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Austrian Journal of Earth Sciences | Vienna | 2019 | Volume 112/1 | 50 - 61 | DOI: 10.17738/ajes.2019.0004

Karst hydrogeology of Lamprechtsofen (Leoganger Steinberge, Salzburg)

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KEYWORDS Lamprechtsofen; Leoganger Steinberge; karst hydrogeology; hydrographs; stable water isotopes

Abstract

The Leoganger Steinberge are a heavily karstified massif largely composed of Dachstein dolomite and limestone hosting the deepest through-trip cave in the world, Lamprechtsofen, whose frontal parts are developed as a show cave. Many parts of this 60 km-long and 1724 m-deep system are hydrologically active. 1.5 km behind the lower cave entrance Grüntopf stream and Kneippklamm stream merge to form the main cave stream. Another underground stream, Stainerhallen stream, flows through the eponymous hall of the show cave. Since 2007 water temperature, electrical conductivity and water level have been monitored in the Grüntopf and Kneippklamm stream. Water temperature and water level in the Stainerhallen and main cave stream have been measured since 2016.

The long-term dataset (2013–2017) shows that the water temperature of the cave streams (Grüntopf stream: 3.7–5.2°C; Kneippklamm stream: 5.1–5.9°C) is largely invariant, but the electrical conductivity varies strongly (Grüntopf stream: 107–210 µS/cm; Kneippklamm stream: 131–248 µS/cm) in response to snowmelt and precipitation events. The event water of the Kneippklamm stream is characterized by a low electrical conductivity and is then followed by slightly warmer and higher mineralized water derived from the phreatic zone. This dual flow pattern also explains the asymmetrical changes of the water level during snowmelt: the fast event water flows directly through vadose pathways to the measurement site, whereas the hydraulic (phreatic) response is delayed. The Grüntopf stream reacts to precipitation and snowmelt events by changes in the karst-water table, which can be explained by a piston flow-model. The Kneippklamm stream reveals evidence of a lifter system.

The altitude of the catchments was calculated using $\delta^{18}O$ values of water samples from the underground streams and from surface precipitation. The Grüntopf stream shows the highest mean catchment (2280 m a.s.l.), which is in agreement with its daily fluctuations of the water level until August caused by long-lasting snowmelt. The Stainerhallen stream has the lowest catchment (average 1400 m a.s.l.). The catchments of the other two streams are at intermediate elevations (1770–1920 m a.s.l.). The integration of the catchment analyses and observations from tracer tests conducted in the 1970s showed that the latter reflected only one aspect of the karst water regime in this massif. During times of high recharge the water level rises, new flow paths are activated and the karst watershed shifts.

Zusammenfassung

Die Leoganger Steinberge sind ein Karstmassiv bestehend aus Dachsteinkalk und –dolomit, in dem sich die tiefste Durchgangshöhle der Welt, der Lamprechtsofen, befindet. Viele Bereiche der 60 km langen und 1724 m tiefen Höhle sind hydrologisch aktiv und im unteren Eingangsbereich wurde die Höhle touristisch erschlossen. Insgesamt können folgende unterirdische Bäche unterschieden werden: 1,5 km hinter dem unteren Höhleneingang fließen Grüntopfbach und Kneippklammbach zusammen und bilden den Haupthöhlenbach. Ein weiterer Bach, der Stainerhallenbach, fließt durch die gleichnamige Schauhöhle. Seit 2007 werden im Grüntopf- und Kneippklammbach Wassertemperatur, elektrische Leitfähigkeit und Wasserstand gemessen. Im Stainerhallen- und Haupthöhlenbach werden seit 2016 Wassertemperatur und Wasserstand aufgezeichnet.

