UNDERSTANDING THE TEMPORAL VARIATION OF FLOW DIRECTION IN A COMPLEX KARST SYSTEM (PLANINSKA JAMA, SLOVENIA)

RAZUMEVANJE ČASOVNE SPREMENLJIVOSTI SMERI TOKA V KOMPLEKSNEM KRAŠKEM SISTEMU (PLANINSKA JAMA, SLOVENIJA)

Georg KAUFMANN[1,*], Cyril MAYAUD[2], Blaž KOGOVŠEK[3] & Franci GABROVŠEK[4]

Abstract   UDC 556.3:551.444(497.4Planina)
Georg Kaufmann, Cyril Mayaud, Blaž Kogovšek & Franci Gabrovšek: Understanding the temporal variation of flow direction in a complex karst system (Planinska Jama, Slovenia)
Karst aquifers are abundant, but vulnerable water resources. Therefore, a deeper understanding of possible mechanisms that determine the properties of karst springs is crucial. In this work, we present an example of Unica Spring and Malni Spring, the two main outlets of a large karst system in the Notranjska karst region, Slovenia. Although the two springs share same catchment area, the flow distribution between them shows an interesting behaviour: At low-flow conditions Malni Spring is the main outlet, while Unica spring receives almost no water. During high water events, discharge of Malni Spring stays limited and Unica Spring becomes the main outlet. We relate these observations to the local geometry of the channels and breakdowns in the remote part of the Planinska Jama (Planina Cave), called Mysterious Lake. There, waters from Rakov Škocjan and Javorniki aquifer merge and further diverge to both springs. At low water conditions, the outflow towards the Unica Spring is restricted by the breakdown, so that most of the inflow is directed towards the Malni Spring. With increasing recharge, the level in Mysterious Lake rises until the water starts to flow over the breakdown along a system of large channels (Rak Branch of Planinska Jama) to the Unica Spring. The breakdown level

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Georg Kaufmann, Cyril Mayaud, Blaž Kogovšek & Franci Gabrovšek: Razumevanje časovne spremenljivosti smeri toka v kompleksnem kraškem sistemu (Planinska jama, Slovenija)
Kraški vodonosniki so izdatni, a ranljivi vodni viri, zato je razumevanje mehanizmov, ki vplivajo na pretoke kraških izvirov, zelo pomembno. V prispevku obravnavamo primer izvira reke Unice v Planinski jami in izvira v Malnih, ki drenirata kompleksen vodonosnik Notranjskega krasa. Čeprav imata izvira skupno zaledje, je porazdelitev pretoka med njima precej nenavadna. Ob nizkem vodostaju prevladuje izvir v Malnih, izvir reke Unice v Planinski jami pa od skupnega zaledja prejema le majhen del vode. Ob visokem vodostaju je pretok izvira Malni omejen, izvir Unice pa postane glavni iztok sistema. V članku ta opažanja pojasnimo z lokalno porazdelitvijo kanalov in podora povezanih s Skrivnostnim jezerom v Planinski jami. Tja se steka voda iz Rakovega Škocjana in vodonosnika Javornikov in od tam odteka proti obema izviroma. Podorno območje pred Skrivnostnem jezerom ob nizkih vodah omejuje odtok proti izviru Unice, zato večino vode odteče proti izviru Malni. Ob naraščanju dotoka se nivo v Skrivnostnem jezeru dvigne nad podor, zato voda prosto odteče v velike rove Rakovega rokava proti izviru Unice. Višina preliva omejuje hidravlični tlak in pretok proti izviru Malni. Opisano dogajanje smo preverili s hidravličnim modelom, ki ga sestavljajo znani in predvideni

[1] Georg Kaufmann*, Institute of Geological Sciences, Geophysics Section, Freie Universität Berlin, Malteserstr. 74-100, Haus D, 12249 Berlin, Germany, Address, e-mail: georg.kaufmann@fu-berlin.de

[2] Cyril Mayaud, Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia. UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia. e-mail: cyril.mayaud@zrc-sazu.si

[3] Blaž Kogovšek, Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia. UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia. e-mail: blaz.kogovsek@zrc-sazu.si

[4] Franci Gabrovšek, Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia. UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia. e-mail: gabrovsek@zrc-sazu.si

* Corresponding Author

keeps the hydraulic head and the flow towards Malni Spring limited. To verify this scenario, a hydraulic conduit model was made based on the known and predicted channels, and inflows calculated from the historical data of discharge measurements at related springs and ponors. An inversion procedure was used to obtain a satisfactory fit to the observed discharge data and to constrain the selected model parameters. The model accurately reproduced the observed discharge behaviour under low- and high-flow conditions.
Key words: Karst aquifer, groundwater hydraulics, speleohydrology, modelling, Notranjski kras, Slovenia.

kanali ter pretoki dotokov v Skrivnostno jezero, pri čemer smo slednje izračunali iz arhivskih podatkov pretokov izvirov in ponornic. Izbrane parametre hidravličnega modela smo prilagajali z inverznim algoritmom in dosegli dobro ujemanje modelskih rezultatov in arhivskih meritev ob različnih vodostajih.
Ključne besede: kraški vodonosnik, hidravlika podzemne vode, speleohidrologija, modeliranje, Planinska jama.

INTRODUCTION

Karst aquifers provide freshwater to about 50 % of the population of Slovenia (Turk 2010). In the Slovene Classical Karst, large springs often present an outflow from active cave systems, evolved in complex tectonic/structural settings and catchments typically characterised by mixed allogenic and autogenic recharge and networks of large conduits (Gabrovšek & Peric 2006; Gabrovšek *et al.* 2010; Mihevc *et al.* 2010; Turk 2010; Ravbar *et al.* 2012; Kaufmann *et al.* 2016). This makes their hydraulic response very variable in time: strong and pronounced flood peaks, steep recession limbs and a minimal base flow during dry periods (Ravbar 2013). The water is transmitted rapidly through the aquifer, and is potentially very vulnerable to contamination (Ravbar & Goldscheider 2007; Ravbar & Goldscheider 2009). Moreover, the geometry of caves (i.e., shape and distribution of water active channels) as well plays an important role in the aquifer hydraulic behaviour. Restrictions may cause backflooding and activation of higher positioned overflow passages, which may as well divert the flow and affect the size of active catchment (Wagner *et al.* 2013).

Flow diversions along overflow passages can influence both quality and quantity of the water resources available, making the management of the aquifer reserves more challenging. While overflow processes are commonly observed in karst aquifers (Herman *et al.* 2008; Ravbar *et al.* 2012; Birk *et al.* 2014; Mayaud *et al.* 2014; Mayaud *et al.* 2016; Gabrovšek *et al.* 2018; Koit *et al.* 2017), they have been up to now rarely investigated as their own (Mayaud *et al.* 2014; Koit *et al.* 2017). Therefore, it is crucial to deepen our understanding of their functioning, in order to better assess the hydraulic response of the aquifer system. Common methods used in characterisation of karst aquifers include continuous monitoring of physico-chemical parameters of water and dye-tracing techniques, which are able to assess the flow directions and velocities during the conditions of injection. These methods were used to investigate karst aquifers where an overflow was also present (Herman *et al.*

2008; Ravbar *et al.* 2012; Koit *et al.* 2017). While these techniques are very efficient to prove connections between the aquifer sinks and sources, they are solely applicable at accessible points such as springs, ponors or water-active caves. As the effect of overflow processes may vary spatially and temporally (Wagner *et al.* 2013; Mayaud *et al.* 2016), the combination of the above mentioned methods with indirect techniques such as groundwater modelling is needed to assess the geometry of aquifer unexplored parts. Groundwater modelling presents the advantage to combine all data available in a given area and to be very versatile: many hypotheses inferred from field observation and results of monitoring techniques can be therefore tested.

Up to now, only Mayaud *et al.* (2014) used groundwater modelling in combination with event-based timesseries analyses to identify the location of an overflow within an Austrian karst aquifer. While the method proved to be reliable and identified properly the overflow location, it was not possible to estimate geometrical parameters controlling the system's hydrogeological behaviour. This was due to the continuum nature of the model employed, which was not considering conduit flow. In addition, as the model was highly simplified and aimed solely to reproduce the overflow behaviour, only numerical data were used as input without any calibration step. Therefore, the use of another modelling approach able to consider the conduit nature of karst aquifers would be recommended to allow both calibration and parameter estimation.

