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Observations of stage and temperature dynamics in the epiphreatic caves within the catchment area of the Ljubljanica River (Slovenia)

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ABSTRACT

Karst ground water dynamics between the Planinsko polje and the springs of Ljubljanica (Slovenia) was studied based on the monitoring of stage and temperature of ground water in four caves. The Unica River, which flows over the Planinsko Polje, and sinks at its E and N rim, is considered as the main input to the observed system. At small flood events its role is none or questionable. At medium and large events, when the discharge of Unica exceeds 25 m^3/s, it becomes an important and/or the dominant input to the system. When the capacity of the primary (eastern) ponors in the polje is exceeded, the stage in a cave, which is fed solely through these ponors, reaches the plateau followed by a very slow recession. The surplus flow goes towards northern ponors causing a fast rise of the stage in adjacent to them. In two of the northernmost caves, the stage response is almost identical, but the temperature variations are different. The uniform water level suggests a highly permeable region bounded by a low permeability barrier in the down-flow direction, while different temperature behavior indicates a different origin of the waters for each cave.

Keywords: ground water flow, caves, flood pulse, recharge, hydrographs, Slovenia

1. INTRODUCTION

The springs of the Ljubljanica River drain more than 1100 km^2 of karst area in central and south-east Slovenia (ŠUŠTERŠIČ, 2000). The catchment comprises a vegetated karst surface and a series of karst poljes, including the periodically flooded Cerkniško and Planinsko poljes. Water from the poljes flows underground towards the springs of Ljubljanica, at the rim of the Ljubljana Basin. Intensive hydrogeological investigations of the area have been carried out for more than a century. Among others, the tracing tests of GOSPODARIČ & HABIČ (1976) have shown clear connections between the ponors and springs. However a more detailed picture of groundwater dynamics in the aquifer is still needed. Part of the system, related to this study, is shown on Fig. 1.

The level of karst ground water between the Planinsko Polje and springs of the Ljubljanica River can be reached through several caves. Some of these are in the imediate vicinity of the Planinsko Polje, close to the ponors. Only three caves reach the level of groundwater further downstream in the direction of the springs (Fig. 1): Gradišnica was explored

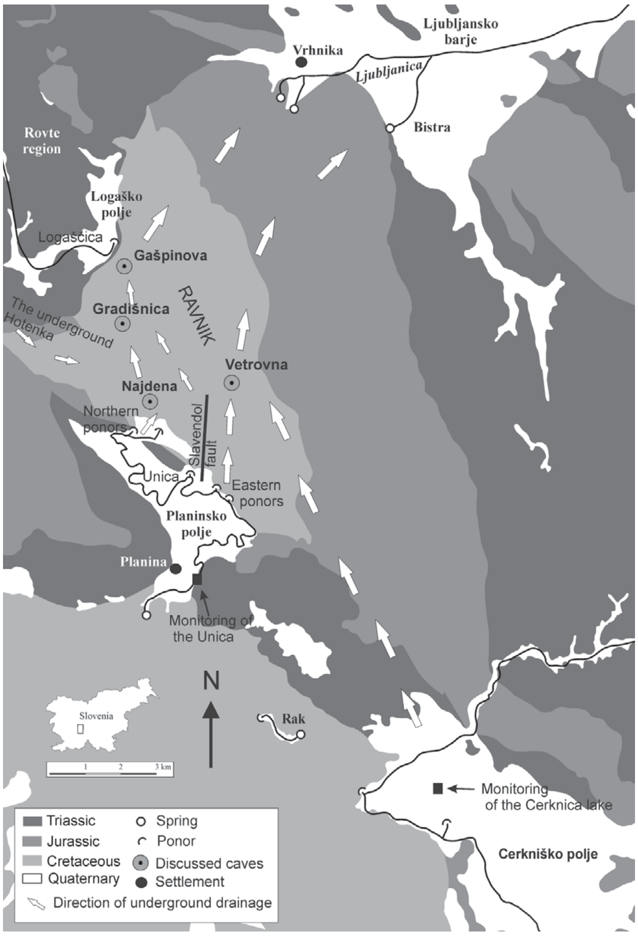

Figure 1: A generalized geological map of the study area. The position of the observed caves, surface waters and presumed directions of groundwater flow are indicated.

more than a century ago, while Vetrovna Jama pri Laški Kukavi (Vetrovna *Jama* = Windy *Cave*) and Gašpinova Jama have been discovered and explored during the last decade. We established simultaneous and continuous logging of ground water level and temperature in these three caves and in Najdena Jama, which is in the immediate vicinity of the northern rim of the Planinsko Polje.

