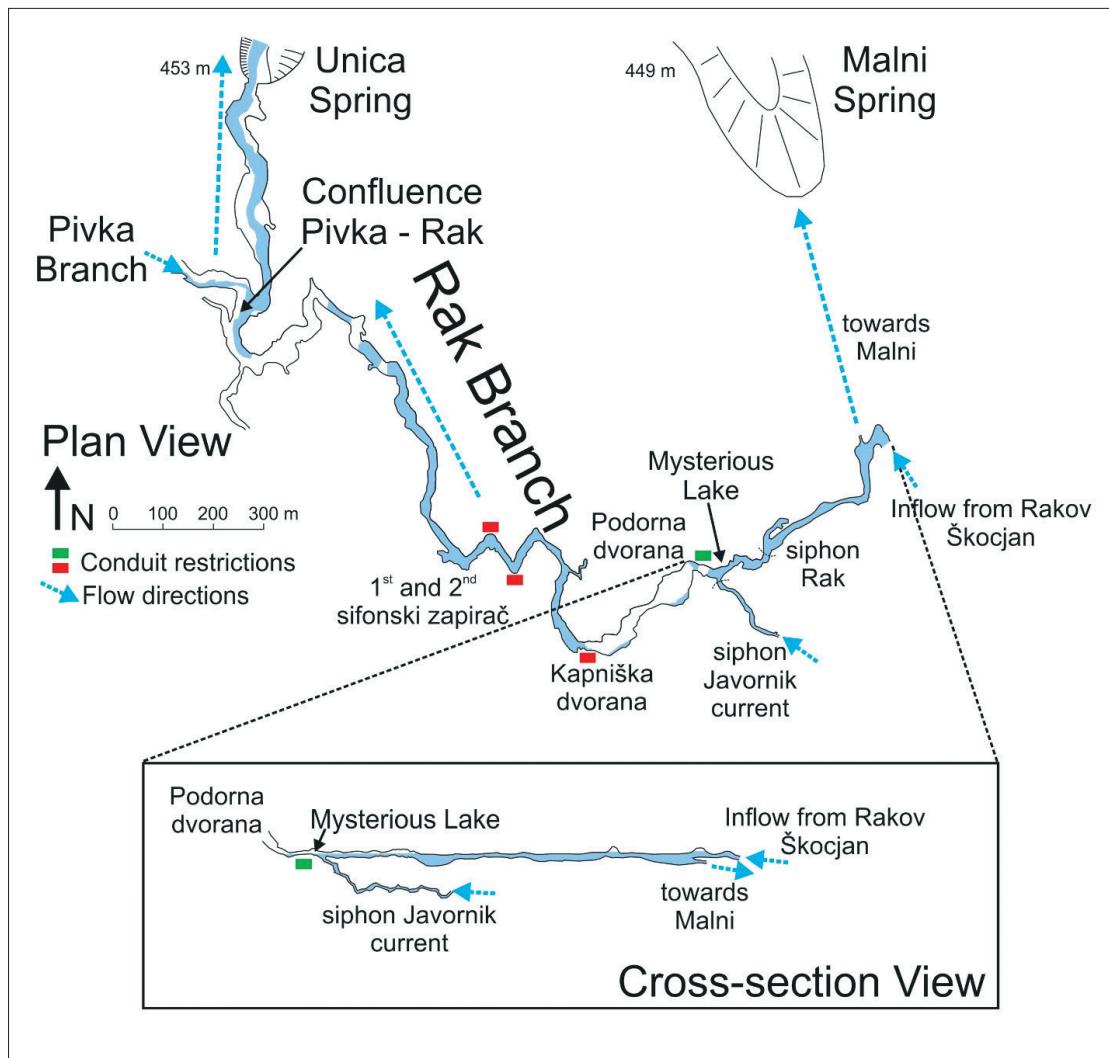


Figure 21: Detailed view of the Rak Branch of Planinska Jama and cross-section of its terminal siphon in the Mysterious Lake (Gams 2004; Kaufmann et al. 2020).

tions ( $\sim 4$  m/h). In the well-developed conduit networks of Karlovica-Zelške Jame, Tkalca-Planinska Jama and Postojnska-Planinska Jama, flow velocities were up to fifty or even ninety times higher during high water (between 170 and 1000 m/h) compared to the velocities observed during low water ( $\sim 4$ -23 m/h) (PETRIČ et al. 2018).

### Groundwater flow between Planinsko Polje and Ljubljana Springs

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.