This work focuses to the temporary flow diversion between the two main springs of the Unica River at the southern rim of Planinsko Polje, Slovenia. The Malni Spring and Unica Spring share a common recharge area, but the distribution of flow between them heavily depends on the hydrogeological situation within the aquifer. During low-flow, the Malni Spring is the main outlet of the system, whilst most of the discharge emerges at the Unica Spring during high-flow conditions (Petrič 2010).

To resolve the mechanisms leading to such behaviour, we focused on the size and distribution of channels in the remote part of the Planinska Jama (Planina Cave) and extracted necessary data from archive hydrographs. All observed and inferred information were integrated into the conduit-based Storm Water Management Model (SWMM) developed by US Environmental Protection Agency (EPA; Rossman 2010). SWMM is an open-access software made primarily to simulate the propagation of flood waves through sewage networks. The model solves Saint-Venant equations for a wide variety of settings and has been successfully applied to simulate flow in conduit dominated karst systems (Campbell & Sullivan 2002; Gabrovšek & Peric 2006; Peterson & Wicks 2006; Wu et al. 2008; Chen & Goldscheider 2014; Kaufmann et al. 2016; Gabrovšek et al. 2018).

The SWMM model approximates the system by considering turbulent flow in a limited set of discrete channels and does not account for matrix flow. While it surely plays an important role during low-flow conditions, the assumption of the conduit-dominated flow is reasonable within this work, as focus is solely made to conditions from medium to high flow.

STUDY SITE

The area investigated within this study is the karst system related to two major springs of the Unica River located at the southern rim of Planinsko Polje. To this extend, we first give a brief description of the regional hydrogeological context and then focus to the local geometry of Planinska Jama (Planina Cave), which gives rise to specific behaviour of the spring discharge.

UNICA CATCHMENT
The Unica Catchment is about 746 km^2 large (Petrič 2010) and belongs to the Ljubljanica Recharge Area, a 1200 km^2 large karstic region located in central Slovenia (Gospodarič & Habič 1976, Fig. 1). The catchment is drained by two permanent springs at the southern rim of Planinsko Polje (Fig. 1). The Unica Spring is located at
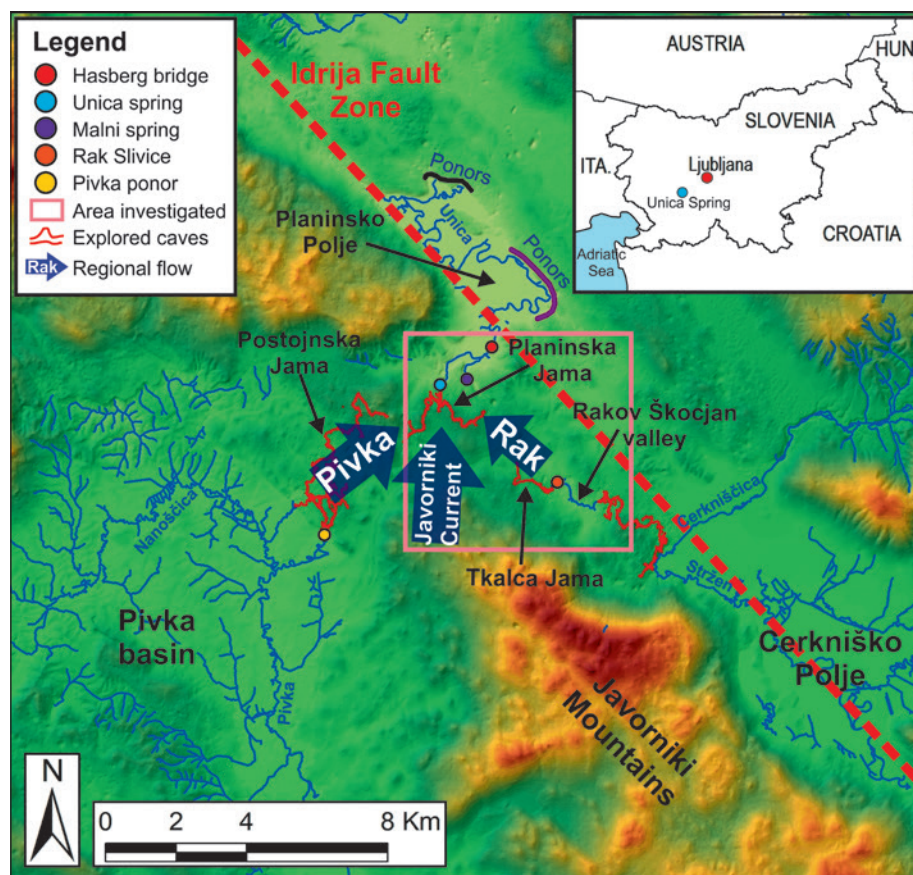

Fig. 1: Map of the Unica catchment with explored cave systems, main springs and ponors, and assumed flow directions. The pink frame delineates approximately the area that is further investigated. Inset: location of the Unica Spring in Slovenia. DEM data (1 m resolution) was provided by the Slovenian Environment Agency (ARSO 2019a).

entrance of Planinska Jama at an elevation of 453 m a.s.l. This spring (Q_{min} = 0.1 m³/s, Q_{max} = 90 – 100 m³/s) is the main outlet of the catchment at high waters. The Malni Spring (Q_{min} = 1.5 – 2m³/s, Q_{max} = 9 – 10 m³/s) is located 800 m eastward from Planinska Jama at an elevation of 449 m a.s.l. and is the system's main outlet at low water conditions (Ravbar 2013). The Malni Spring is an important regional source of freshwater, supplying a population of about 20,000 people (Petrič 2010). This spring flows as Malenščica River for one kilometre and joins the Unica River before the Hasberg Bridge gauging station (Fig. 1). The Unica River crosses Planinsko Polje and sinks along two major ponor zones located at the eastern and northern border of the Polje.

The position of the spring zone is pre-determined by the regional structure and lithology. The major regional structural element is the Idrija Fault Zone, which acts as a flow barrier for groundwater flowing from the Notranjska region towards the Ljubljana Basin on the north.

The Idrija Fault Zone forces the groundwater to surface, which led to the formation of a series of Dinaric Poljes, with springs and ponor zones at the rims and over-crossing superficial streams (Kovačič & Ravbar 2010; Blatnik *et al.* 2017; Blatnik *et al.* 2019).

PLANINSKA JAMA (PLANINA CAVE)