The study had two main goals: to determine the groundwater dynamics in the described system by analyses of stage and temperature hydrograms, and to demonstrate the potential use of caves as points of groundwater monitoring.

2. DESCRIPTION OF THE STUDIED AREA

All the monitored caves belong to the Ravnik area, which is comprised of a well-karstified Cretaceous limestone with patches of dolomite. A more impermeable Triassic dolomite forms the bottom of the Planinsko and Cerkniško poljes (see Fig. 1) (PLENIČAR et al., 1970).

The Unica River emerges at the contact of the Cretaceous strata with the Triassic dolomite and flows across the Planinsko Polje, sinking again at the eastern and northern margin of the polje. Cerkniško, Planinsko and Logaško poljes are covered by the Quaternary sediments.

Recharge of the system

Recharge of the studied system is complex. The majority of water comes from the ponors of the Unica River at the eastern and northern rim of the Planinsko polje. The Unica is not a typical allogenic river it has several karstic springs at the southern rim of the Polje and acts as an overflow of the waters arriving from the Cerkniško polje, the Pivka Basin and Javorniki Mountains to the south. The complexity and origin of the Unica are not the concerns of this paper, but it is simply considered as a sinking river providing input to the observed system.

Some of the water in the observed caves may originate directly from the Cerkniško Polje. Its direct connection to the springs at Bistra has been proven by dye tracing (GOPODARIČ & HABIČ, 1976). Another area of recharge is a dolomitic region in Logaške Rovte to the west. Two surface streams emerge and sink in this area. These streams are much smaller than the Unica river, but can play some role at specific hydrological events. The Logaščica sinks in the town of Logatec, which is downstream (north) of all the observed caves. The ponor is in the proximity of Gašpinova jama, and it could also have an influence on the stage in Gradišnica. Hotenka sinks further Ssouth-west most probably joins the system in the region where the observations were made. However, this has not been proven so far. The only data available concerns the discharge of the Unica and precipitation. Other recharge data is lacking.

Discharge of the Unica was measured downstream from all the springs and about 5 to 6 km upstream from the eastern ponors, and 16 km upstream from the northern ponors. These ponors are the main, but not the only sinking points, as the river leaks at many other locations along its meandering course over the Planinsko Polje. Mean annual discharge of the Unica River at the gauging location is 26 m^3/s, the minimum is a few cubic metres per second and the maximum may be more than 100 m^3/s (BREZNIK, 1988). The Polje starts flooding when discharge is greater than 60 m^3/s (ŠUŠTERŠIČ, 2002).

3. MATERIALS AND METHODS

3.1. The data sources

To measure and log pressure and temperature of water, we used Schluberger Diver™ instruments, which were fixed to cave walls at selected locations (Fig. 2). Pressure is converted to the height of the water column. The temperature and pressure accuracy is 0.1 °C and ±0.2 % of the measurement range respectively. The instruments are programmed via an optical bridge using a PC or a pocket PC. The storage capacity is 24000 readings in fixed or event based time intervals. During this study a time interval of 30 minutes was chosen. Based on experiences from similar systems (GABROVŠEK & PERIC, 2006) this interval was considered sufficiently short to record all the important variations and separate the arrival of flood pulses to different measurement points. The loggers were relatively remote in the caves,

Figure 2: Data logger in a cave (left) and connected to a PC via optical bridge (right).

therefore their autonomy was important to avoid too many trips; 30 min intervals with 24000 readings gives 16 months recording before the logger's memory is full.

Daily precipitation data from Planinsko Polje (station Planina, Fig. 1) were obtained from the Environmental Agency at the Ministry of the Environment and Spatial Planning of Slovenia.

The system was observed between June 2006 and December 2007, although all stations were not active during the whole period. Records from Vetrovna Jama and Najdena Jama are missing for spring 2007. The Unica River was monitored from September 2006 and the Cerkniško Polje after May 2007.