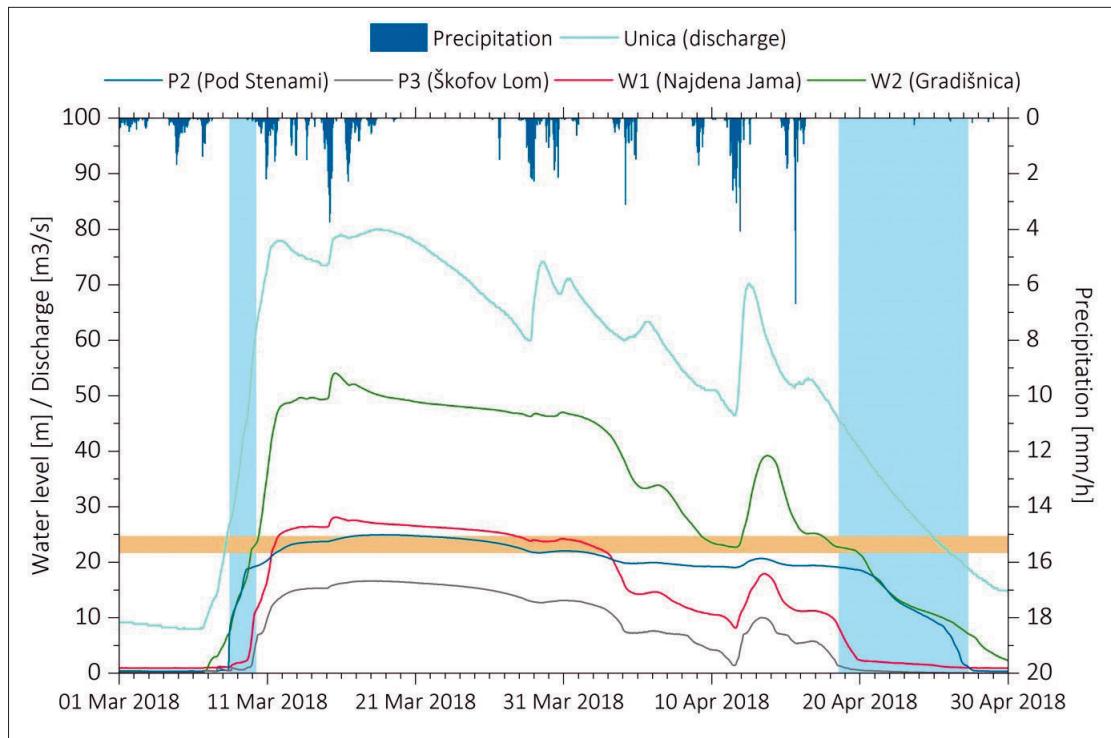


Figure 22: Water level dynamic in selected caves between Planinsko Polje and Ljubljana springs during high water event in March and April 2018. Blue areas denote different response of water level change, orange area denotes temporal slower increase(decrease) of water level in cave Gradišnica.

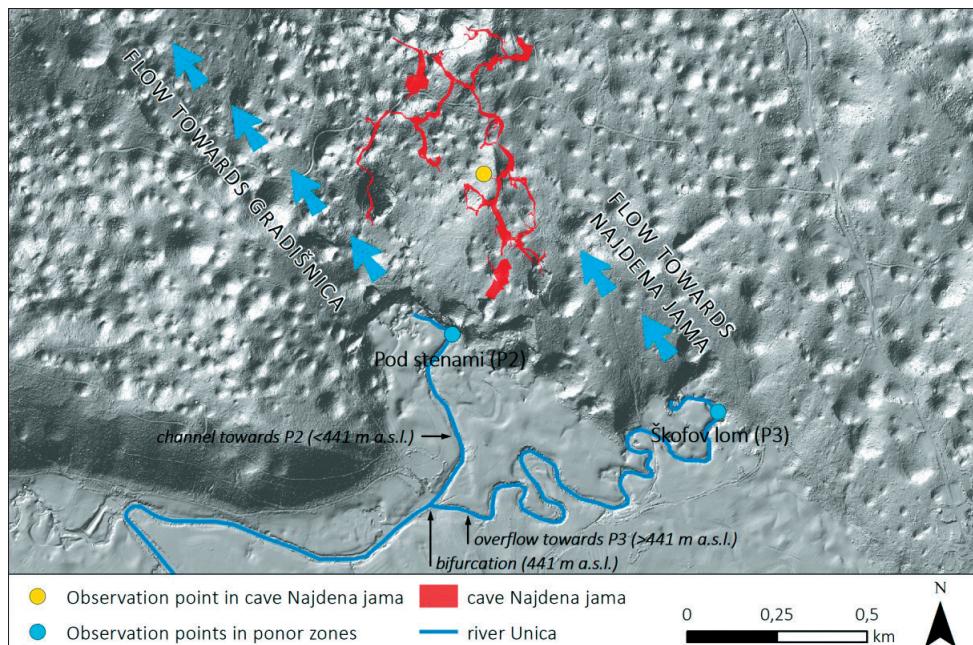


Figure 23: Assumed groundwater flow directions between the northern ponors (Pod Stenami and Škofov Lom) and Najdena Jama and Gradišnica.