Most of the water emerging at the springs flows through Planinska Jama (Planina Cave). The cave is known for its unique confluence of two major underground streams (Figs. 1 & 2). The streams capture waters from two distinct sub-catchments (Ravbar 2013): a) The *Pivka Branch* receives water from the Pivka Basin, an area of 250 km² drained by two major streams, the Pivka River and its tributary the Nanoščica River (Fig. 1). b) The *Rak Branch* is recharged by waters from a cascading set of poljes and intermediate karst aquifers located to the south-east. The last in the line is the Rakov Škocjan karst valley, where the water sinks into the ponor of Tkalca
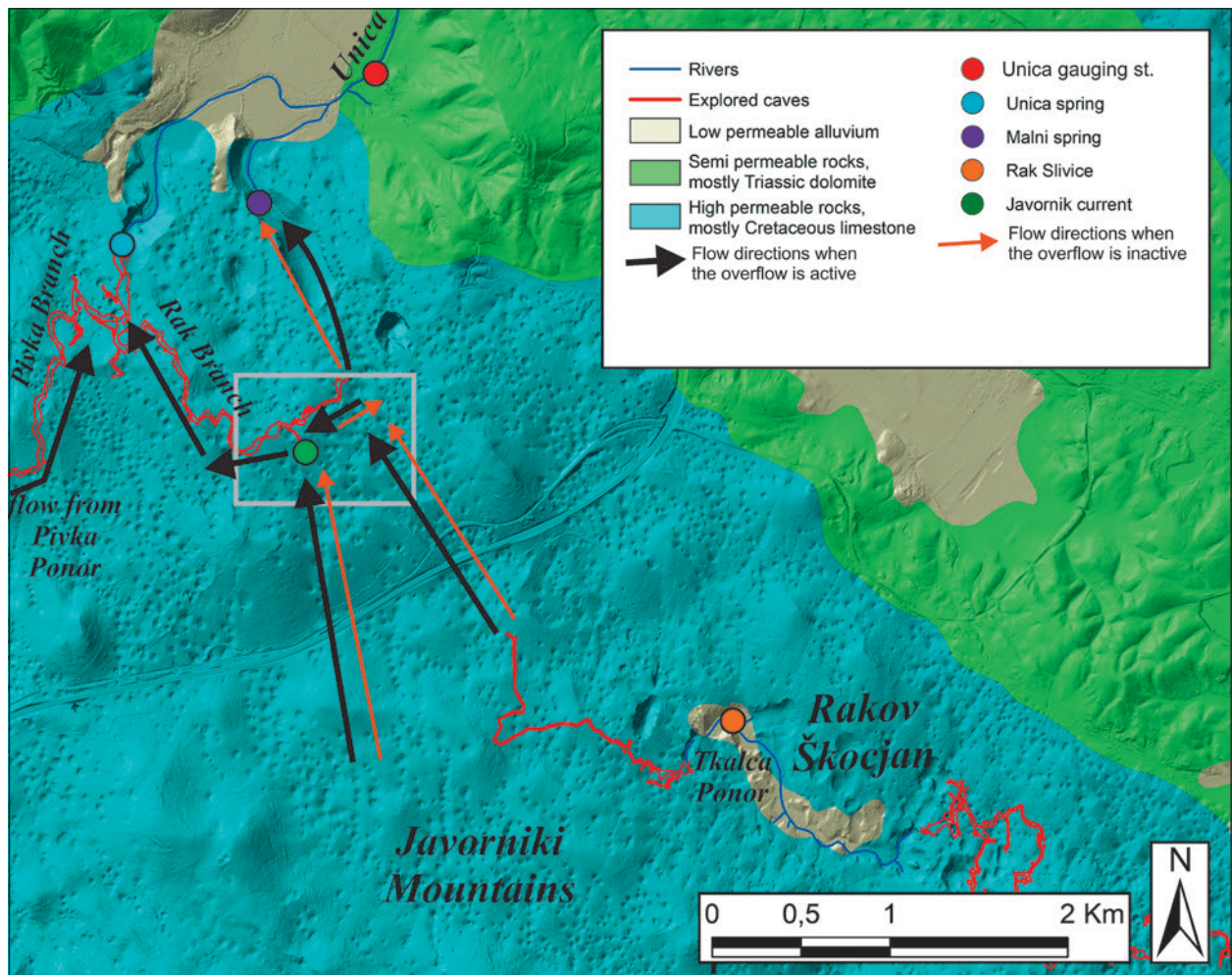

Fig. 2: Hydrogeological map of the investigated area with relevant in- and outlets. The flow directions and supposed catchment boundaries depending on the water level in the aquifer system are represented. Part of the Pivka Branch is also visible on the right. DEM data (1 m resolution) was provided by the Slovenian Environment Agency (ARSO 2019a).

Jama (Tkalca Cave) and contributes to the Rak Branch. The Rak Branch also receives an autogenic component from the Javorniki Mountains called Javorniki Current (Figs. 1 and 2).

Rak Branch and Mysterious Lake

The Rak Branch is a 1.5 km long open-flow channel extending between its junction with the Pivka Branch and its most remote part called Misteriozno Jezero (referred as Mysterious Lake hereafter, Fig. 3). The channel has a large cross-section (> 10 m x 10 m) along most of its length. Few relatively short constrictions - marked in red on Fig. 3, show signs of occasional pressurised flow, but are not known to cause substantial backflooding. Minor breakdowns cause local ponding as well, but do not hinder the flow along the channel. However, two large breakdown chambers in the terminal part of the channel present major flow disturbances (Fig. 3).
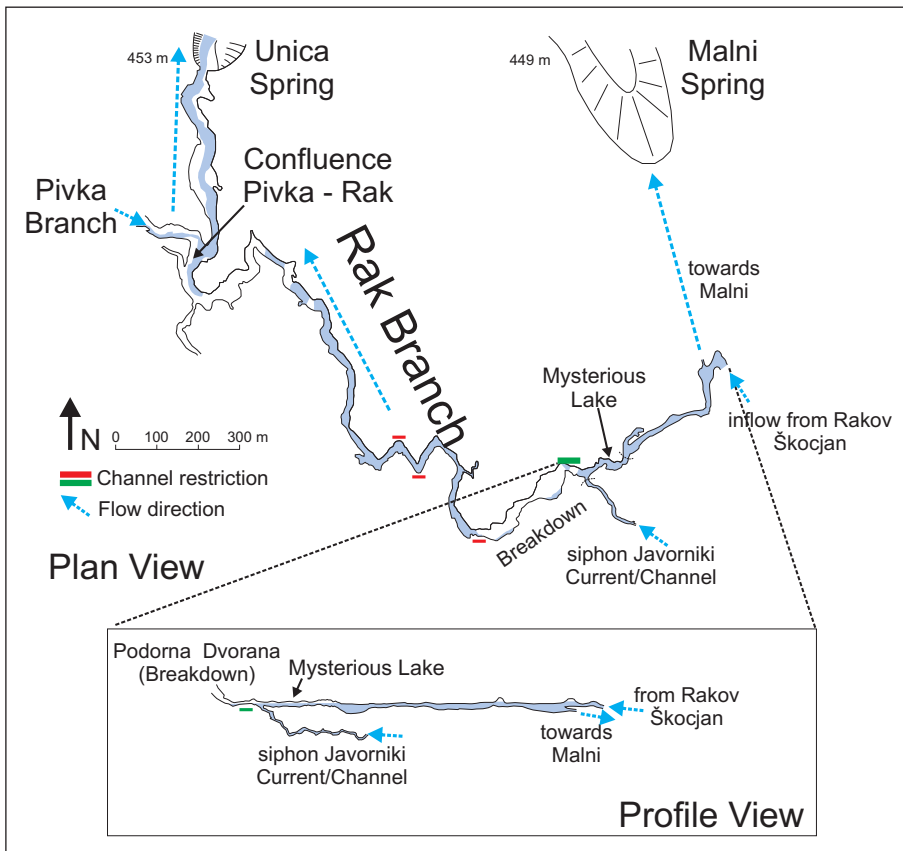

Fig. 3: Plan and cross-section view of the explored passages of the Rak Branch. The constrictions described in the text are indicated in red and green. The figure was composed based on two maps covering the Planinska Jama cave system (Gams 2004) and the last cave diving explorations upstream from the Mysterious lake (Cave Register 2019).
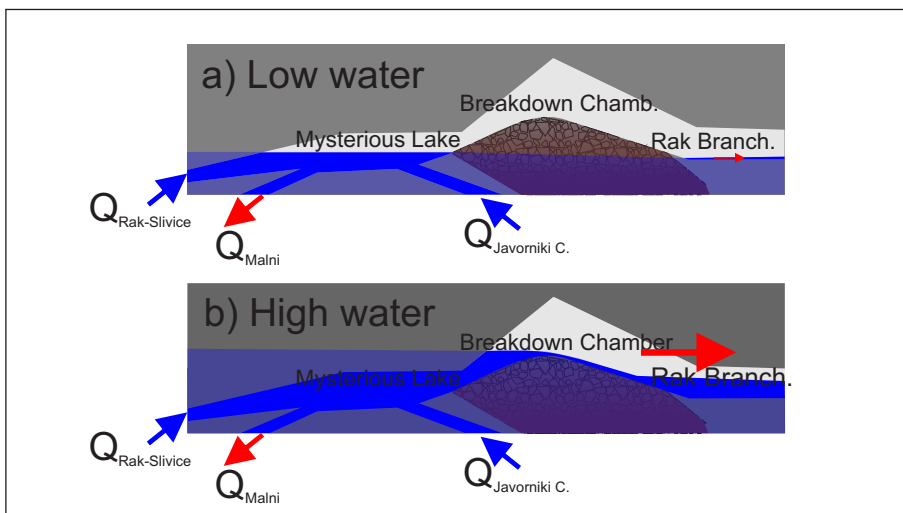

Fig. 4: Conceptual hydrological model of the Mysterious Lake leading to overflow into the Rak Branch at high water situations; (a) low-flow, (b) high-flow conditions.

