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UNRAVELING THE FUNCTIONING OF THE VADOSE ZONE IN ALPINE KARST AQUIFERS: NEW INSIGHTS FROM A TRACER TEST IN THE MIGOVEC CAVE SYSTEM (JULIAN ALPS, NW SLOVENIA)

RAZKRIVANJE DELOVANJA VADOZNE CONE ALPSKIH KRAŠKIH VODONOSNIKOV: NOVA SPOZNANJA IZ SLEDILNEGA POSKUSA V JAMSKEM SISTEMU MIGOVEC (JULIJSKE ALPE, SZ SLOVENIJA)

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Abstract UDC 556.322/.33:543.3:57.08(234.323.6)

Franci Gabrovšek, Matej Blatnik, Nataša Ravbar, Jana Čarga, Miha Staut & Metka Petrič: Unraveling the functioning of the vadose zone in alpine karst aquifers: New insights from a tracer test in the Migovec cave system (Julian alps, NW Slovenia)

The aquifers of alpine karst and high karst plateaus are abundant water resources. They are difficult to characterise due to their complex, partly glaciokarstic, evolution in active tectonic environments, and an unsaturated zone up to two kilometres thick. We present and discuss the results of a tracing test in the alpine karst of the Julian Alps (Slovenia), more precisely in the Migovec System, the longest cave system in Slovenia (length = 43 km, depth = 972 m). The cave extends below a mountain ridge that separates the Soča and Sava Valleys, thus forming a topographic divide between the Adriatic and Black Sea basins, which gives the test greater regional significance. In early September 2019, three kilograms of uranine were injected into a perched lake in a remote part of the system, approximately 900 metres below the plateau and 100 metres above the low water table. All known springs in the valleys on either side of the mountain were monitored by manual or instrumental sampling and a field fluorometer. Due to the unexpectedly dry season, no tracer was detected at any site for two months until a heavy rainfall event in early November. Subsequently, about 60-65 % of the tracer mass appeared within 60 hours in the

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Franci Gabrovšek, Matej Blatnik, Nataša Ravbar, Jana Čarga, Miha Staut & Metka Petrič: Razkrivanje delovanja vadozne cone alpskih kraških vodonosnikov: nova spoznanja iz sledilnega poskusa v jamskem sistemu Migovec (Julijske alpe, SZ Slovenija)

Vodonosniki visokega in alpskega krasa so pomembni viri pitne vode. Dinamika toka skozi te vodonosnike je izjemno kompleksna, saj je njihova struktura posledica večfaznega, deloma glaciokraškega razvoja v tektonsko aktivnem območju. Debelina vadozne cone visokogorskih kraških vodonosnikov lahko presega dva kilometra. V članku predstavljamo in obravnavamo rezultate sledilnega poskusa v alpskem krasu Julijskih Alp (Slovenija), natančneje v Sistemu Migovec, najdaljšem jamskem sistemu v Sloveniji (dolžina = 43 km, globina = 972 m). Jama se razteza pod gorskim grebenom, ki ločuje dolini Soče in Save ter tako tvori topografsko ločnico med jadranskim in črnomorskim bazenom. V začetku septembra 2019 smo injicirali tri kilograme uranina v jezero Colarado, približno 900 metrov pod planoto in 100 metrov nad nizkovodnim nivojem podzemne vode. Znane izvire v dolinah na obeh straneh razvodnice smo spremljali z ročnim ali samodejnim vzorčenjem in terenskim fluorometrom. Do izjemnega padavinskega dogodka v začetka novembra sledila nismo zaznali na nobenem od opazovanih mest. Ob dogodku se je sledilo zanesljivo pojavilo le

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Tolminka River. No tracer was detected at other sites, either because it was not present or because it was highly diluted. The study suggests that the lake containing the tracer is bypassed by the vadose flow and that the tracer was only mobilised during large events when the lake became part of the epihreatic flow. The linear peak flow velocity from the injection site to the Tolminka Spring was only about 1.7 m/h. However, assuming that the tracer was only mobilised by the large rain event, the velocity would be 70 m/h. The study highlights the challenges and pitfalls of water tracing in alpine karst systems and suggests ways to avoid them.
Keywords: karst aquifer, unsaturated zone, tracer test, Adriatic-Black Sea watershed, Julian Alps.

na vzorčevalnem mestu v zgornjem toku Tolminke, kjer je po grobi oceni v 60 urah prešlo 60-65 % mase sledila. Na drugih mestih je bil dvig koncentracije, zaradi odsotnosti sledila ali prevelikega razredčenja, premajhen, da bi lahko potrdili pojav sledila. Rezultati kažejo, da vadozni tokovi ob manjših dogodkih niso sprožili zaznavnega prenosa sledila, pač pa je do tega prišlo šele, ko je epifreatični tok ob izjemnem dogodku dosegel nivo vodnih teles s sledilom. Če upoštevamo celoten čas od injiciranja do zaznave sledila, je navidezna hitrost potovanja 1,7 m/h, ob predpostavki, da je sledilo mobiliziral novembrski padavinski dogodek, pa je navidezna hitrost 70 m/h. Študija opozarja na izzive in pasti pri sledenju vode v alpskih kraških sistemih ter predlaga načine, kako se jim izogniti.
Ključne besede: kraški vodonosnik, nezasičena cona, sledilni poskus, Jadransko-Črnomorsko razvodje, Julijske Alpe.

1. INTRODUCTION

Carbonate rocks cover about 15 % of the world's land surface. Approximately 31 % of this area, representing potential karst aquifers, occur in plains, whereas 69 % in hilly and mountain regions (Goldscheider et al., 2020). Karst aquifers are important freshwater resources for approximately 750 million people worldwide. In countries such as Austria and Slovenia, karst water sources provide about half of the drinking water needs (Stevanovic, 2018). Important and only partly used groundwater reserves are in the areas of alpine karst, which have an enormous potential for future water supply.

Aquifers of high-mountainous karst usually have a complex hydrogeological structure where recharge and subsurface flow mechanisms are conditioned by orography, meteorological conditions, vegetation cover and hydraulic gradients, as well as by the geological and structural context (Becker, 2005; Gremaud et al., 2009; Goldscheider & Neukum, 2010; Müller et al., 2013; Petrič et al., 2018; De la Torre et al., 2020). Dominantly diffused recharge from rainfall and snowmelt bypasses the vadose zone via system of fractures, shafts, vadose canyons and abandoned phreatic passages. The vadose zone in alpine karst systems is often several hundred meters thick, and reaches over two kilometres in extreme. Since most of these systems are in active tectonic settings with complex structure, the groundwater table is spatially and temporarily variable. Epiphreatic zone is often several tens to over hundred meters thick. All these factors make alpine karst aquifers extremely difficult if not impossible to delineate. Flow processes are highly dependent on hydrological conditions causing groundwater level fluctuations of several tens of metres and variations of flow velocity by several orders of magnitude (Filippini et al., 2018; Kogovšek & Petrič, 2004). High mountainous karst is also the origin of large lowland watersheds, as it recharges the springs and surface streams which continue to large lowland river system.