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 22 presents the recorded dynamics of underground water in March and April 2018.

Water level measurements showed complex dynamics in water level variations (up to 60 m, Figure 22) 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 depen-

dent on the duration of flooding of Planinsko Polje (Figure 22). 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. 22 & 23). This dynamic explains late response in cave Najdena Jama in comparison to nearby located ponor zone Pod Stenami. There, the water bypasses cave Najdena jama, which is recharged through more apparent ponor zone Škofov Lom (Figure 23). Water level hydrographs also shows in-



Figure 24: 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).

flection 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.

### The Springs of Ljubljanica River

The water of the Ljubljanica karst catchment emerges at number of springs located near Vrhnika, at the rim

of the Ljubljana Basin. The line of spring generally follows the contact of Jurassic limestone and Quaternary sediments underlain by Triassic dolomite (CELARC et al. 2013) (Figure 25). Most important springs are aligned along the gradually retreating pocket valleys of Močilnik and Retovje. The springs at Močilnik ( $Q_{av} \approx 6-7 \text{ m}^3/\text{s}$ ) feed Mala (=small) Ljubljanica and springs at Retovje ( $Q_{av} \approx 16 \text{ m}^3/\text{s}$ ) feed Velika (= big) Ljubljanica, the main tributaries related to karst springs of the Ljubljanica River. Easterly, another tributary Ljubija ( $Q_{av} \approx 6-7 \text{ m}^3/\text{s}$ ) is also fed by several springs. The eastern-

most set of springs at Bistra are already positioned in Triassic dolomites and add on average  $7 \text{ m}^3/\text{s}$  to the last true karstic tributary of Ljubljanica. Mean annual discharge of the Ljubljanica karst springs is about  $24 \text{ m}^3/\text{s}$  (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 (Figure 26). The temperature lag is higher and the hydrograph lacks short-time disturbances. This indicates longer retention time (BLATNIK et al. 2019). Water tracing in 1970s also revealed, that the direct flow from the Cerkniško Polje, mostly goes to the Bistra springs (GOSPODARIČ & HABIČ 1976).

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 & STEPPIŠNIK 2011).

Between Logatec and Vrhnika several large collapse dolines formed along the main drainage pathways of underground Ljubljanica River (CELARC et al. 2013). Table 1 lists the bottom elevations, and dimensions of the largest. Estimated volume of the biggest of them (Velika Drnovica) is around 1.6 million  $\text{m}^3$ .