Die langjährige Datenreihe (2013–2017) zeigt, dass die Wassertemperatur der Höhlenbäche (Grüntopfbach: 3,7–5,2°C; Kneippklammbach: 5,1–5,9°C) kaum variiert, wohingegen die elektrische Leitfähigkeit (Grüntopfbach: 107–210 µS/cm; Kneippklammbach: 131–248 µS/cm) stark auf Schneeschmelze und Niederschlagsereignisse reagiert. Im Kneippklammsystem erreicht zuerst das gering mineralisierte Ereigniswasser, das in der vadosen Zone abgekühlt wird, den Datensammler und erst später kommt es durch etwas wärmeres und stärker mineralisiertes Wasser aus der phreatischen Zone zum Wasserstandsmaximum. Der Zwei-Komponenten-Abfluss erklärt auch das asymmetrische Abflussverhalten bei Schneeschmelze: das schnelle Ereigniswasser fließt direkt durch die vadose Zone ab, wohingegen der hydraulisch bedingte Abfluss verzögert ist. Der Grüntopfbach reagiert auf Änderungen des gesamten Karstwasserspiegels, wie es durch den Kolben-Effekt beschrieben wird. Des Weiteren zeigt der Kneippklammbach Anzeichen für ein Heber-System.

Die monatlichen Wasserproben der Höhlenbäche sowie des Niederschlages wurden auf $\delta^{18}O$ analysiert, und somit konnte eine mittlere Einzugsgebietshöhe berechnet werden. Der Grüntopfbach hat das höchste mittlere Einzugsgebiet (2280 m), was wiederum mit den langanhaltenden täglichen Abflussschwankungen bedingt durch die Schneeschmelze übereinstimmt. Der Stainerhallenbach hat das niedrigste Einzugsgebiet (durchschnittlich 1400 m) und die Einzugsgebiete der beiden anderen Höhlenbäche liegen dazwischen (1770-1920 m). Der Vergleich der Einzugsgebietsberechnungen mit den Ergebnissen von Markierungsversuchen aus den 1970er Jahren zeigte, dass letztere das hydrologische Regime bei einem bestimmten Wasserspiegel widerspiegelten. Durch ein höheres Wasserangebot kann der Wasserspiegel ansteigen, neue Wasserwege werden aktiviert und die Wasserscheide verlagert sich.

1. Introduction

The Northern Calcareous Alps of Austria and southernmost Germany host some 13000 caves concentrated in karst massifs between the provinces of Salzburg and Lower Austria (Plan and Spötl, 2016). While most of these cave systems are now in the vadose zone due to tectonic uplift since the Miocene, several extend down into today´s (epi)phreatic zone. Vadose shafts connect palaeophreatic cave levels to the overlying karst plateaus and karst springs are commonly but not exclusively located close to the present-day valley floor. The deepest cave which can be traversed from the plateau (2388 m a.s.l.) to the lower entrance at 664 m a.s.l. is Lamprechtsofen, which ranks as the deepest through-trip cave in the world and the deepest cave in Europe (1724 m elevation difference). Located in the Leoganger Steinberge, many parts of this 60 km-long system are hydrologically active. The galleries behind the lower entrance have been developed into a show cave and are prone to flooding, posing a hazard for the visitors (Pfarr, 2016).

The hydrogeology of the Leoganger Steinberge was only studied some four decades ago (Völkl, 1974). Since then exploration in this cave as well as the technology of hydrological monitoring have made considerable progress. The aim of the present study is to advance the understanding of the discharge systematics of the karst streams in this cave system as well as their responsiveness to snowmelt and precipitation events. In addition to stream and spring monitoring, this study for the first time also employs stable isotope analyses to define the catchments of the cave streams in order to establish a robust karst-hydrological model.

2. Geological and hydrological setting

The karst massif of the Leoganger Steinberge comprises an area of 85 km² reaching its highest elevation at Birnhorn (2634 m a.s.l.). High-lying areas of this mountain range are heavily karstified, in particular Ebersbergkar, an elongated north-facing cirque, as well as adjacent east-facing cirques.

The massif consists of well bedded, north-dipping Middle to Upper Triassic carbonate rocks (Dachstein dolomite and limestone) dissected by faults and forms part of the Staufen-Höllengebirgs nappe. The lower part of Lamprechtsofen follows the strike of one of these tectonic structures (Fig. 1 – Stingl, 1984; Heinisch et al., 2015).