Despite numerous hydrogeological studies carried out in the past, the behavior of alpine karst aquifers is still not well understood, especially regarding flow in the unsaturated zone (Maloszewski et al., 2002; Mudarra & Andreo, 2011; Turk et al., 2015; Filippini et al., 2018). Enlarged fractures, shafts, and conduits provide quick water flow paths and are highly vulnerable to contamination, whereas the less permeable parts of the carbonate rock may act as a storage component with a long residence time (Parise et al., 2018; Petrič et al., 2018; Poulain et al., 2018; Kaminsky et al., 2021).

In addition to the already complex behavior of karst systems, climate change presents a challenge in managing such alpine karst aquifers. Climate change scenarios project more heavy rain events in the future, but also more and longer dry periods, and a smaller thickness and duration of the snow cover (Dobler et al., 2013; Rössler et al., 2012; Collados-Lara et al., 2019).

Understanding the functioning of these complex karst aquifers is, therefore, essential for assessing their potential as a drinking water source, their proper use, and protection. Tracer tests represent an appropriate technique for studying the recharge and groundwater flow properties of karst aquifers as well as delineation of catchments (Benischke et al., 2007). However, they are usually less frequently applied in high plateaus and mountains (Goldscheider, 2005; Finger et al., 2013), since they can be costly and long-lasting and results frequently questionable. Furthermore, information acquisition is often very difficult or limited, injection and sampling sites are often difficult to access, and strong tailing effects in the tracer breakthrough may be expected (Lauber & Goldscheider, 2014). Based on the results of individual tracer tests that were carried out in the alpine karst areas, some general characteristics can be assessed. Broad ranges of flow velocities from 0.7 to 662 m/h and from 0.03 to almost 100 m/h were assessed from several tracer test in the karst area of Berchtesgaden Alps in Germany (Kraller et al., 2011) and Kaisergebirge in Nordtirol (Benischke et al., 2010), respectively. In the Cansiglio-Monte Cavallo karst area in Italy, a multi-tracer test was carried out with injection of three fluorescent dyes in different sections of a cave with water flow. Although large quantities of tracers were used (5 to 10 kg) only one tracer was detected in one of the observed springs and a linear maximum flow velocity of 74 m/h was calculated (Filippini et al., 2018). It was noted though that such flow velocity in the period of intensive recharge by precipitation only represents the fast response accentuated by the significant recharge events, and is 4.6 times higher than the maximum one determined by other tracer test in the same aquifer performed at low-flow conditions (Vincenzi et al., 2011). In the high karst area in Vorarlberg in Austria two tracer tests were performed with the injection of tracers into a small stream, fed by snow melt water, at the altitude of 2300 m. In total 25 springs and river locations were investigated with water samples or activated charcoal bags. Only one sampling location led to positive tracer detection with maximum velocities of 229 and 161 m/h, and peak velocities of 144 and 113 m/h (Frank et al., 2021).

In the Slovene alpine karst, tracer tests with a total of 32 injection points have been carried out so far (Petrič et al., 2020). Most of them aimed at finding the main underground water connections (Gams, 1966; Novak, 1990; Cucchi et al., 1997; Trišič et al., 1997; Zini, 2014). The most thoroughly investigated is the area of Kamnik-Savinja Alps where a series of multi-tracer tests were carried out as a basis for planning the protection of karst water sources (Novak, 1995; Ravbar et al., 2021).

This study focuses on the high karst area located between the town of Tolmin in the Soča Valley and Bohinj Lake in the Sava Valley. The region is defined by a high mountainous ridge stretching between the peaks of Tolminski Kuk (2085 m a.s.l.) and Vogel (1922 m a.s.l.), acting as a watershed between the Adriatic (Soča River) and Black (Sava River) Seas. Reliable data on this watershed are currently lacking. However, below the ridge and to the south lies the Migovec system, the longest cave system in Slovenia, spanning over 43 km in length and 972 m in depth, characterized by its complexity and multilevel nature. Establishing a groundwater flow connection between the cave and the main springs on either the Adriatic or Black Sea side of the mountain would undoubtedly provide crucial information about regional groundwater flow distribution. This initiative to trace the flow in the cave system was driven by cavers, who played an essential role in supporting the artificial tracer injection and sampling processes. Short preliminary report on this study has been published by Staut and Stržinar (2020).

The primary objective of this study is to gain a better understanding of the vadose zone's functioning in different hydrological conditions in high karst areas, enabling the creation of a conceptual flow model. Additionally, the research aimed to explore the characteristics of groundwater flow within the Migovec System.

2. MATERIALS AND METHODS

2.1 STUDY AREA

Almost half of Slovenia is covered by carbonate rocks, of which about a quarter (approx. 2200 km^2) is in the high mountains of the Southern Alps (Petrič, 2004). The area consists mainly of Upper Triassic shallow-water carbonate strata. Jurassic and Cretaceous deposits are relatively rare (Buser, 1986; Jurkovšek, 1986; Šmuc, 2005). The relief of the Julian and Kamnik-Savinja Alps is characterised by high glaciokarstic plateaus above 1500 m a.s.l. and deeply incised glacial/fluvial valleys. Practically all plateaus are heavily karstified and densely populated with cave entrances, karren fields and glaciokarstic depressions. Cavers have explored deep and extensive cave systems in most karst massifs. Karst springs occur at altitudes between 100 and 900 m above sea level. The thickness of the vadose zone is over 1 km in most plateaus and over 2 km in some. Perennial surface streams are rare and limited to deep valleys.

The study area is in the Triglav National Park in the Julian Alps. The area is part of the extended mountain ridge and high karstic plateaus between the valleys of Tolminka River and Zadlaščica River in the south and the Bohinj Lake, the largest Slovenian natural lake, and