There are two known inflows and two known outflows into/from the Mysterious Lake (Figs. 3 & 4):

- The water from Rakov Škocjan and Javorniki Mountains enters Mysterious Lake along two channels that are submerged and only partially explored.
- The water from Mysterious Lake is diverted towards the Malni Spring and into the Rak Branch further toward the Unica Spring. The conduits toward the Malni Spring are submerged and unexplored.

Flow divergence at Mysterious lake

The assumptions on the flow divergence at Mysterious lake are based on sporadic observations and observed flow distribution at the springs. During low- and medium-flow conditions, most of the water from the Mysterious Lake is diverted towards the Malni Spring as large breakdowns in Podorna dvorana (marked green in Fig. 3, see also Fig. 4) prevents outflow along the Rak Branch (Fig. 4a). At high water (Fig. 4b), the level in the Mysterious Lake rises to accommodate increasing head loss in the conduits connected to the Malni Spring. When the level is above the lowest position of the breakdown pile, the water starts to flow freely into the highly conductive Rak Branch toward the Unica Spring.

This mechanism also explains the flow distribution between both Malni Spring and Rak Branch. During low water conditions, the Malni Spring is the main outlet of the system and the flow along Rak Branch is minimal. However, the discharge at Malni is limited to about 9 – 10 m³/s during high water conditions, where most of the flow is along the Rak Branch to the Unica Spring (Fig. 2). This implies a change of the main flow direction due to the activation and deactivation of an overflow, which leads to a spatial and temporal variation of the catchment size and reserves. Tracer experiments conducted under different hydrological situations in 2008 and 2009 (Gabrovšek *et al.* 2010; Ravbar *et al.* 2012) showed an activation of the Rak Branch when the total discharge of the Unica River was above 4 m³/s at the Hasberg Bridge gauging station. Therefore, when the system is at low water level and the Rak River does not sink into the Tkalca ponor, the recharge of Malni Spring can be reduced to the autogenic water coming from the Javorniki mountain range (Fig. 2). This implies an important variation of water quality, as the recharge switches from mostly allogenic to completely autogenic.

DISCHARGE OBSERVATIONS, CALCULATIONS AND ESTIMATIONS

WATER BALANCE OF THE UNICA SYSTEM: OBSERVED AND CALCULATED HYDROGRAPHS

We now turn to the observed hydrographs of the system as these are crucial constraints of the numerical model presented in the following sections. As the currently available monitoring network does not yet provide data for calculation of all required hydrographs, historical data from 1975 are used. They allow an estimation of all required inputs and outputs. This year was selected due to its hydrological variety (it contains high-flow and low-flow periods). The data are publicly available in archives of the Slovenian Environmental Agency (ARSO 2019b). The data include daily stage and discharge values (measured once per day) for the Malni Spring, for the Unica River at the Hasberg Bridge, for the Pivka River at the Pivka Ponor and for the Rak River at the Slivice station, located a few hundred meters before the Tkalca Jama ponor (Fig. 1). These data enable assessment of flow along the Rak Branch and inflow from the Javorniki Channel under the assumptions of no other sources/sinks. Fig. 5 shows the assumed flow distribution. Assuming flow conservation and no unknown inputs along the whole aquifer system, one can calculate the unknown values from the measured ones:
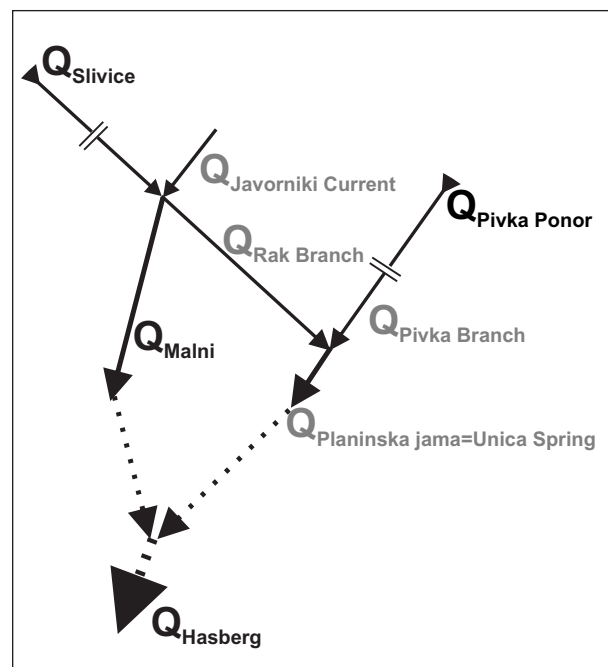

Fig. 5: Distribution of inputs, outputs and flow along the studied system. Black labels represent measured values, grey labels the estimated and calculated values. The figure is not to scale.

$$Q_{Pivka\,Branch} = Q_{Pivka\,Ponor}$$
$$Q_{Planinska\,Jama} = Q_{Hasberg} - Q_{Malni}$$
$$Q_{Rak\,Branch} = Q_{Planinska\,Jama} - Q_{Pivka\,Ponor} = Q_{Hasberg} - Q_{Malni} - Q_{Pivka\,Ponor}$$
$$Q_{Javorniki\,Current} = Q_{Rak\,Branch} + Q_{Malni} - Q_{Slivice} = Q_{Hasberg} - Q_{Slivice} - Q_{Pivka\,Ponor}$$

(Eq. 1)

The reader should have in mind that the estimated discharge is not free of errors due to measurements uncertainties at all stations, especially during high water periods. Furthermore, the assumption that $Q_{Pivka\,Branch} = Q_{Pivka\,Ponor}$ is quite crude, as it neglects possible gain/loss and storage between Pivka Ponor and Planinska Jama. Additional inputs may exist between Slivice and the inflow of Rak into the Mysterious Lake. This would lead to an overestimation of $Q_{Javorniki\,Current}$, but would not change the estimation of outflow from the Mysterious Lake. All flow connections have been confirmed by numerous tracing tests under different hydrological situations (Gospodarič & Habič 1976; Gabrovšek *et al.* 2010; Ravbar *et al.* 2012). However, their quantitative relations have not been determined.

The most critical point is the daily resolution of the dataset, which makes errors in flow calculations, particularly at the onset of large events. Nevertheless, observations made during fieldwork indicate that all neglected values are small compared to the data used, even if the latest should still be taken with some caution.