3.2. Temperature variations

The highest temperature changes in the system occur during the flood events when an event water with different temperature invades the system. Waters of different origin carry different temperature signals.

As a surface river, the Unica River exhibits diurnal variations of temperature with amplitudes of up to 2 °C at the point of observation. Amplitudes become higher further downstream at ponors and sometimes even in the caves. There is no other source of diurnal temperature variations besides the Unica. These variations, mainly driven by shortwave solar radiation, are preserved along the underground flow, although the amplitude decreases because of the heat exchange with the streambed and surrounding rocks (WICKS, 1997; GU & LI, 2002). For the observed system, the presence of diurnal temperature variations in any of the caves shows the presence of the sinking Unica River. Assuming that the temperature signal is dominantly transported by advection, the phase shift between the temperature maxima and minima in the river and at observation points in the caves or between the two observation points in the caves is a good approximation for the transit time of water between the different locations (STONESTROM & CONSTANTZ, 2003; BIRK et al., 2004).

4. RESULTS

Figure 3 shows precipitation at Planina, stage and temperature hydrograms in caves and a flow and temperature hydrogram of the Unica River for the period between September 10th and October 20th, 2007. Grey areas numbered 1 to 3 denote three events discussed in detail below. They occurred in an increasing order of magnitude.

Small event (Fig. 4a) presents the hydrographs of Event 1 from Fig. 3. It was triggered by 30 mm of rain on September 11th, 2007. The discharge of the Unica increased from 4 m^3/s to 6 m^3/s. The stage hydrograms of Gradišnica and Gašpinova Jama are very similar and symmetrical. In contrast, a fast response in Najdena Jama is followed by slow recession. Such a response could be caused by local runoff from the neighbouring Planinsko Polje or a fast flow of autogenic origin.

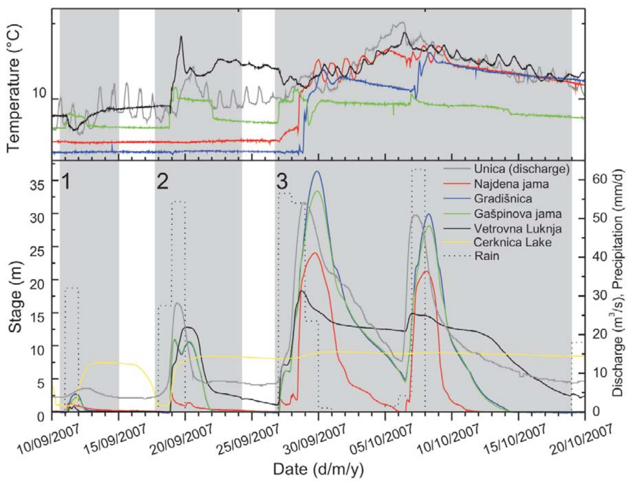

Figure 3: Stage and temperature hydrographs of the four monitored caves, Cerkniško Polje (yellow) and the Unica River for the period between September 10th and October 20th, 2007. Shaded areas numbered 1 to 3 represent three events which are discussed in more detail and shown in Figs 4a–c.

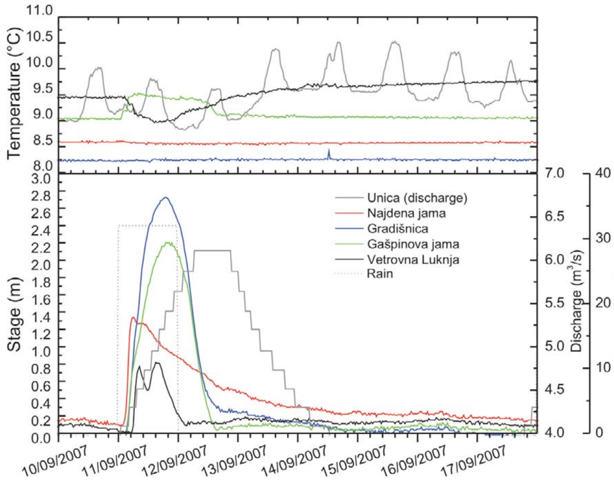

Figure 4a: Hydrographs for Event 1.