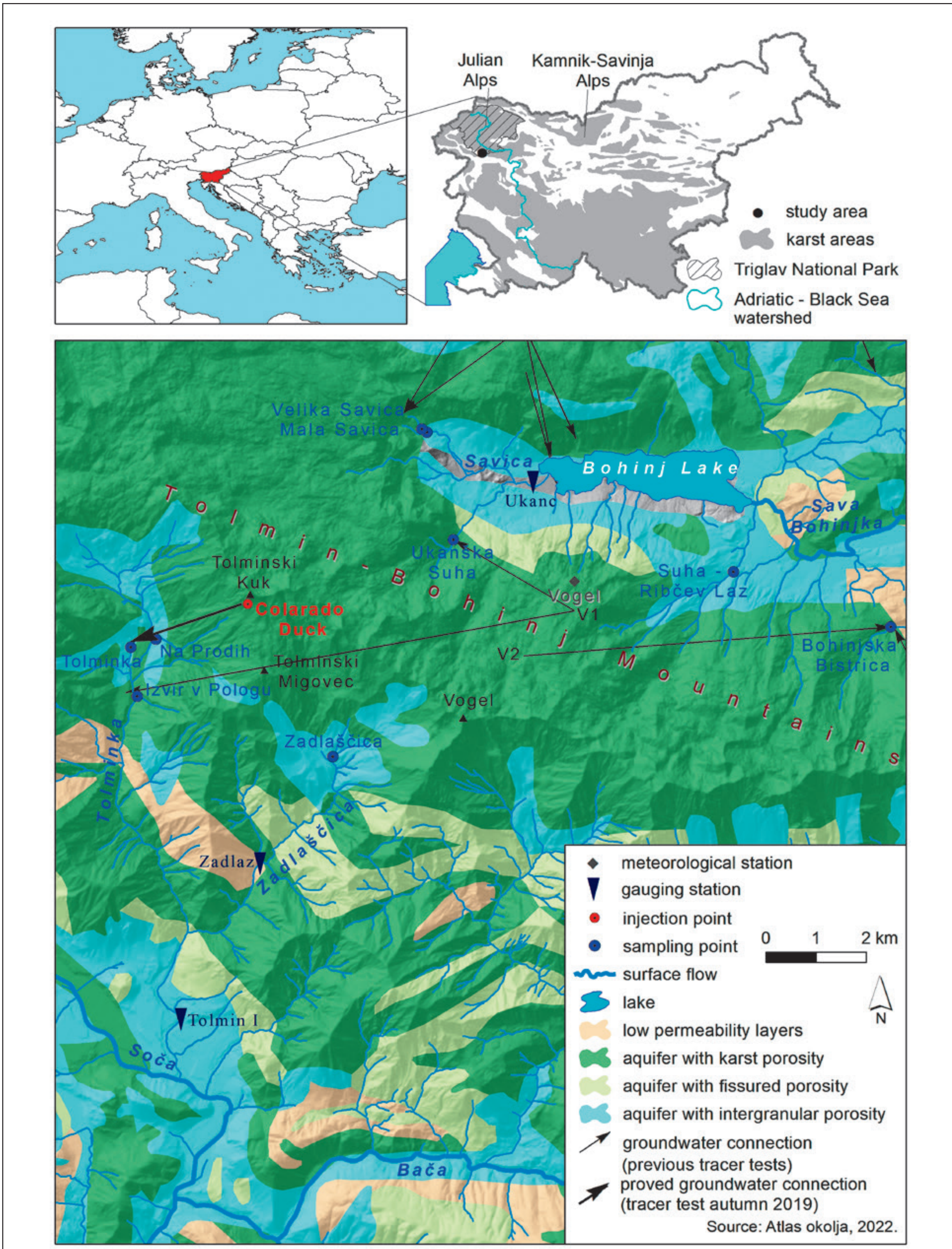

Figure 1: Location of the study area and the hydrogeological map with proved groundwater flow connections and spatial information of tracer test performed in autumn 2019.

its springs Velika Savica and Mala Savica in the north (Figure 1).

The geological structure of the area is characterised by thrust nappes with Upper Triassic carbonate units (Dachstein Limestone and Main Dolomite) thrusted over Jurassic and Cretaceous marls and limestone (Figure 2). Thrust structures are cut by several neotectonic strike slip faults (Placer, 1999; Kastelic et al., 2008).

Climatically, the area received an average annual precipitation of about 3000 mm in the period 1991 - 2021 at the Vogel meteorological station, located at an altitude of 1530 m (ARSO, 2022). On average, there are 178 days with snow and the average annual air temperature is 4.9°C, the average air temperature in January -2.5°C and in June 12°C.

Considerable amounts of snow in winter and its thaw in the spring months influence the discharge hydrographs of mountain rivers. Minimum and mean monthly discharges are highest in the period from April to June, only maximum discharges are higher in the autumn months due to greater rainfall (ARSO, 2020a). Low discharges are recorded in the winter and summer months.

The Migovec System is located between the peaks of Tolminski Kuk and Tolminski Migovec, defining a broadly rectangular karstified plateau of 1 x 2 km (Racine, 2019b; Cave Registry, 2022). It is formed principally in well- stratified and heavily faulted Dachstein Formation. The underlying formation of bedded to massive Main Dolomite Formation outcrops on the NE side of the Tolminka Valley and is less karstified.

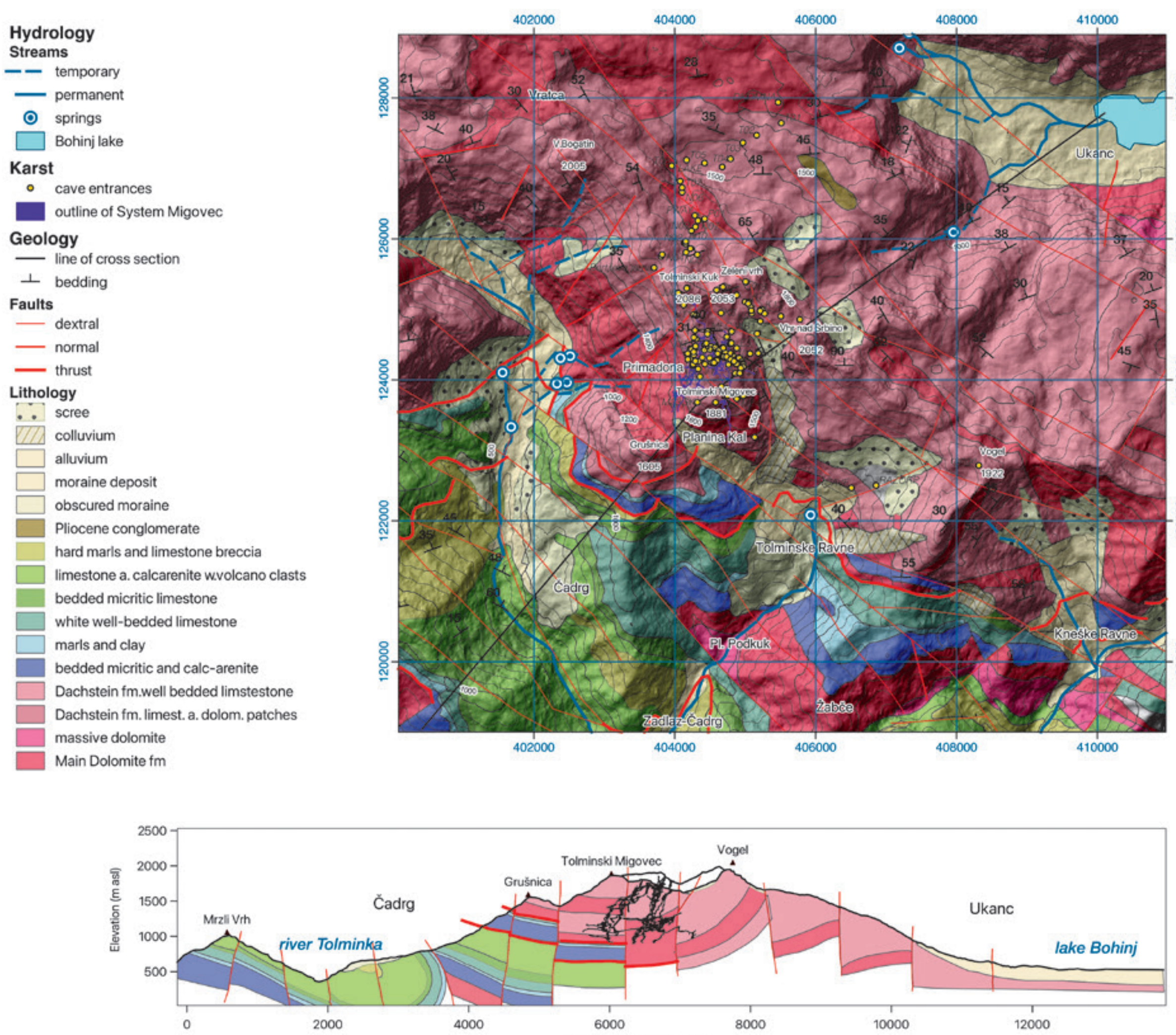

Figure 2: Geological map and simplified section of the Migovec area, based on the geological map by Buser (1986) (from Racine, 2019).