HYDROLOGICAL SITUATION IN 1975
Two characteristic flood events occurred in 1975 (Fig. 6). The first lasted from the beginning of March to the beginning of May, the second one from the middle of November to the end of December. Between these high-water events, low water conditions prevailed. They were only disturbed by small events mostly triggered by summer storms between the middle of May until the end of
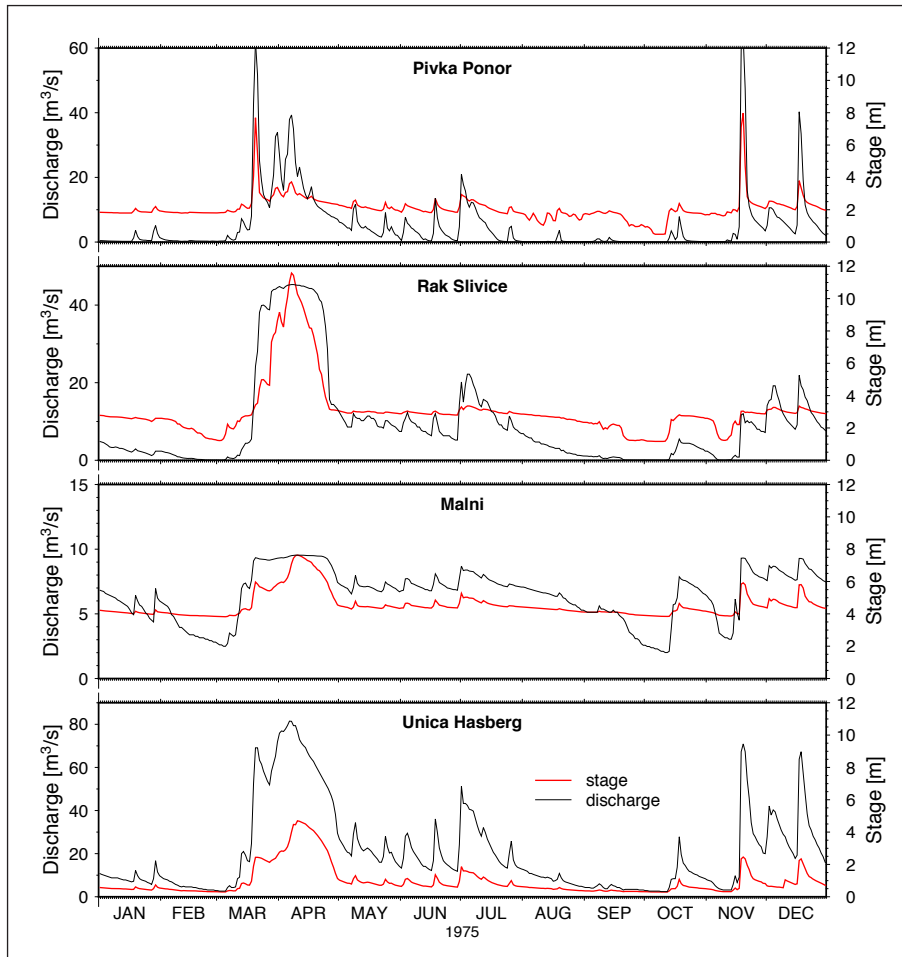

Fig. 6: Observed discharge and stage for the four gauging stations Pivka Ponor, Rak Slivice, Malni Spring, and Unica Hasberg for the year 1975.

July. After that low water conditions lasted from the beginning of August to the end of September.

The gauging station *Pivka Ponor* recorded two events with maximum stage above 7 m (Fig. 6). The first one occurred in March and the second in the middle of November. These maxima were intense and short, but the discharge surpassed twice 60 m³/s.

In opposite, the gauging station at *Rak Slivice* recorded only one extreme event in spring, where the entire valley of Rakov Škocjan was flooded for more than a month. The autumn event was much less pronounced at Rakov Škocjan than at the Pivka Ponor. This indicates a different response in the two recharge areas. In spring, the discharge reached approximately 45 m³/s for more than a month, whereas it fluctuated between 15 and 20 m³/s during the winter period. The flat discharge plateau recorded in March-April indicates an important backflooding caused by a restriction in Tkalca Jama.

On the other side of the catchment, the *Malni Spring* reacted to both events with a similar pattern: the discharge peaked at slightly below 10 m³/s during both high water periods, indicating a strong damping of the system. Accordingly, the recession was very slow, with a minimum base flow of 2 m³/s in late September. At that time, the Malni Spring was the main outlet of the system and drained exclusively autogenic water from the Javorniki

Current. Finally, the important increase of stage during spring is related to a flood in Planinsko Polje.

The gauging station *Unica-Hasberg* monitors the sum of all outlets of the Unica Catchment (Fig. 4). The high water period occurring in spring 1975 showed discharges above 80 m³/s and stages up to 4 m, which resulted in a flood of high amplitude in Planinsko Polje. In opposite, the response to the event of November-December was less intense, with peak flow close to 70 m³/s and a duration too short to cause flooding in the polje. This can be explained by the small reaction of Rak Slivice. Finally, a period of low water level was recorded during the months of August and September, similarly to all other stations.

ESTIMATED HYDROGRAPHS FOR 1975

We now turn to the non-recorded hydrographs derived from Equation 1. Both Planinska Jama/Unica Spring and Rak Branch show similar behaviour to the recorded stations, with two high water periods occurring in spring and winter 1975. The time series of Javorniki Current show oscillations at both the onset and the end of larger events. The reason lies in the fact that the flow-through times are ignored in the mass balance equation (Eq. 1) and that the daily resolution of data does not allow capturing changes in small time-scales.
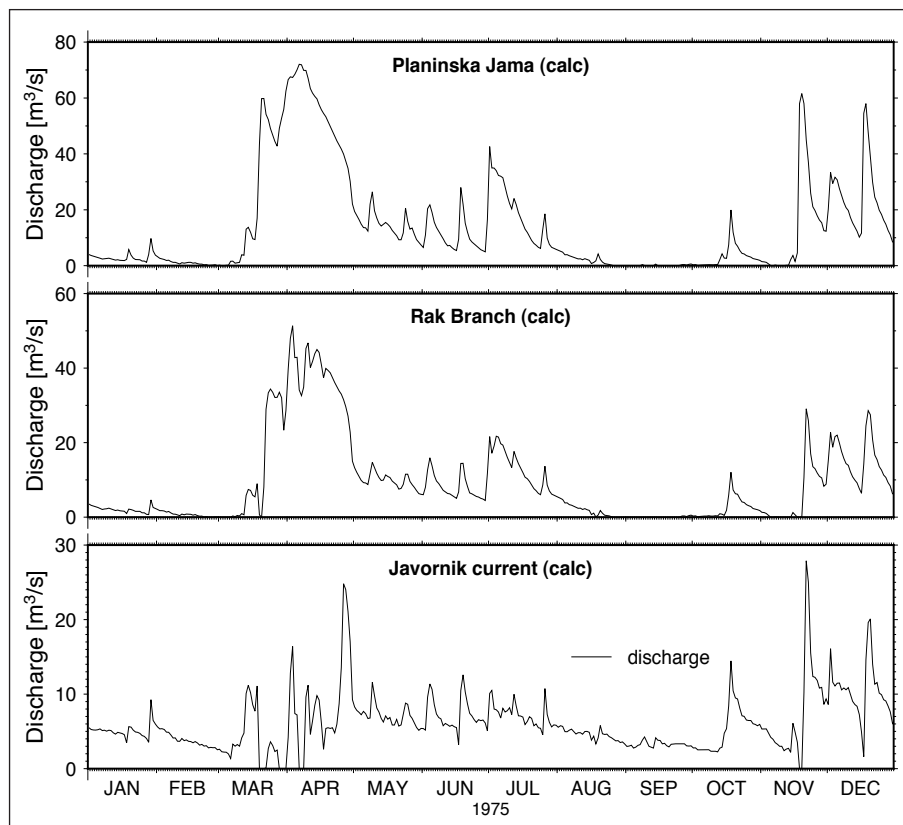

Fig. 7: Estimated discharge time-series for Planinska Jama (Unica Spring), Rak Branch and Javornik Current for the year 1975.

Finally, the estimation of the Javorniki Current time-series gives the opportunity to assess conditions when no water is sinking into the Tkalca Ponor. The system is solely driven by the Javorniki Current contribution, which supplies only the Malni Spring while the overflow towards Planinska Jama is inactive. However, the estimated contribution from the Javorniki Current is highly dependent on the quality of the observed contributions. Therefore, the data of the Javorniki Current should be interpreted with caution, especially if they present strong oscillations within a short time interval.

MODELLING

In this study, Storm Water Management Model (SWMM) is combined to a formal inverse procedure to simulate flow divergence at Mysterious Lake and to assess the key parameters and mechanisms driving it.

THE MODEL SETUP
We first integrate all information given above into a conceptual hydrological model of the flow convergence and divergence at the Mysterious Lake. The set-up shown in 3D in Fig. 8 and is composed of inputs, outlets, conduits and junctions.

Inputs:
1) The Rak River Inflow from Tkalca Jama. Recharge is obtained from the hydrographs of the Slivice Station (Fig. 6).
2) Javorniki Current, recharge derived from Eq. 1 (Fig. 7).

Outlets:
1. The Rak Branch, discharge derived from Eq.1 (Fig. 7).
2. The Malni Spring, discharge observed (Fig. 6).
    The model of conduits and junctions is derived

from the known survey of the cave. Initial estimates of the unknown conduits are guessed. The model presents the simplest possible scenario that can simulate the observed hydraulic behaviour.