Lamprechtsofen is a water-active cave with three different underground streams: Grüntopf, Kneippklamm and Stainerhallen stream. 1.5 km behind the lower entrance at an altitude of ca. 880 m a.s.l. Grüntopf stream and Kneippklamm stream merge to form the main cave stream. The data logger which monitors the main cave stream is located in the Walterhalle, which is a large dome close to the lower cave entrance. This stream emerges at the Altach spring, also called Forscherteil stream, close to the lower cave entrance. During flood events parts of the main cave stream merge with the Stainerhallen stream in the show cave.

The Kneippklamm stream is the only stream in the upper hydrologically active parts of the Lamprechtsofen. The data logger is installed in the Kneippklamm, approximately 150 m before the Kneippklamm stream merges with the Grüntopf stream. The Grüntopf stream flows through several siphons, which are connected by waterfalls, but is not present in the upper parts of the cave system. The data logger is located adjacent to the Grüntopf siphon 50 m before both underground streams merge. The independent third underground stream, Stainerhallen stream, flows through the eponymous hall of the show cave (Klappacher and Knapczyk, 1977 – Fig. 1).

In addition to Lamprechtsofen and its adjacent spring (Altach spring or Forscherteil stream) several other springs drain this massif. These include springs south and north of Lamprechtsofen (e.g. Hacker and Eis springs) as well as Birnbachloch, a large karst spring in the south. In order to trace the subsurface drainage pattern tracer tests were performed between 1970 and 1977 (Fig. 1 – Völkl, 1974; 1977). The first tracer injected in the Ebersbergkar (at 2330 m a.s.l.) in July of 1971 reappeared 18 hours later at the Forscherteil stream. Another test demonstrated the hydrological connection between this cirque and the Hacker and Eis springs. A tracer injected in the Dürrkar was detected in the Birnbachloch. The first test from 1971 was repeated in 1975, but this time the injection point was 13 m further to the south and the tracer reappeared at the Birnbachloch rather than at the Forscherteil stream. The last tracer test was performed in 1977 in an underground stream of Wieserloch, another cave north-west of Lamprechtsofen, and the tracer emerged at the springs in the northwestern part of the massif (Völkl, 1974; 1977).