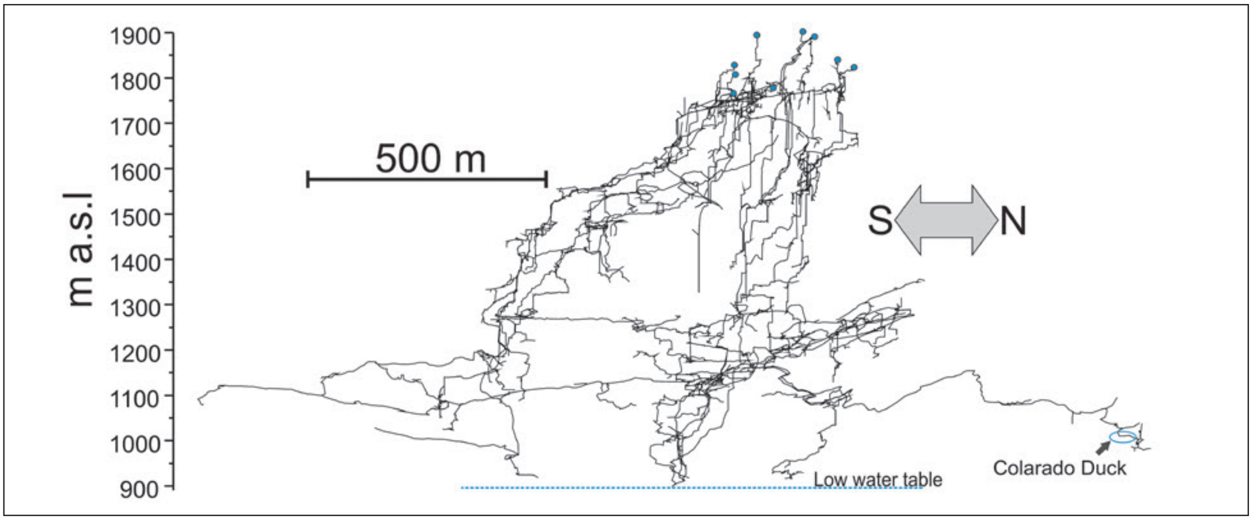

Figure 3: N-S (facing 270°) cross-section of the Migovec System. Blue dots present entrances (export from the Aven 1.4.5; data provided by JSPDT and ICCC).

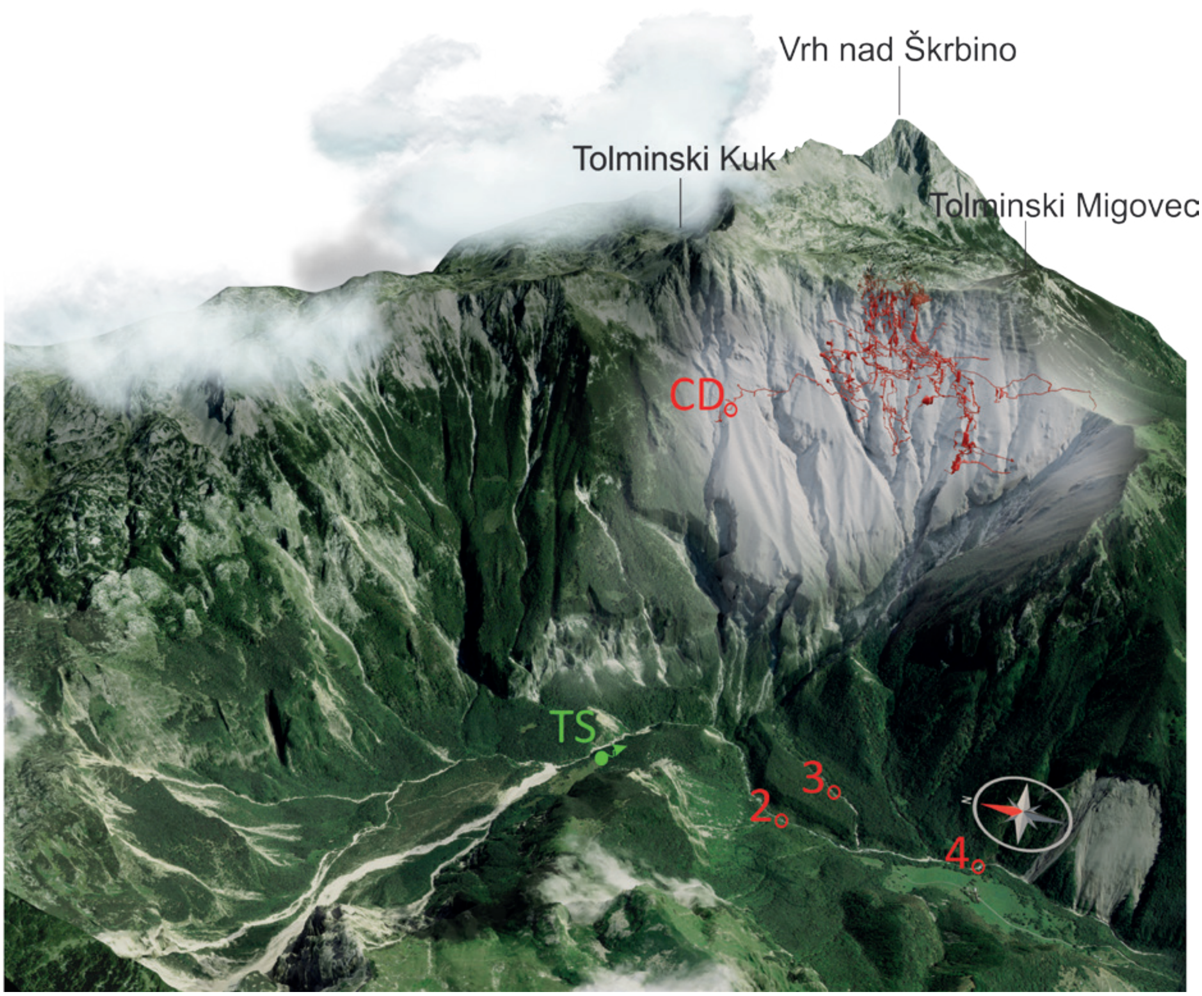

Figure 4: The mountains above Tolminka Valley with the Migovec System (in red; view from the west). TS=Tolminka Spring, CD=injection point Colarado Duck, 2-4 sampling sites in Tolminka Valley (see Table 1). (Processing and design: Tomaž Grdin).