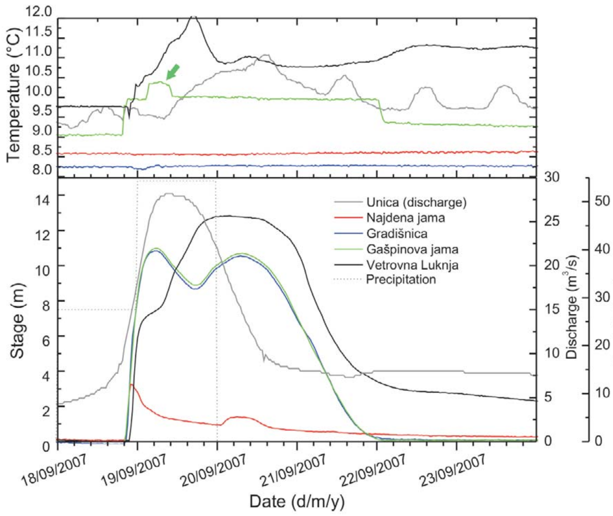

Figure 4b: Hydrographs of Event 2. The green arrow indicates a step change in Gašpinova Jama (see text).

The stage hydrograph in Vetrovna Jama shows a double peak; it cannot be resolved if the peaks belong to waters of different origins or if it is simply the consequence of the temporal distribution of rainfall intensity. The peak stage in all caves precedes the peak flow of the Unica, and it hterefore follows that the recharge of Unica has little importance for small events.

There was no temperature change in Najdena Jama and Gradišnica. The step change of temperature in Gašpinova Jama is apparent, as the sensor had been above the water surface prior to the event (in other caves the sensor is always below the water surface). There is a slight decrease of temperature in Vetrovna Jama.

A Medium event (Event 2, Fig. 4b) was triggered by rain on September 18th and 19th. The first peaks in the stage hydrographs correspond to those in Figure 4a. They all precede the peak flow of the Unica River. The stage hydrographs in Gradišnica and Gašpinova Jama are almost identical. The stage hydrograph in Vetrovna Jama has one broad peak. A clear inflection point in the rising limb probably corresponds to the first peak of Event 1, but the peak is not clear as it is overprinted by the arrival of the main water which raises the stage to 13 m.

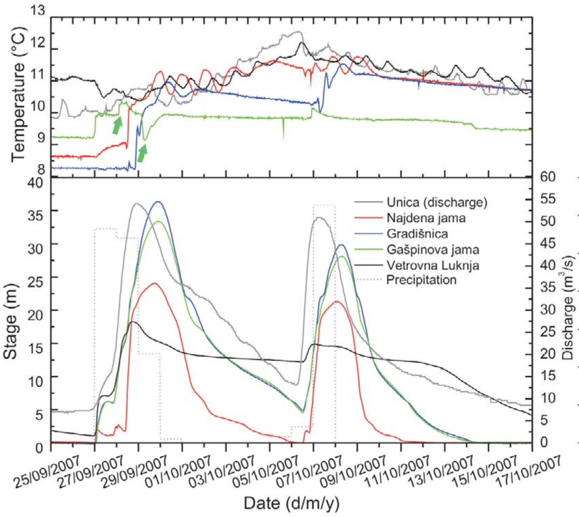

Figure 4c: Hydrographs of Event 3.

Secondary peaks in Gradišnica, Gašpinova Jama and Najdena Jama are clearly following the peak flow of Unica. There are no temperature variations in Najdena Jama and Gradišnica. The temperature hydrogram in Gašpinova Jama shows the additional step change (indicated by the arrow in Figure 4b), which is not present in any other cave. Such a step change also occurs at other similar events (not presented here) and probably indicates a local inflow.

There is a clear increase in water temperature in Vetrovna Jama caused by surface water. It shows no clear correlation with the temperature of the Unica river. However, the river is heated between the observation points and the ponors and it is possible that the temperature remains higher until water reaches the cave. But, diurnal variations are not present in the cave, which is in conflict with the previous argument. Temperature hydrographs of the Unica and Vetrovna jama for other similar events (not presented here) are clearly correlated (TURK & GABROVŠEK, 2009).