Apart from the conduits shown in the Fig. 8, both Rak Branch and Unica Branch of the Planinska Jama as well as the channels and conduits connected to Rakov Škocjan are also included into the numerical model (Fig. 9).

The following list summarizes list of conduits included into the modelling domain:
1. Rak Branch, with parameters taken from the cave survey.
2. Base flow and overflow conduits connecting the Mysterious Lake and the Rak Branch. The two conduits b_1 and b_2 (Figs. 8 & 9) represent the transmissivity of breakdowns. The conduit b_3 represents the flow along the side and above the breakdown.
3. Malni base conduit (a_2 on Figs. 8 & 9). The base flow conduit connecting the Mysterious Lake to the Malni spring. The conduit presents a restriction, which raises the level in the Mysterious lake and causes overflow into the Rak Branch.
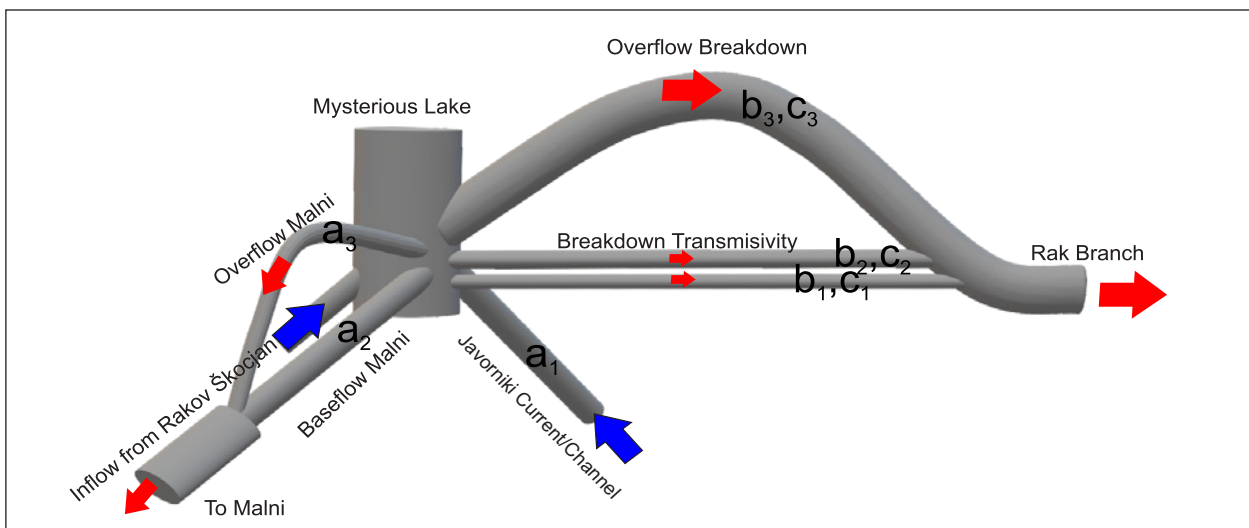

Fig. 8: A 3D model of conduits recharging and draining the Mysterious Lake. See also Fig. 9 for a broader picture of the modelled system.
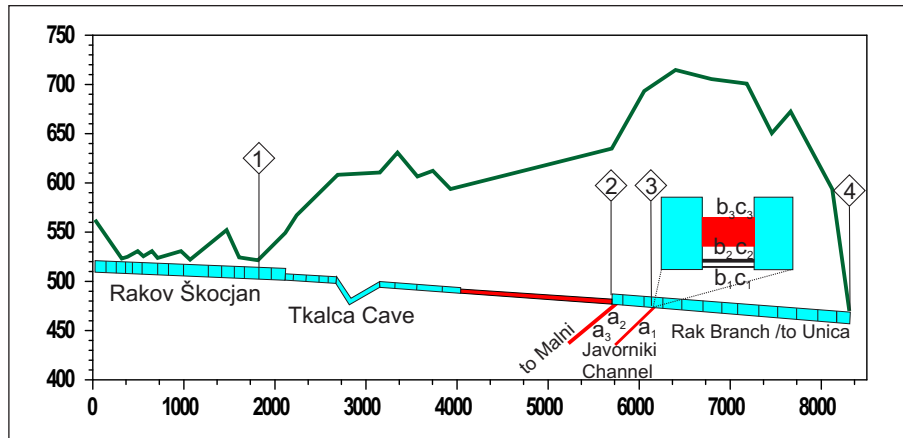
Fig. 9: Simplified SWMM geometry used for modelling. Topography is shown as thick green line, and modelled cave cross-sections as blue (rectangular geometry) and red (circular geometry). The locations are marked with diamonds and numbered. The constriction before the Mysterious lake is additionally shown as enlargement in the inset.

4. Overflow conduit to Malni (a_3).

5. Javorniki Channel (a_1) with inflow from the Javorniki current.

6. Tkalca Jama and unknown conduits connecting Rakov Škocjan to the Mysterious Lake (Fig. 9). The conduits transfer the inflow from Slivice (Rakov Škocjan) towards the Mysterious Lake.

The geometry of the Rak Branch follows the cave survey presented in Fig. 3 and was mostly modelled by rectangular or rectangular-trapezoidal cross-sections (Fig. 9). The siphons and unknown parts between the different caves are modelled with circular conduits. The conduit development and slope of the unknown parts were extrapolated respectively as straight line with a constant dip.

The optimisation procedure was related to characteristics of the overflow toward the Rak Branch and the conduits connecting the Mysterious Lake to the Malni Spring. These include the following parameters:

(i) the diameters of the two modelled conduits towards the Malni Spring (),

(ii) the diameters of the two low-flow conduits in the Rak Branch presenting the breakdown transmissivity (),

(iii) the overflow heights of the two low-flow conduits in the Rak Branch below the breakdown ()

(iv) the diameter of the Javorniki Channel a_1.

MODEL CALIBRATION AND VALIDATION

This section presents the model results arising of both forward and inverse calculations based on the SWMM model for the cave geometries.

Due to its high discharge variability, the event going from October to December 1975 was chosen as test period to invert the model parameters characterising the constrictions around the Mysterious Lake. The event going from March to May 1975 is then used as an independent test to validate the goodness-of-fit.

Inverse Strategy: Test period: October – December 1975

The Neighbourhood Algorithm (NA, Sambridge 1999a, b) was used as an inverse procedure wrapped around the SWMM model to determine the value of the model parameters. The NA method can be applied to a large variety of non-linear inverse problems with complex dependencies between model and data. The inverse algorithm follows a two-step procedure: (i) during the search stage, a multi-dimensional parameter space is sampled with different combinations of the chosen parameter values. The search is driven by randomly created initial ensembles. (ii) the misfit between model and data is then used to drive the inverse algorithm towards a reduction in misfit. The NA algorithm is based on the concept of Voronoi cells, representing nearest-neighbour regions around a sampling point. The Voronoi cells guide the sampling procedure (Sambridge 2001).

The root-mean-square (rms) between observed and modelled discharge time series is chosen as evaluation criteria (Steffen & Kaufmann 2005):

$$\text{rms}_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_{obs,i} - Q_{pred,i}(x_j)}{Q_{err}}\right)^2} \qquad \text{(Eq. 2)}$$

with $Q_{obs,i}$ and $Q_{pred,i}$ [m³/s] the observed and modelled discharge values for all stations and sampled times (counter $i = 1,n$), x_j the model parameter vector (our free parameter values), and Q_{err} the discharge uncertainty, set to 0.5 m³/s in our case to achieve rms values in a reasonable range.

The sampling strategy is guided by the time-consuming forward run of the SWMM model, which takes approximately 8-10 min for a single run. This duration does not allow inverting all parameter values simultaneously. Therefore, groups of the free parameter values are determined in four steps:

(i)   Find a forward model with reasonably good fitting parameters as an initial guess.

(ii)   Determine a_1, a_2, a_3 while fixing b_1, b_2, c_1, c_2 to initial values.