Dachstein limestone predominates also in northeastern direction towards the Bohinj Lake. Locally Quaternary sediments are developed as scree, alluvium, moraine and lacustrine chalk (Buser, 1986).

The Migovec System (Figure 3) consists of nine entrances, located between 1727 m and 1858 m a.s.l. (Racine, 2019b). With a length of 43 km, it is the longest cave system in Slovenia and reaches the depth of 972 m. Exploration of this cave system began in 1974 under the efforts of Jamarska sekcija Planinskega društva Tolmin, Slovenia (JSPDT). Since 1994, the exploration has been a collaborative effort between JSPDT and the Imperial College Caving Club (ICCC) from London.

Through the explorations, researchers have identified at least four distinct cave levels with (epi)phreatic development, interconnected by various vadose shaft-meander systems. The deepest parts of the cave lead to sumps at elevations between 892 and 911 m a.s.l. The southern branch of the system extends towards Zadlaščica Valley, while the northern branch terminates below Tolminski Kuk, which is part of the ridge in the Tolmin-Bohinj Mountains. The uranine injection point was Colarado Duck at the far northern part of the system. Colarado Duck is about ten meters long lake. In dry season airspace allow further "dry" progress to the passage called True Adventure, which continues to partly dry, partly flooded passages with some prospects for further explorations.

The exploration and research in Migovec system is described in more detail in the article by Racine (2019b) and in a number of publications by ICCC and JSPDT (Frost & Hooper, 2007; Racine, 2019a).

The glacial and fluvial down-cutting processes over the geological history have created a narrow and deep valley that cuts right into the karst massif between Tolmin and the ridge (Figure 4). The springs of Tolminka are distributed in talus deposits in the gable of the Tolminka Valley, at the altitudes between 680 and 690 m a.s.l. Position of outflows varies with recharge; at low water only the springs downstream in the riverbed are active (Janež, 2002). Further resurgences hidden in the streambed provide additional recharge along the upper part of the river, as well as several small springs located above the valley bottom (e.g., Na Prodih and Izvir v Pologu on the left bank).

The second major karst spring in this area is Zadlaščica at an altitude of 780 m a.s.l. approximately 5 km south-eastern from Tolminka Spring (Figure 1). The spring is tapped for drinking water supply. Zadlaščica flows into Tolminka River, which is a tributary of the Soča River within the Adriatic Sea basin. Discharge of the Tolminka River is measured only at the gauging station Tolmin I which is positioned 1.4 km upstream from the confluence with the Soča River and 2.1 km downstream from the confluence with the Zadlaščica River. Therefore, it measures a total flow of Tolminka and Zadlaščica, which in the period from 1953 to 2014 ranged from 0.41 to 130 m^3/s and the mean discharge was 7.93 m^3/s. Discharges of Zadlaščica were only measured at the gauging station Zadlaz in the period from 1954 to 1966. The discharges ranged from 0.01 to 58.6 m^3/s, and the mean discharge was 2.23 m^3/s (ARSO, 2020a).

Geological mapping of the springs area was not conducted as part of this project. Nevertheless, our expectations regarding the springs' location in Tolminka Valley and Zadlaščica Spring are informed by prior mapping and comprehensive structural analyses (Kastelic et al., 2008). These analyses suggest a connection between the springs and the Ravne fault, along with associated geological structures. Furthermore, it is worth noting that the springs' positions align with the thrust contact between the Triassic Carbonates and the underlying Cretaceous flysch.Savica River is the major tributary of Bohinj Lake on the northern side of Tolmin-Bohinj Mountains. Upstream from the lake, the river is only 4 km long and consists of two tributaries in the upper part: Mala Savica and Velika Savica. Mala Savica is a 600 m long cave, which is currently still under exploration and extends in direction of Tolmin-Bohinj Mountains. The cave is an overflow spring; during low water season, the water first appears lower in the river bed. The Velika Savica spring is an entrance to a 550 m long cave with the entrance at 836 m a.s.l. (Cave Registry, 2022). The cave entrance opens 75 m above the foot of the big wall, which terminates the cirque of Bohinj. The water from the cave forms a well-known picturesque Savica Waterfall (Skoberne, 1988).

The discharge of Savica River is measured only at the gauging station Ukanc which is located 720 m before the river enters the Bohinj Lake (Figure 1). Between 1997 and 2015 the discharge ranged between 0.04 and 113 m^3/s, the mean discharge was 4.64 m^3/s (ARSO, 2020a). There are several tributaries (e.g., Ukanška Suha stream as right tributary), but since they are mainly dry and function only as torrents, the two main springs contribute the majority to this discharge (Brenčič & Vreča, 2016). From the Bohinj Lake flows the Sava Bohinjka River, which is one of the two original branches of the Sava River, a tributary of the Danube River within the Black Sea basin. In this area two right tributaries of the Sava Bohinjka are Suha in Ribčev Laz and Bohinjska Bistrica (Figure 1).

2.2 PREVIOUS TRACER TESTS

Racine (2019b) mentions that some simple tracer tests were carried out in the Migovec area from 1997 to 2001, however no detailed data is given. Only a comment that no conclusive link was drawn to either the river Tolminka to the west, Zadlaščica to the SE or Savica to the NE.

More information is available in an unpublished report about a multi-tracer test in the Vogel area (Trišič, 2014). In autumn 2002, on the slopes dipping from the Vogel peak towards the Bohinj Lake, 10 kg of amidorhodamine G was injected into a borehole V2 and 5 kg of uranine into a borehole V1 (Figure 1). Sampling was organised at 15 locations in the Soča and Sava basins. Amidorhodamine G was detected in Bohinjska Bistrica and uranine in Ukanška Suha and Izvir v Pologu. However, the concentrations were very low and further investigations are needed for reliable confirmation of these groundwater connections.

Several tracer tests were performed in the area northern from the Bohinj Lake and the groundwater flow connections with the Velika Savica spring were proved (Figure 1) (Trišič et al., 1997).

2.3 METHODS

Daily precipitation data at the Vogel meteorological station (ARSO, 2019) and discharges of the Tolminka River at the hydrological station Tolmin I in 30-minute intervals (ARSO, 2020b) were obtained from the publicly available online datasets of the Slovenian Environment Agency. The main streams contributing to the water flow in this hydrological station are the Tolminka and the Zadlaščica. In the years 1954 to 1966, the discharges of the Zadlaščica were also measured (ARSO, 2020a), and these data were used to compare the contributions of the two rivers to the total flow.

The passage leading to Colarado Duck in the far northern part of the Migovec system is closest to the topographical divide between Soča and Sava basins (Figs. 1 and 2). Although the first explorers considered it a siphon (Colarado Sump), later cavers found an airspace above the water surface, passed through the duck, and explored another 270 m long passage named True Adventures. To avoid swimming, the Colarado Duck was chosen as the injection site. The Colarado Duck is at a depth of 879 m, a good 90 m above the level of the lowest siphons in the cave, which presumably mark the groundwater level. The lake is about 10 m long and contains a large volume of fine silt. The passage leading to Colarado Duck appears to be well washed out, indicating substantial and relatively rapid water flow.