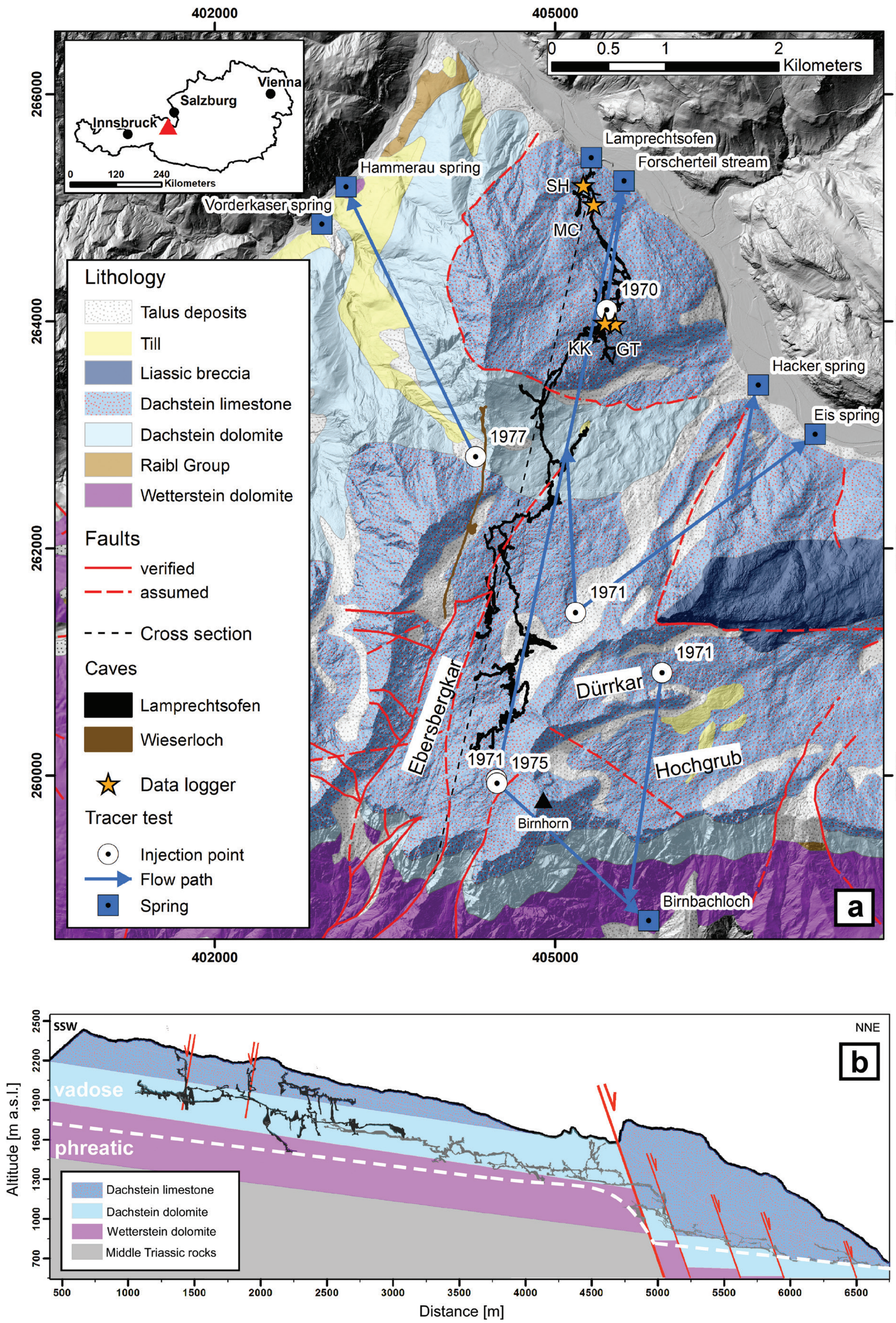

Figure 1: (a) Geological map of the Leoganger Steinberge showing the outline of Lamprechtsofen and Wieserloch, the locations of the underground data loggers (GT= Grüntopf; KK = Kneippklamm; SH = Stainerhalle; MC = main cave), the location of the most important springs and the results of the tracer tests (with the year of the injection) (after Stingl, 1984; Heinisch et al., 2015; Völkl, 1974; 1977). (b) Simplified geological cross section of Lamprechtsofen (see dashed black line in panel (a) and the assumed position of the karst water table (dashed white line).

3. Methods

3.1 Physical parameters

Four data loggers recorded the physical parameters of the cave streams at Kneippklamm, Grüntopf, Walterhalle and Stainerhalle (Fig. 2). The data loggers (model YSI 600) at Kneippklamm and Grüntopf registered water level, electrical conductivity (EC) and water temperature since 2007. The data were initially recorded every hour and since 2013 every 15 minutes. In this study the data from 2013–2017 were analyzed. Since 2016 the water level and the water temperature of the main cave stream have been logged at Walterhalle (Fig. 1). This logger, however, records water levels up to 11 m only. Since 2017 a data logger in the Stainerhallen stream measures water level and water temperature. These parameters have also been monitored since 2015 at Forscherteil stream and Hacker spring. The data from the hydrographs of the underground streams were compared to the precipitation data from the meteorological station Vorderhorn (1895 m a.s.l.).

3.2 Isotope analysis

Between August 2016 and August 2017, monthly water samples were taken in Stainerhalle, Walterhalle (main cave stream), Forscherteil stream, Hacker and Eis springs. The Kneippklamm and Grüntopf streams were sampled once in January 2017 only (these cave parts are flooded between spring and autumn). The $\delta^{18}O$ values were analyzed at the University of Innsbruck using a Picarro L2140-*i* CRDS instrument. The precision of the measurements is ± 0.1‰ $\delta^{18}O$.