(iii)   Determine b_1, b_2 with the best-fitting a_1, a_2, a_3 from the previous inversion, while still fixing c_1, c_2 to initial values.

(iv)   Determine c_1, c_2 with the best-fitting a_1, a_2, a_3, b_1, b_2 from the previous inversions.

While part (i) is our initialization step, parts (ii) to (iv) are the three sub-sets of the inversion. We start with constraining a_1, a_2, and a_3 to find a good approximation of the low-flow behaviour first, then move to the free parameter values controlling the overflow in Mysterious Lake. For all sub-sets, we run 100 models in the first iteration, then pick the best two models having the lowest rms values and resample their vicinity 10 times using the NA algorithm. Then, the step procedure is repeated four times. This procedure results in 140 forward runs altogether per sub-set, thus 420 runs in total.

Search ranges for the free parameter values are listed in Table 1 together with their best-fitting values obtained from the inversion. For each sub-set, a confidence parameter as additional statistical information is computed (Steffen & Kaufmann 2005):

$$\Psi_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_{pred,i}(x_{best}) - Q_{pred,i}(x_j)}{Q_{err}}\right)^2} \quad \text{(Eq. 3)}$$

with $Q_{pred,i}(x_{best})$ and $Q_{pred,i}(x_j)$ the best-fitting and the other modelled discharge values for all stations and sampled times (counter $i = 1, n$), and x_{best} the parameter vector of the best fitting parameter values. The Ψ-confidence parameter reports the goodness-of-fit with $\Psi < 2$ for models comparable with the best-fit model within the 2σ-uncertainty, and $\Psi < 1$ for models comparable with the best-fit model within the 1σ-uncertainty.

Fig. 10 shows the fitted model parameter values for the three subsets. The figure describes for each of the parameter values the range of parameter for all calculated models (light grey), the best-fitting model (red dot), all
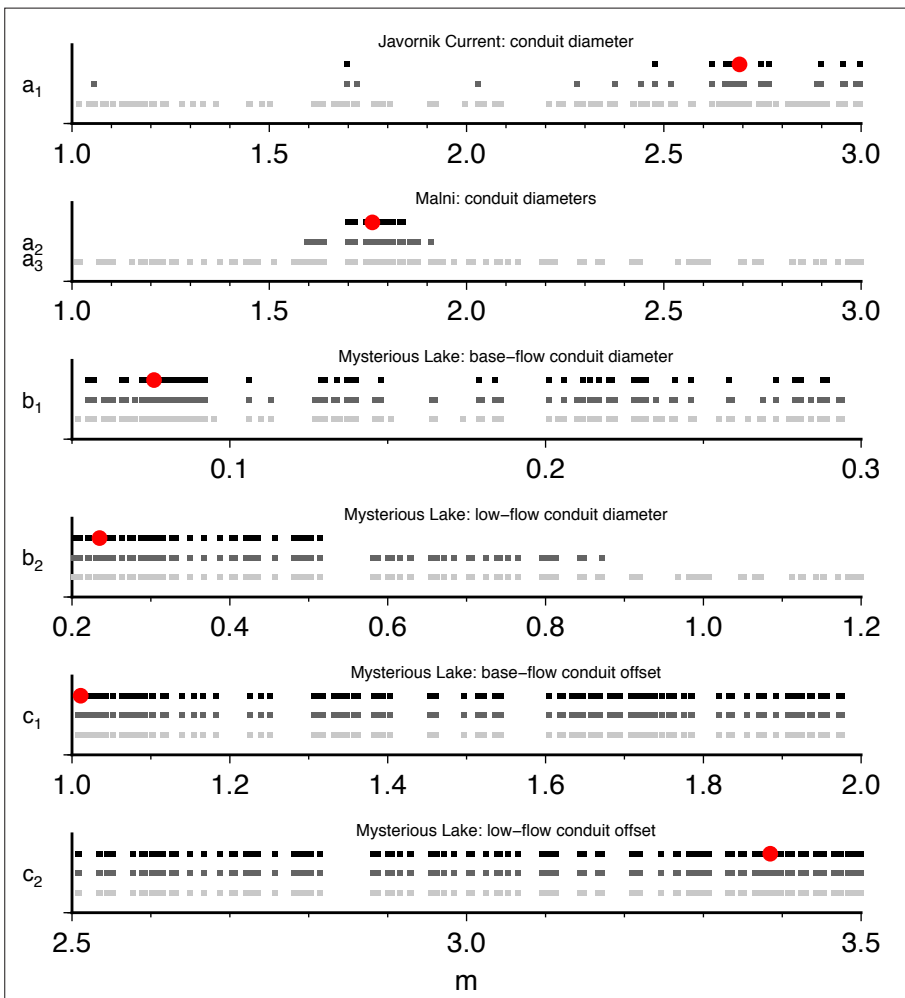

Fig. 10: Parameter ranges used for the inverse run. Shown are the fitted parameter values (a1, a2=a3, b1, b2, c1, c2), for all tested models (light grey), all models with 2-uncertainty range (dark grey), all models with 1-uncertainty range (black), and the best-fit model (red dot)
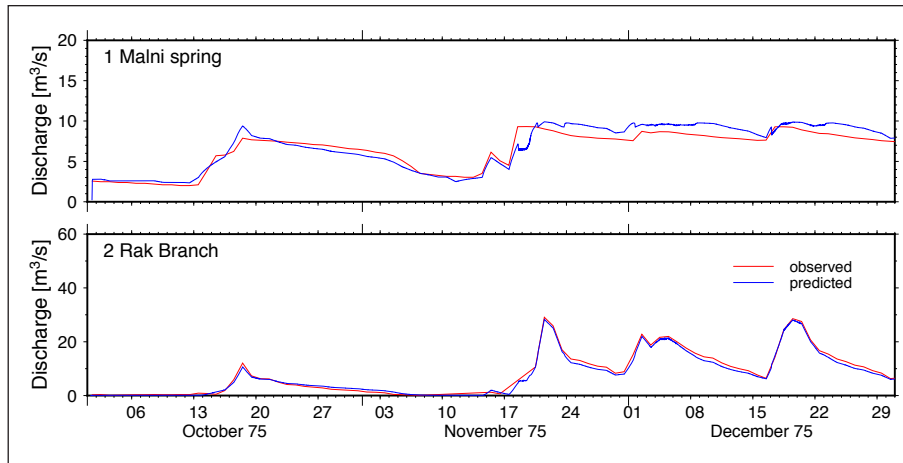
Fig. 11: Observed (red) and modelled (blue) discharge for the period October - December 1975 at the two stations Malni Spring and Rak Branch.

models similar to the best-fitting models within the 2- (dark grey) and 1σ-(black) confidence range.

For the conduit diameter of the Javorniki Current, the best values were determined around $a_1 \in 2.5$ - 3.0 m within the 1 confidence range, which is a sizeable conduit and is also verified by diving exploration into this part of the cave. The unknown downstream connection towards the Malni Spring is characterised by a well-determined fit, with conduit diameters of around $a_2 = a_3 = 1,7$ m for the 1σ confidence range. These conduits carry the base- and low-flow water from both Javornik Current and the Rak River towards Malni Spring.

Downstream to the conduit of the Javornik Current, the passage toward Planinska Jama is characterized by a breakdown area between the large room Podorna Dvorana and the Mysterious Lake. This constriction is inhibiting flow toward the Rak Branch during low-flow conditions. The two conduits allowed to drain during these low-flow conditions are located in (variable) heights above the cave floor and have a rather small diameter. In the second sub-set, we explore the diameter ranges for these conduits. The lowest conduit is not well constrained with a diameter between $b_1 \in 0.1$ - 0.3 m within the 1σ confidence range, but just needs to be small

enough to act as an overspill during higher flow conditions. The second conduit has its best diameter values around $b_2 \in 0.2$ - 0.5 m within the 1σ confidence range. It is also constrained to carry only a small portion of water.

In the third sub-set, we determine the height of these two conduits above the cave floor, our free parameter values c_1 and c_2, which are, however, not well constrained even within the 1σ confidence ranges. Here, the inverse procedure does not favour any particular height between $c_1 \in 1$ - 2 m and $c_1 \in 2.5$ - 3.0 m, all offset elevations provide satisfactory fits. The reason for this large variability is the small relevance of the base-flow and low-flow conduit through the breakdown area; during low-flow conditions almost no water passes through the Rak Branch.