Three kilograms of uranine were injected into Colarado Duck (Figures 3 and 4) at the depth of 858 m (GKY 404520, GKX 124610, z =1000 m) at 5:30 pm on September 4, 2019. At the time of injection, inflow to the lake was minimal, less than 0.05 L/s. Due to the difficult access, a team of 4 people participated in the injection, and the entire operation in the cave took 19 hours.

Based on the known regional hydrogeological characteristics, a total of nine sites were chosen for the sampling. In the period from September 4 to November 11, 2019, samples were taken at the springs of Zadlaščica, Tolminka, Na Prodih and Izvir v Pologu on the Tolmin side in the Soča catchment, and in Mala Savica and Velika Savica, Ukanška Suha, Suha in Ribčev Laz and Bohinjska Bistrica on the Bohinj side in the Sava catchment (Tab. 1). Several blank samples were collected beforehand at all the sites.

The ISCO 6712 automatic samplers were installed on September 3, 2019 at Zadlaščica, Tolminka and Mala Savica. All three springs are very difficult to access, and the organization of automatic sampling is practically impossible there, so the samplers were placed downstream in suitable places. The water from the Zadlaščica spring is piped to the Zadlaščica hydroelectric power plant, and sampling was organized at the outlet of the pipes on the premises of the hydroelectric power plant. At the same location, a Götschy Optotechnik LLF-M field fluorometer was installed for continuous fluorescence measurements in 30-minute intervals. The automatic samplers on Tolminka and Mala Savica were installed at surface streams 1.6 km and 0.4 km downstream of the springs, respectively (Figures 1 and 5).

Table 1: Coordinates of sampling sites, their type (i.e., P-outlet of the pipe, SP-spring, SS-surface stream) and linear distances L between the injection point and the sampling sites.

No.	Sampling sites	Type	GKY	GKX	Z (m)	L (km)
1	Zadlaščica	P	406185	121546	777	3.5
2	Tolminka	SS	402157	123729	467	2.5
3	Na Prodih	SP	402654	123892	558	2.0
4	Izvir v Pologu	SP	402285	122751	470	2.9
5	Mala Savica	SS	408060	128030	652	5.0
6	Velika Savica	SS	408060	128087	654	5.0
7	Ukanška Suha	SS	410128	126990	528	5.1
8	Suha in Ribčev Laz	SS	414526	126075	569	10.1
9	Bohinjska Bistrica	SP	419464	126100	505	15

Figure 5: Left: The sampling site at Mala Savica. Right: Risky crossing of Tolminka River was required to reach the sampling locations at high water level in early November 2019.

The sampling frequency ranged from every six hours at the beginning of the test to twice a day at the end. The sampling was completed on November 11, 2019.

Between September 7 and November 10, 2019, manual sampling once a day was conducted at six sampling sites (Na Prodih, Izvir v Pologu, Velika Savica, Ukanška Suha, Suha in Ribčev Laz, Bohinjska Bistrica) by cavers of the two caving clubs. They covered considerable distances, and crossing the Tolminka was a particular challenge, especially during the heavy rains of early November, when they needed some ingenuity and daring (Figure 5).

All collected samples, altogether 627, were properly stored at ~4°C in dark vials. In order to establish the presence of uranine, they were analysed in the laboratory of the Karst Research Institute ZRC SAZU with the PERKIN ELMER LS 45 Luminescence Spectrometer (E_{ex}=491nm, E_{em}=512nm). Its detection limit is 0.001 µg/L. However, low concentrations above this limit may be due to increased turbidity and the presence of organic matter. Therefore, only concentrations above 0.05 µg/L were considered as a possible occurrence of uranine.

3. RESULTS

The results are summarised in Figure 6. Figures 6a and 6b show daily precipitation at Vogel weather station and discharges of the Tolminka River at the ARSO hydrological station Tolmin I for the period of tracer test, respectively. Figures 6c and 6d present uranine concentrations in Zadlaščica and Tolminka rivers.

The tracer was injected at low water conditions. The occasional rainfall in September and October 2019 (total 342 mm) did not significantly increase the Tolminka River discharge, although several precipitation events with up to 75 mm of rainfall (Figure 6a) were expected to mobilise the tracer. However, during this period, the tracer did not appear in any of the observed springs. Heavy rainfall in early November 2019 (618 mm of precipitation was measured at Vogel between November 3 and 9) resulted in an extreme increase of discharge up to 105 m^3/s at Tolminka. The high water activated the tracer transport to Tolminka spring: uranine concentration of 0.37 mg/m^3 was measured in the sample collected at 12:30 on November 4, 2019. The first tracer detection occurred only 12 hours prior to this peak.

Since there is no data on Tolminka spring discharges, only a very rough estimate of the recovered tracer is possible. Based on the data on the discharges of the Zadlaščica and the Tolminka in the period 1954-1966, it was assumed that the Tolminka spring contributes about 70 % to the total flow of the Tolminka at the Tolmin I station. Considering this proportion of Tolminka discharge at Tolmin I station during the tracer test, the proportion of recovered tracer can be estimated at 60-65 %.