A Large event (Event 3, Fig. 4c) was triggered by two consecutive rainfall events between September 28th and 30th and on October 7th. Peak flows of the Unica were 54 m^3/s and 51 m^3/s respectively. The initial stage response in all caves resembles that of small and medium events. The peaks precede the peak flow of the Unica, but are immediately followed or masked by a much larger secondary peak.

A stage hydrograph in Gradišnica and Gašpinova Jama shows only small differences. The maximum rise is 36 m in Gradišnica and 33 m in Gašpinova Jama. Recession is well correlated with the recession of the Unica. The stage hydrograph in Najdena Jama shows several small peaks prior to the large one, when the stage rises to 25 m.

The hydrograph in Vetrovna Jama is different. The initial peak turns into a steep rise of stage to 17 m. The second event caused another peak at 16 m again followed by a slow recession.

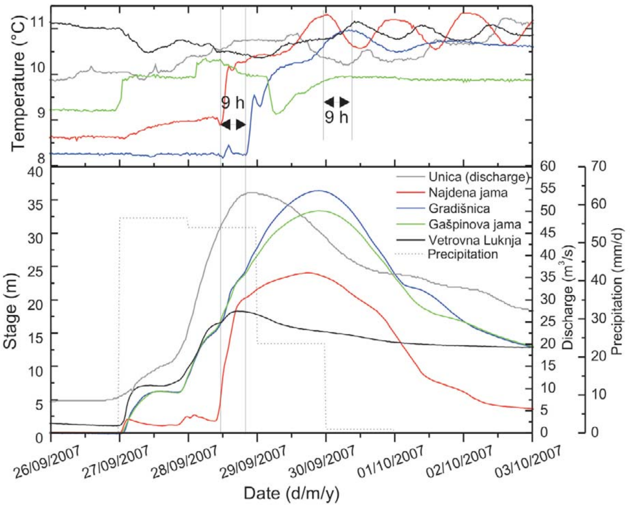

Figure 5: Detail of Event 3, showing a delay between the temperature signals in Najdena Jama and Gradišnica.

A slow recession followed, until discharge of the Unica dropped below 13 m^3/s, when a faster recession began. Such stage hydrographs are typical for Vetrovna jama for all large events. A fast initial rise to 15–18 m followed by a slow recession until the discharge of the Unica drops below 13 m^3/s.

Temperature hydrograms show clear diurnal variations in Vetrovna Jama and Najdena Jama. When the discharge of the Unica is above 30 m^3/s, diurnal variation of temperatures is also present in Gradišnica. Figure 5 shows the details of Event 3. A characteristic change of temperature in Najdena Jama appears 9 hours latter in Gradišnica. The same lag in both caves is recorded between diurnal maxima. Diurnal temperature variations "fade out" in Gradišnica when the discharge of the Unica drops below 30 m^3/s.

The temperature variations in Gašpinova Jama are different. The step increase in temperature is followed by an inflow of relatively colder water at the first flood event. The temperature is only slightly disturbed at the second event. Diurnal temperature variations in Gašpinova Jama are present only at events, when the discharge of the Unica exceeds 60 m^3/s.

Direct recharge from the Cerkniško Polje

So far we have not commented on the hydrographs obtained in the Cerkniško Polje which are also shown on Fig. 3. The instrument was installed into the ponor at the bottom of the lake. These ponors are fed by the Stržen stream which flows over the polje. Although the stream "leaks" into the observed ponors, most of its flow continues to the series of ponor caves at the western rim of the polje, which are part of the Unica catchment. The capacity of the observed ponors is low (probably below a few hundred litres per second). This is also demonstrated by the data shown on Fig. 3, where the observed area was filled during most of the time, except for the two short periods following very dry weather in September. Tracing tests in the 1970s (GOSPODARIČ & HABIČ, 1976), showed that water from the observed ponors preferentially flows directly to the Ljubljanica springs therefore we expected to sense this water in some of our caves, particularly in Vetrovna Jama. However the data show no clear sevidence of this. Neither stage nor temperatures in any of the caves show clear correlations with the Cerkniško Polje. If a connection exists, recharge from the lake should be small compared with the recharge from the Unica River and other sources.

5. DISCUSSION

The observations described above are also representative of additional events not presented here. Differences between the events exist due to the variable distribution of rainfall intensity in the recharge zone, which is a topic for future study. However, there are several characteristics of the system, which are observed during all events.