Best-fitting model

In Fig. 11, the modelled discharge of the Rak Branch and Malni Spring are compared to the observed time-series for the period October-December 1975. The input of the SWMM model is driven by both the allogenic inflow recorded at Rak Slivice and the autogenic recharge of the Javornik Current.

The fit of discharges at both locations is very convincing, with rms values below 2.3. Both the amplitudes

Table 1: Range of model parameters and best-fit parameters.

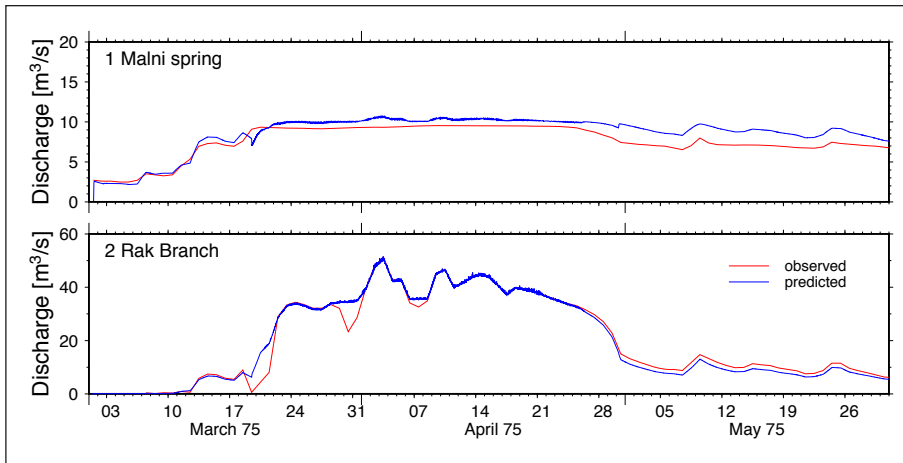| Name	parameter	initial value [m]	range of values [m]	best value [m]
Javorniki Channel	a1	2.00	1.00-3.00	2.69
Malni Conduits	a2	2.00	1.00-3.00	1.76
	a3	2.00	1.00-3.00	1.76
Rak Branch				
Overflow diameter	b1	0.10	0.05-0.30	0.08
	b2	1.00	0.20-1.20	0.24
	b3	5x5	fixed	
Overflow offset	c1	2.00	1.00-2.00	1.01
	c2	3.00	2.50-3.50	3.39
	c3	4.00	fixed	

Fig. 12: Observed (red) and modelled (blue) discharge data for the period March - May 1975 at the Malni Spring and Rak Branch.

and the recession limbs are fitted perfectly for the Rak Branch, and satisfactorily for the Malni Spring time-series. For the latter, the recession limbs for higher flow conditions deviate slightly from the observations. This could be explained by the activation of some overflow springs during higher flow conditions, by an improper characterization of the geometry of the cave network or by the approximation made during the computation of the water-balance of the catchment.

Validation period: March - May 1975
The best-fitting SWMM model is tested with the large recharge event occurring between March and May 1975. This large-scale recharge event shows observed discharges above 30-40 m³/s in the Rak Branch during an extended period, and is well predicted by our best-fitting SWMM model (Fig. 12). Only two abrupt recession spikes visible in the observed record of the Rak Branch are not reproduced. This could indicate more small-scale flow routes through the breakdown area, uncertainties in the observed data and their derived quantities, or an over simplification of the model setting. The Malni Spring is fitted satisfactorily. However, it presents the same deviations as in the time series before for large discharge rates, probably pointing to the (un-modelled) overflow springs.

Extension to Pivka Branch
The model presented so far can easily be coupled to the model of Pivka Branch, which has been presented and validated by Kaufmann *et al.* (2016). The complete setting of the SWMM model is shown on Fig. 13, while Fig. 14 shows the results when the contribution of Pivka Branch and Rak Branch are combined. Using the strong recharge event between March and May 1975, the model was able to predict the observed discharge for most of the times with high accuracy (green line). Splitting up the contributions from the Pivka and Rak branches, we can identify now the flashy behaviour of the Pivka Branch

(blue dashed line), with strong pronounced peaks and short recession limbs, and the slightly damped response of the Rak Branch (red dashed line), with longer recession limbs. Note that during most of the event, the majority of flow comes from the Rak Branch. Conversely, the majority of the outflow consists of water from the Pivka Branch during low-flow conditions.

Three notable exceptions labelled **a**, **b**, and **c** are seen when comparing both observed and modelled data. These over-estimations of discharge coincide well with peak discharge values from the Pivka Branch of the system. Therefore, three explanations for this over-estimation are possible: (i) Some of the high flow water through the Pivka Branch is lost on the way downstream and re-appears in another spring, (ii) The system has another yet unknown restriction along its flow path, which causes partial backflooding and storage during high flow conditions, (iii) Uncertainties in the observed discharge data and their derived counterparts can in part be responsible for small-scale deviations. While (i) seems to be hardly realistic as no field observations nor tracer tests could confirm it, (ii) and (iii) can be considered as the most probable explanations.
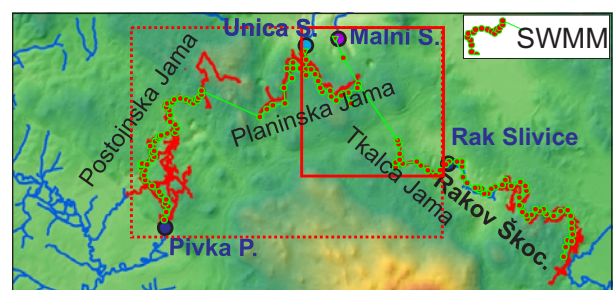

Fig. 13: View of the aquifer system comprised between Cerkniško Polje, the Pivka Valley and Planinsko Polje with the network of conduits built in SWMM. The solid rectangle marks the domain modelled in these paper. The dotted rectangle marks the domain including the flow of Pivka through Postojnska Jama and Pivka Branch.

CONCLUSIONS

This work attempted to model the groundwater flow within a complex karst system governed by an overflow leading to a flow inversion, and to determine the parameters controlling the system behaviour.

By integrating field observations from the cave, spring and ponor hydrographs within a numerical model we have demonstrated that low/high water switch between the Unica and Malni Springs is governed by an overflow phenomena caused by the breakdown in the remote part of Planinska Jama. Similar mechanisms exist in many karst systems with high variability of flow and geometry such as in the Reka-Timavo system (Gabrovšek *et al.* 2018), where overflow along higher positioned conduits in Kačna Jama is active only during flood events.

Results show the usefulness of extrapolation methods such as groundwater modelling to assess the geometry of key parameters controlling the hydrological behaviour of the system. Furthermore, it is shown that field observations and caving surveys provide meaningful information needed to construct complex flow models of mature karst aquifer.

Despite all uncertainties related to input data, a high goodness of fit between model and field observation was obtained. Other parameters affecting the flow rate in conduits, (such as wall roughness, conduit lengths, local head loss parameters) could have been tested. Furthermore, the other configurations of unknown conduits could as well give a good fit. We are aware that the geometry of flow system is more complicated than the one presented. The resulting diameters are a crude approximation of what is there, therefore a critical distance has to be taken. Nevertheless, one of the aims of this work was to demonstrate that a fit based on the physical processes despite limited knowledge of structure and physical parameters, can give surprisingly good results.

Another important aspect of the results is also the variable catchment size of Unica Spring. This could be envisaged in many other springs, also those captured for the water supply. Analyses and comparison of spring hydrographs in a chosen catchment could be a first step to identify such mechanisms. The method can be very helpful when managing karst aquifer. Taking into account those processes would improve vulnerability and resources management studies in karst aquifers considerably.

As mentioned, a broader measurement network has been recently established to better constrain the system. These includes autonomous measurements of water level, temperature and specific electric conductivity at all relevant point in the system combined with frequent flow measurements to establish the stage-discharge curves. The measurements will lead to further refinement of the model presented here.

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