The isotopic altitude gradient for the study area was determined by using rainwater samples collected monthly with a PALMEX rain collector at 2051 m a.s.l. between July and September 2017, a snow profile dug at 1965 m a.s.l. and precipitation data from the station at Saalfelden (748 m a.s.l.) 10 km SE of Lamprechtsofen. The snow profile was taken at the Schmittenhöhe (16 km south of Lamprechtsofen) on 28 March 2017 in an area with little wind drift and before snowmelt had started. To obtain the mean isotopic composition of winter precipitation

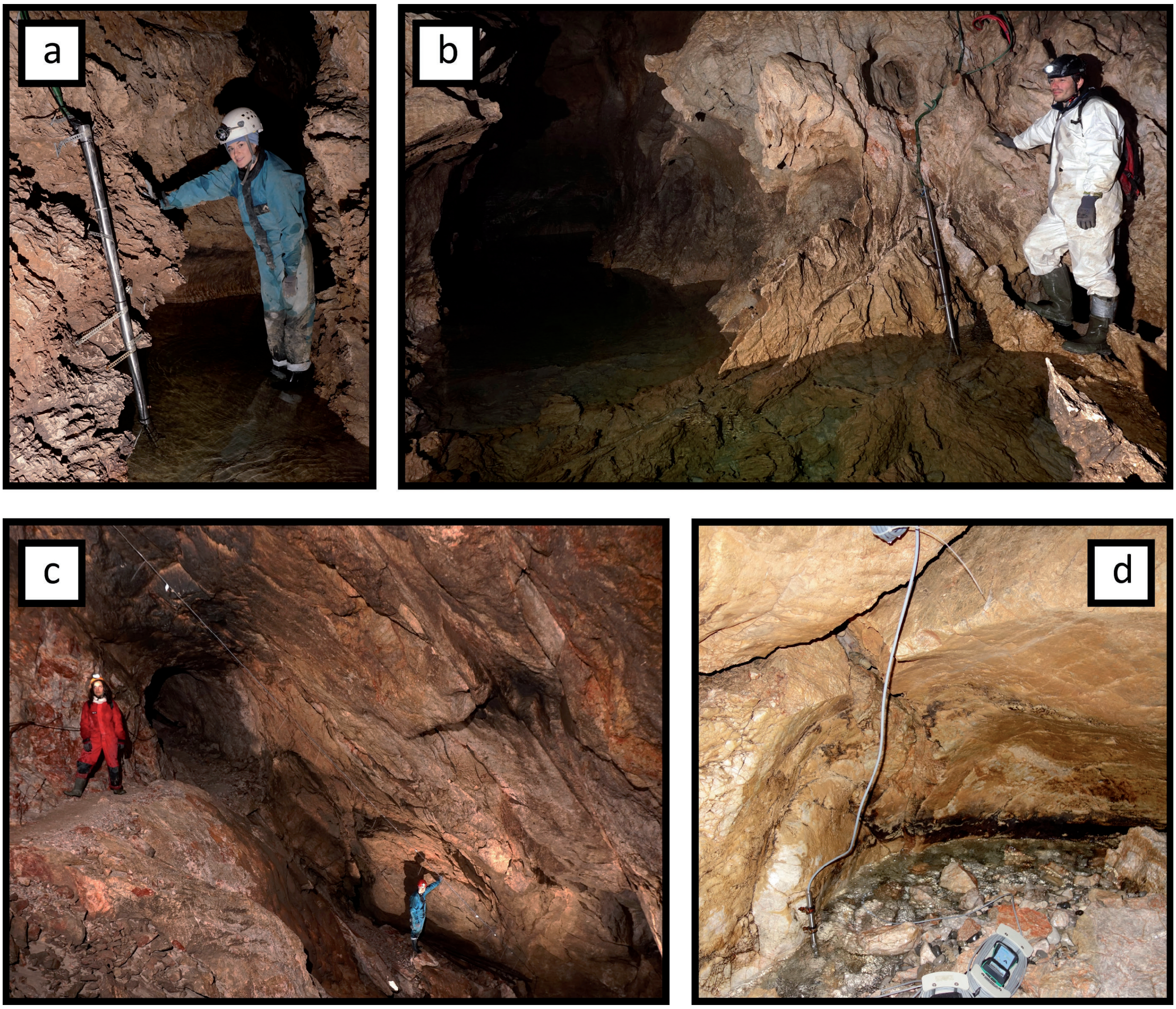

Figure 2: Images of the data loggers in Lamprechtsofen: Kneippklamm (a), Grüntopf (b), Walterhalle (main cave stream) (c) and Stainerhalle (d).