Almost identical stage, but considerably different temperatures show that Gradišnica and Gašpinova Jama are hydraulically well connected, but they belong to different flow paths within the aquifer. Only at extremely high floods, when the discharge of the Unica approaches 60 m^3/s, do temperatures in these two caves almost equalise. The water table in this part of the aquifer is very uniform; it is about 70 m above the spring level at Vrhnika. Between Gašpinova jama and the spring of Ljubljanica, no other known cave reaches the water level. These facts indicate the presence of a relatively impermeable barrier downstream from the region of the two caves. Such a barrier would explain a uniform water table in the very conductive zone upstream. A candidate for the low permeability zone is a band of Triassic dolomite that extends in a NW-SE direction north of the observed caves as shown schematically on Fig. 7.

During the observation period the stage in Vetrovna Jama never rose above 19.5 m. It remains high until the discharge of the Unica falls below 13 m^3/s. When the stage in Vetrovna Jama approaches its maximum, the Unica invades through northern ponors, resulting in a large increase of stage and the occurrence of diurnal temperature variations in Najdena Jama and Gradišnica. These observations suggest a limited capacity for the eastern ponors. When this is reached, higher discharge of the Unica has no influence on the stage in Vetrovna Jama, all the surplus flow goes to the northern ponor causing a massive inflow in the region of Najdena jama. However, we should also be aware that the eastern ponors are located at different altitudes and when discharge increases sufficiently, and then additional ponors are activated. This may explain the highest peaks on the stage hydrographs in Vetrovna Jama (see peaks above the »plateau« on Fig. 3). Flow from Najdena Jama continues towards the north and reaches Gradišnica in several hours. Only when the discharge of the Unica drops below 13 m^3 does the outflow in Vetrovna Jama become larger than the inflow and faster stage recession starts. Such benaviour could also be explained by the divergence of subterranean flow (TURK & GABROVŠEK, 2009).

The stage in caves which are close to the points of concentrated recharge is often determined by hydraulic restriction from channels of small diameter, breakdowns etc. The rate of change of stage in front of such restrictions is

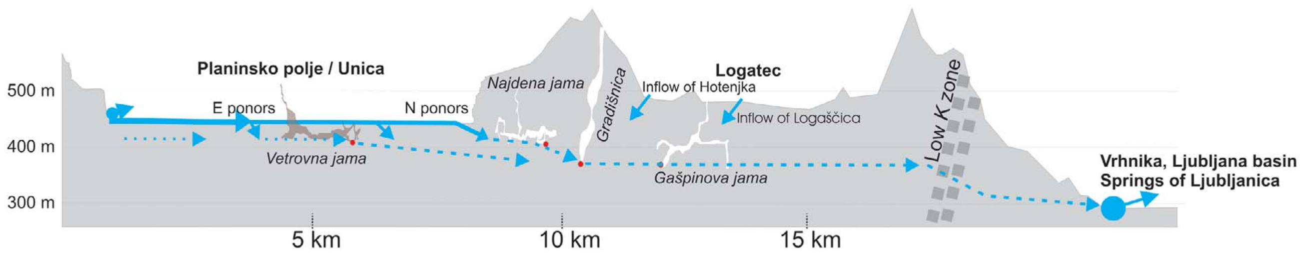

Figure 6: An elevation profile of the area between Planinsko Polje and Ljubljana Basin in an approximate north-south direction. The cross-sections of the caves are generalised and simplified. Vetrovna Jama is shifted to the south, because it would overlap with Najdena Jama if positioned correctly. This way its connection to eastern ponors is emphasised. Dashed lines show the estimated level and direction of groundwater flow.

$dh/dt = A(h) \times (Q_{in}–Q_{out})$, where Q_{in} and Q_{out} are input and output flow rates and A(h) is the area of the water surface at height h. (GABROVŠEK & PERIC, 2006). Stage hydrograms in such scenarios show fast rise and slow recession. Najdena Jama and to some extent Vetrovna Jama also fit into this category.

The input to caves which are deeper in the system is filtered by the upstream restrictions, therefore hydrograms become more symmetrical. Such are the stage hydrographs of Gradišnica and Gašpinova Jama, but use of a simple reservoir-restriction model is questionable here. These caves can be considered as natural piezometers in an aquifer with a well developed and braided conduit system.