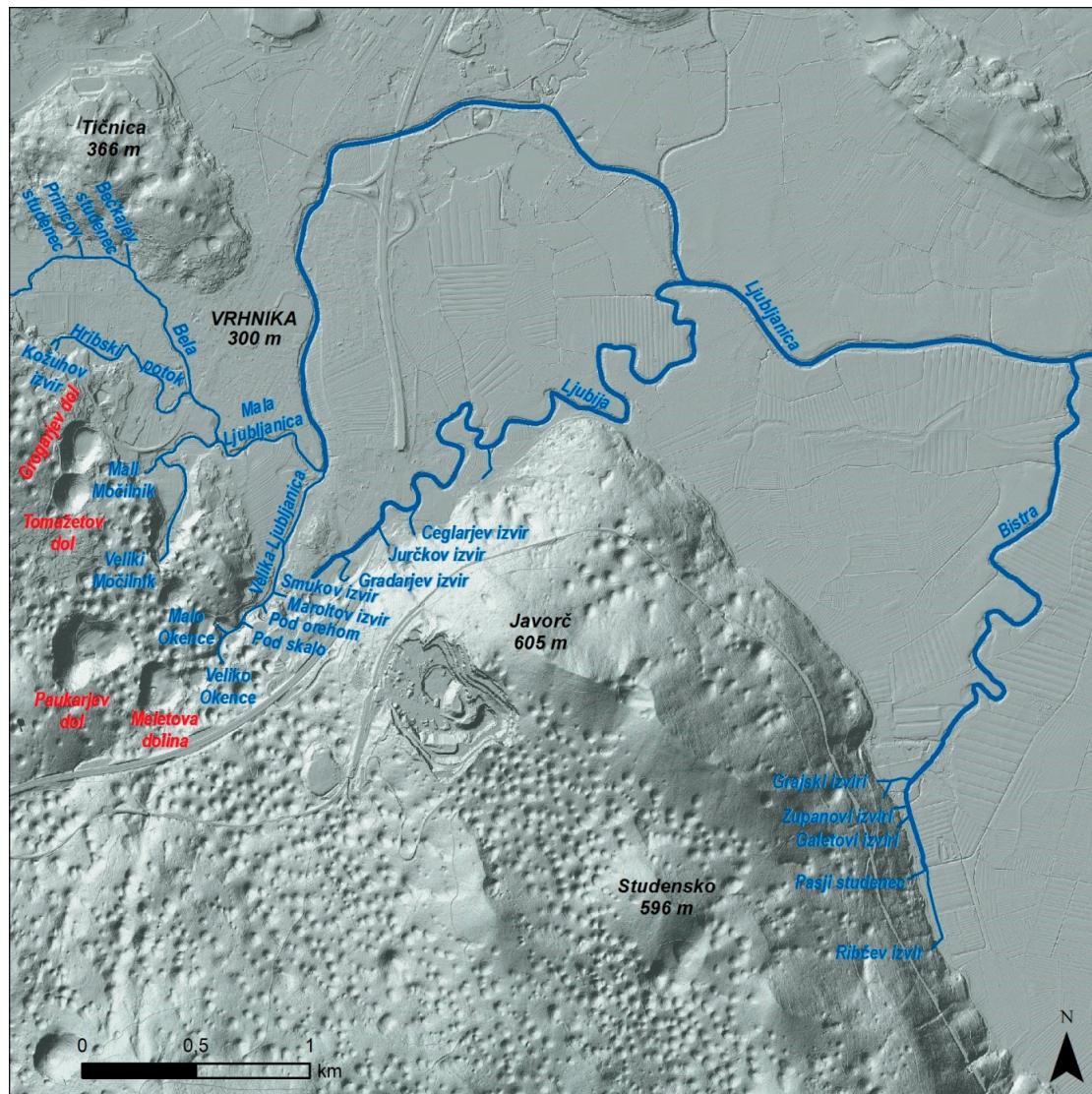


Figure 25: Location of collapse dolines and Ljubljanica springs near Vrhnika.

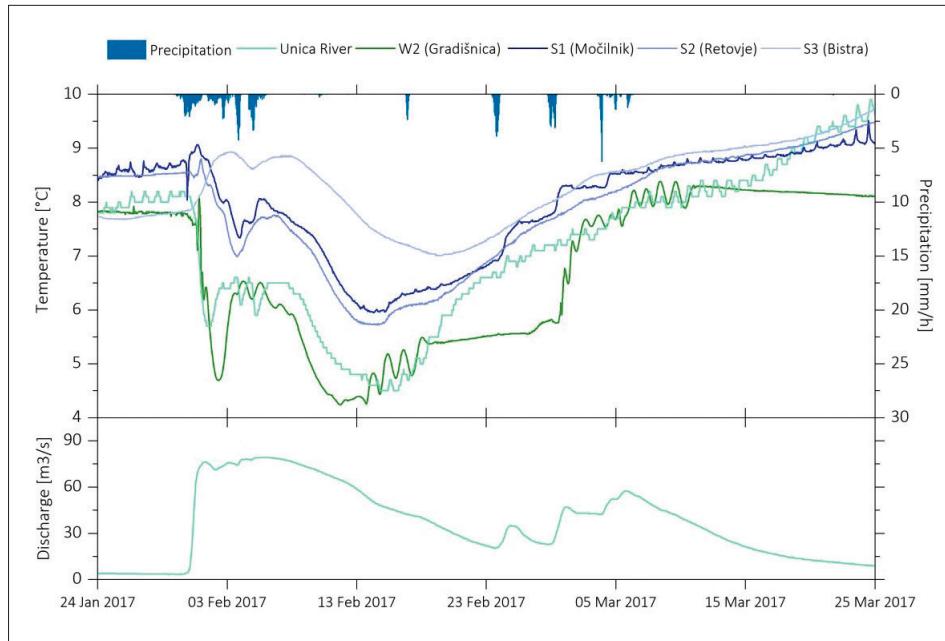


Figure 26: Temperature hydrographs at springs of Ljubljanica compared to the cave Gradišnica and Unica River.

Tab. 1: 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 the immediate hinterland of the main Ljubljanica spring (Tab. 2, Figure 25). The bottoms are relatively levelled and covered with over 30 m thick loamy sediment. The elevation of the

bottoms of all these dolines are within 10 m of each other. Flooding has been observed in Grogarjev Dol. The estimated volume of Paukarjev dol is about 1 million m<sup>3</sup> (GABROVŠEK & STEPNIK 2011).

Tab. 2: 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

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