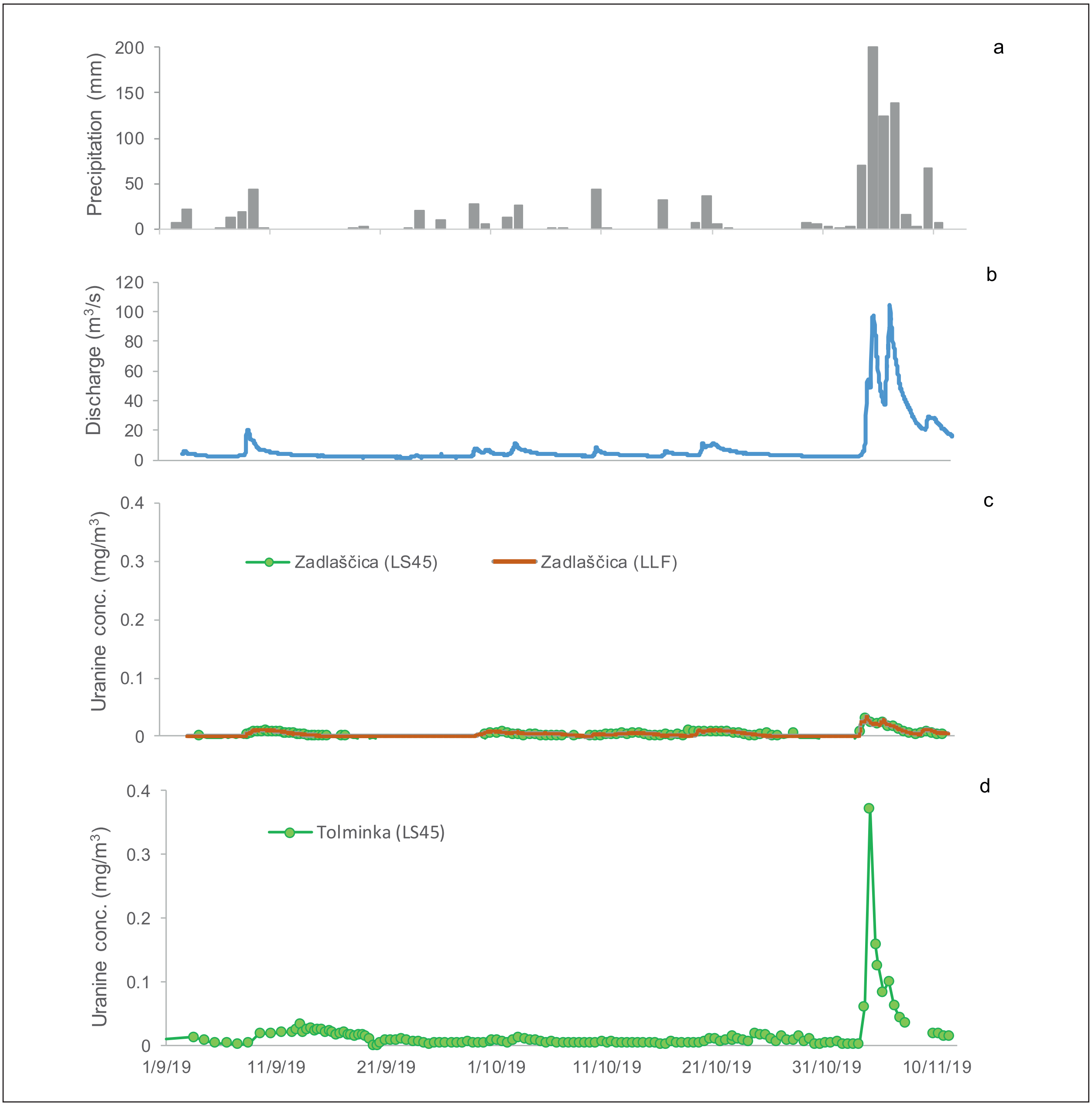

Figure 6: Daily precipitation at the Vogel station (a) and discharges of the Tolminka River at the Tolmin I station (b), uranine concentrations in samples from Zadlaščica and Tolminka (c, d) (LLF: measured with field fluorometer; LS45: measured in samples in laboratory).

Taking into account the possible range of the proportion of Tolminka flow between 60 and 80 %, the proportion of the recovered tracer in Tolminka would be between 53 and 71 %. It can be concluded that, under the given conditions, the tracer test confirms the main flow direction from the Colarado Duck to the Tolminka River.

In Zadlaščica, concentrations up to a maximum of 0.03 mg/m^3 were measured (Figure 6c), which is not sufficient to confirm the connection. The same is true for the other observed springs (Figure 7), where slightly higher concentrations (up to 0.07 mg/m^3) were measured after each rain event, but these can be explained by increased turbidity and leaching of organic substances from the karst system. However, it cannot be completely ruled out that the tracer was also present at lower levels in these springs, but was diluted due to the very high discharges during the main rainfall event and could not be detected at sufficiently high concentrations to reliably confirm the connection. There is always a possibility that transit time to some springs is still longer than the sampling period.

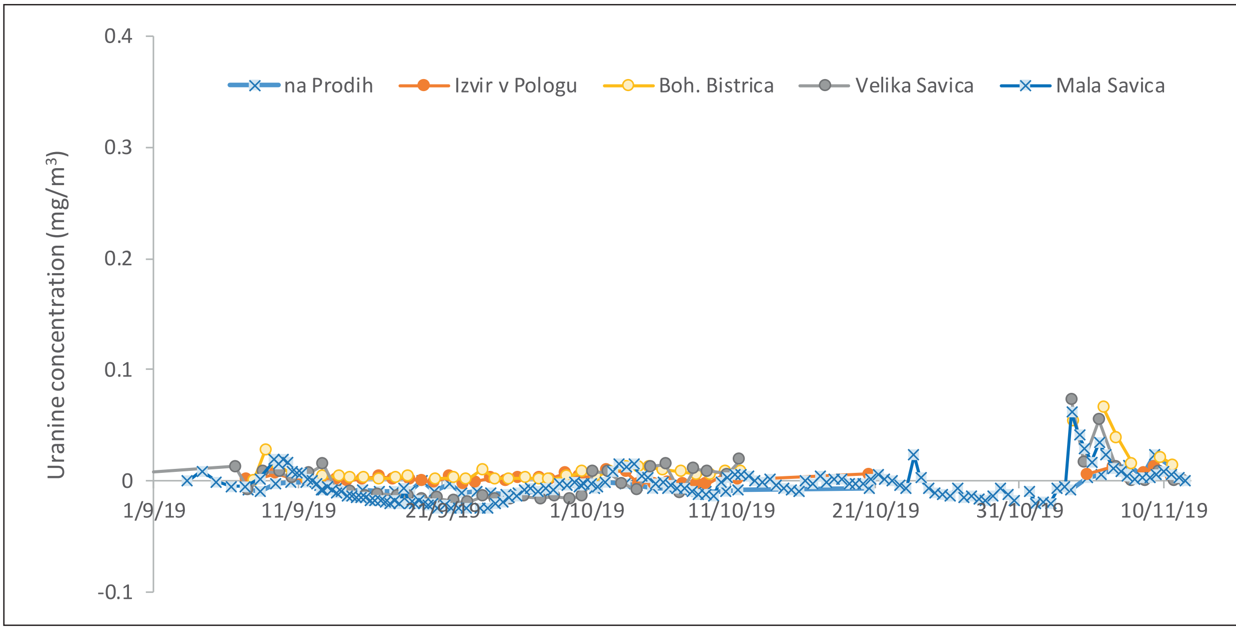

Figure 7: Results of fluorescence measurements at other sampling sites.

4. DISCUSSION

This tracer test had few specifics: the tracer was injected at low water conditions into a perched epiphreatic lake, several tens of meters above the groundwater level. The results indicate that majority of the tracer was not mobilised during small and medium rain events in September and October. Only an extreme event starting on November 3 mobilised the water body with the tracer and flushed it primarily towards the Tolminka Spring.

The question remains, why the preceding rain events had not mobilised the tracer. These events must have triggered some amount of vadose flow and if this flow would pass the Colarado Duck it would also trigger the tracer transport. To address these observations, we propose a conceptual model presented in Figure 8. Here we assume that most of the gravitational vadose flow bypasses the passage with Colarado Duck and that the springs recharge occurs via other vadose pahtways. The transport through the Colarado Duck is activated only when the passage becomes part of the epiphreatic flow, during high precipitation events, when the groundwater level rises above the level of the Colarado Duck. It is also possible that the tracer was not confined only to Colarado Duck, but was tranported to another perched water body. However, we cannot confirm these assumption.

The nature of the passage leading to Colarado Duck shows some characteristics, which support above assumptions: the passage has not distinct vadose entrenchment and shows signs of being regularly flooded along the entire perimeter. However, observations based on one visit cannot be taken as a definite evidence. To confirm the model, additional research would be needed.