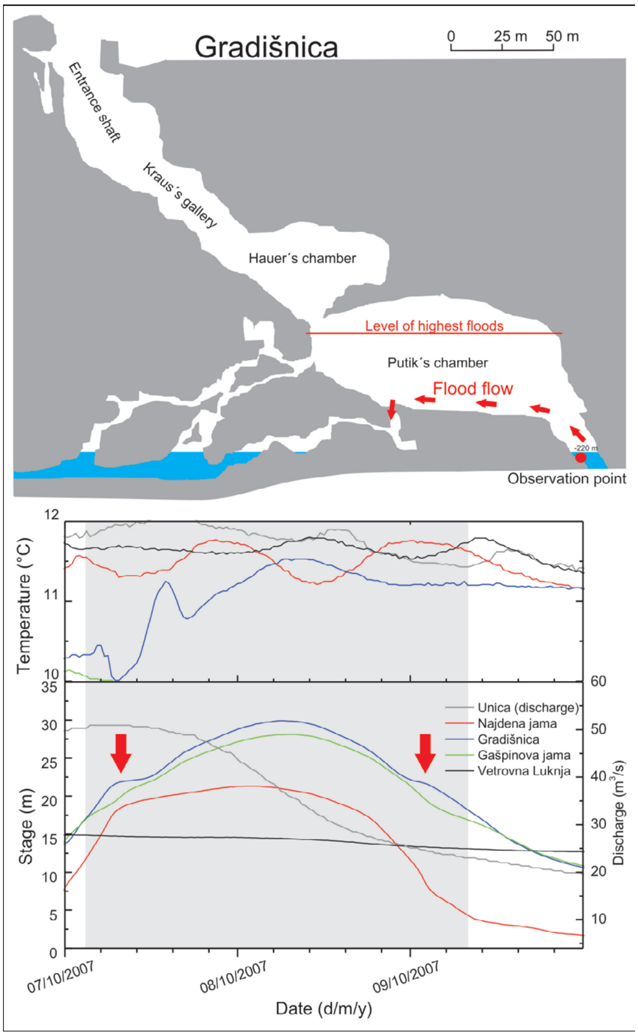

Figure 7: a) Simplified cross-section of Gradišnica adapted from NAGODE (1997) with the position of the observation point and assumed flow direction at high floods. b) Detail of Event 3 with the inflection in the stage hydrograph, which occurs when the Putick's chamber is filled and emptied.

Fig. 6 shows an elevation profile of the terrain between Planinsko Polje and Ljubljana Basin. Very generalised profiles of the observed caves are shown and some conclusions as to the groundwater level and direction as obtained by this study are presented.

Selection criteria for the observation points within the cave have not been discussed and, depending on the role and position of a cave in an aquifer, this can be an important issue. For example, Fig. 7 shows a generalized cross-section of Gradišnica and an extract from Event 3. The instrument is located in the terminal lake at a depth of 220 m as indicated on Figure 7a. During small and medium events the level of the lake oscillates, but there is no or only minor flow of the event water and temperature changes through the site. At large events, when the recorded stage is higher than 20–23 m, the lake water rises to the level of the large Putick´s chamber and flows to a system of channels on the other side of the chamber. The event water passes the observation point as can be seen from the temperature hydrographs which exhibit large and even diurnal variations.

For all large events, the stage hydrograph in Gradišnica has an inflection point at about 22 m. This is valid for both limbs of the hydrograph. At this level the water from the lake starts to fill Putik´s chamber which has a large storage capacity. As the rate of change of stage is inversely proportional to the surface of the area that the water fills or drains, the rise and drop of the stage is reduced when the water level is at the position of the largest surface area.

6. CONCLUSION

Monitoring enabled a new insight into the aquifer. Caves are important windows to the groundwater and representative observation points. However, the study posed more questions than answers. Further research should be undertaken in order to delineate the sources of recharge. The flow and sinking of the Unica river should also be investigated in more detail. Results should be compared to the results of monitoring at the springs.

Although the Planinsko polje floods regularly at least once per year, it was not flooded during our study. To this extent important information on what happens when the Polje is flooded for few weeks was missed. Ironically, it was flooded twice within a few months after the monitoring ceased.

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