The calculation of linear flow velocity considering the time from injection to detection of tracer may be misleading in such case, because most of the tracer was not mobilised prior to the November event. Using time from the injection to the breakthrough and linear distance of 2.5 km, calculation of maximal and peak flow velocities gives low values of 1.7 m/h (Tab. 2). If, instead of the total residence time since injection, only the time from the onset of heavy precipitation to the measured maximum concentration of the tracer were considered, the maximum velocity would be 104 m/h and the peak velocity 70 m/h. Comparing the results of this experiment with some previous experiments conducted in similar geological and climatic environments, we find that the flow velocities are very comparable. Tracer experiments conducted in the Slovenian Alpine karst show linear flow velocities of up to 70 m/h as well (Petrič et al. 2020). The velocities are also comparable to those obtained from previous tracing from the Vogel area (Trišič 2014). On the other hand, some previous tracings in the wider area confirmed the bifurcation

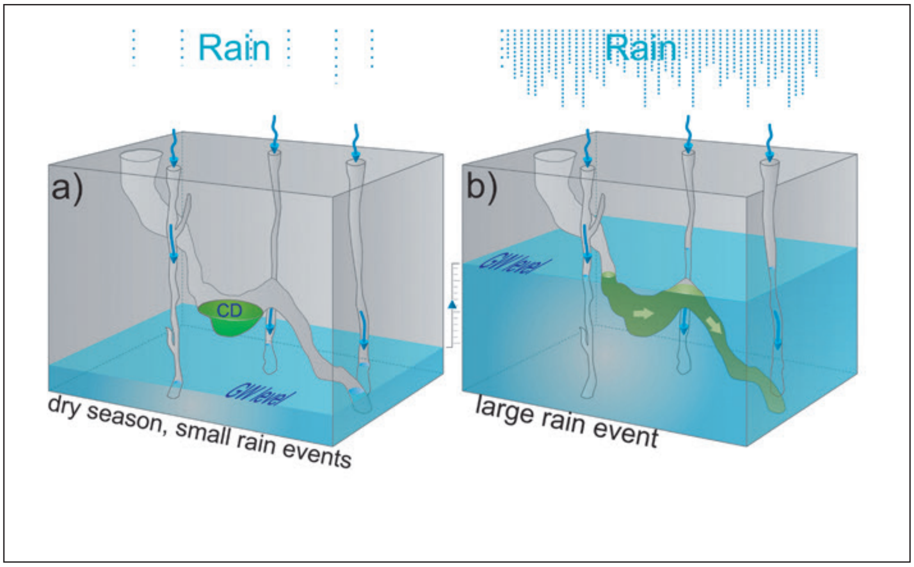

Figure 8: Conceptual interpretation of the results: a) the majority of tracer confined to the Colarado Duck (CD) with vadose flow (blue arrows) bypassing the passage; b) rise of the groundwater level during the extreme rain event and activation of tracer transport (white arrows). Artwork: Gorazd Koščak)

zone at the watershed between the Soča and the Sava, and thus also between the Adriatic and Black Sea watersheds, which is not the case in this tracer experiment.

Short breakthrough curve with a single distinct peak and high tracer recovery show that there is a direct connection between Colarado Duck and the spring at high water, without flow deviations. Similar tracer test results in an Alpine area were observed in a recent study by Ravbar et al. (2021), in which groundwater was proved to flow through a system of interconnected and well-permeable karst conduits and channels. All of the above arguments indicate that the tracer in this tracer tests was confined to a small area and was not widely dispersed in the aquifer prior to the November rain event.

Detected minor increases in measured concentrations in the other springs after very intense precipitation in early November 2019 are not sufficient to confirm the connection and are more likely the result of increased turbidity and leaching of organic matter from the karst system. However, due to the unfavourable hydrologic conditions for tracer detection (very high discharges after a long dry period), the possibility of a secondary connection, i.e., flow to other springs in a much lower proportion, cannot be completely ruled out. Due to the high dilution, the tracer could not be reliably detected.

Because of the rapid flow in the phreatic zone and the proximity of the spring, the tracer was detected only a few hours after precipitation began, and the breakthrough curve lasted less than two days. If sampling were done only once a day during this period, e.g., at 12:30 p.m., the maximum detected concentration would be only 0.16 mg/m^3. However, if sampling were done every other day, the occurrence of the tracer would be overlooked because the maximum concentration measured would be only 0.08 mg/m^3, which would not be sufficient to reliably confirm the connection. Therefore, it is very useful to use field fluorometers that can monitor the occurrence of the tracer at shorter intervals, in our case every 30 minutes. Unfortunately, in our case, only one was available and it was placed at the most important spring, which is however not in the direction of the main groundwater flow from the injection point.

Table 2: Uranine appearance at Tolminka sampling site; L – linear distance between injection point and sampling site; t_1 – time interval from injection to the first tracer detection; v_{max} – linear maximum flow velocity; c_{max} – highest measured tracer concentration; t_p – time of maximum tracer concentration (calculated from the time of injection or from the time of the precipitation event that pushed the tracer towards the spring); v_p – linear peak flow velocity; R – estimated proportion of recovered tracer.

	Time from injection		Time from precipitation event			Time from injection		Time from precipitation event		
L	t_1	v_{max}	t_1	v_{max}	c_{max}	t_p	v_p	t_p	v_p	R
(km)	(h)	(m/h)	(h)	(m/h)	(mg/m^3)	(h)	(m/h)	(h)	(m/h)	(%)
2.5	1447	1.7	24	104	0.37	1459	1.7	36	70	60-65

5. CONCLUSIONS

The results indicate that the water from the Migovec System flows into Soča River Basin. However, flow connections to other sites on both sides of the ridge, cannot be excluded based on a single test done in rather specific hydrological situation.

The tracer test once more confirmed the challenges of water tracings in the alpine karst. It turned out that the tracer was "trapped" in the perched epiphreatic lake, with no or minimal flow through, despite of several post injection precipitation events with up to 75 mm of rainfall. The flow and transport was activated and the tracer appeared at the spring only during an extreme rain event, which rose the groundwater level to or above the elevation of the injection point.

Therefore, sufficiently long and frequent sampling was crucial to detect the occurrence of the tracer in the spring. In recent years, quite a few tracer tests have been carried out in the alpine karst aquifers that did not yield results because sampling was stopped too quickly. Because of the possible short duration of the tracer breakthrough curve, the sampling frequency should remain sufficiently high even in these later periods. It is useful to adjust the sampling frequency to precipitation conditions, since precipitation events in particular can trigger tracer transfer.

One could use this experience for conducting tracer tests in areas with highly dynamic epiphreatic flow. By tracer solution at certain elevation in a confined reservoir and water level logger, we could establish an exact time of tracer transport activation, which would allow much better assessments of transit times and flow velocities under known conditions.

Thanks to the careful preparation of the experiment, good organization, and, above all, consistency, perseverance, and resourcefulness in injection and sampling under demanding field conditions, the described tracer test in the Tolminski Migovec area could be considered successful. In this respect, it could be described as an exemplary case study with efficient cooperation between cavers and researchers.

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