between January (first snowfall) and the end of March the snow of the complete profile was sampled in an air-tight bag, slowly melted, and an aliquot was analyzed. For these three months (January–March) the isotopic altitude gradient for the winter of 2017 was determined by using the corresponding weighted mean isotope value from the valley station (Saalfelden). The weighted isotopic compositions of the months June to September from the rain collector and from Saalfelden were taken in order to calculate the altitude gradient for the summer. The average of the winter and summer gradient was used as the isotopic altitude gradient for the year 2017. The altitude of the catchments of the different cave streams was then calculated following Etcheverry and Vennemann (2009):

$$mean\ altitude\ of\ catchment = \frac{\left(\delta^{18}O_{prec} - \delta^{18}O_{waters}\right)}{IAG} + EP$$

$\delta^{18}O_{prec}$ weighted mean annual value of precipitation at Saalfelden
$\delta^{18}O_{waters}$ mean annual value of sampled waters
IAG isotopic altitude gradient ($\delta^{18}O$) per m of elevation
EP elevation of meteorological station at Saalfelden in meters

3.3 Discharge measurements and calculation of catchment area

Discharge measurements in a cave are challenging, because measurements during flood conditions are commonly too dangerous and most parts of Lamprechtsofen, including Kneippklamm and Grüntopf, are accessible only in the winter months when the water level is low. Therefore discharge of the cave streams was only measured when the cave was not flooded. The salt dilution method was applied to measure the discharge for the Stainerhallen stream and the main cave stream on a monthly basis between August 2016 and August 2017. The discharge of the Kneippklamm stream was calculated using the Manning-Strickler formula (Strickler, 1924) assuming a rectangular stream-bed cross section with a measured width of 1.24 m and a height given by the water level. A friction coefficient of 30 was used to calculate the cross-sectional velocity. For the Grüntopf stream the discharge was assumed to be the difference between the discharge of the main cave stream minus that of the Kneippklamm stream taking into account the time lag of the water level changes of the three streams.

The discharge of the Forscherteil stream and the Hacker spring were measured monthly by the Hydrographic Service of Salzburg using a flowmeter and a wading rod to obtain the cross section of the stream.

Based on the water balance equation precipitation and discharge are related to each other (Richter and Lillich, 1975):

$$Precipitation = D_{surface} + D_{peak} + D_{base} + ET$$

$D_{surface}$ surface water
D_{peak} peak flow (level to which a stream rises after a precipitation event)
D_{base} base flow (flow which is sustained between precipitation events)
ET evapotranspiration

There is no surface runoff in the Leoganger Steinberge and discharge therefore consists of base and peak flow of the underground streams only. The value for evapotranspiration was taken from the literature as a percentage of the measured precipitation at the station Weißbach (666 m a.s.l.). Harlacher et al. (2003) used 12–22 % evapotranspiration for a catchment at 1600–2000 m a.s.l. in the Totes Gebirge, a large karst plateau further east. For the Dachstein massif at 1830 m a.s.l. Gattermayr (1976) calculated an evapotranspiration value of 2 % for bare rock surfaces and 23–35 % for alpine meadows. The tracer tests showed that some catchments are located at high elevations (2330 m a.s.l.) where bare rocks dominate the land surface, while some catchments are lower (1800 m a.s.l.) with more evapotranspiration due to vegetation. We therefore used a range of 2–22 % for the evapotranspiration in the catchments of the cave streams. Because of the absence of surface runoff, precipitation minus evapotranspiration equals groundwater recharge (i.e. effective precipitation) in this karst system. In order to determine the size of the catchments (Grüntopf, Kneippklamm, main cave stream, Forscherteil stream and Hacker spring) the cumulative discharge volume ($D_{cumulative}$) of one hydrological year (February 2016 – February 2017) was divided by the effective precipitation for the same time period, assuming that part of the rainwater replenishes the storage and that during a discharge event part of the water is derived from the storage (Richter and Lillich, 1975):

$$size\ of\ the\ catchment\ area\,[km^2] = \frac{D_{cumulative}}{\sum effective\ precipitation}$$

No calculation was performed for the Stainerhalle, because the observation period was too short (November 2016 – June 2017).

Given the uncertainties of the discharge measurements and the assumptions made, this calculation provides a semiquantitative estimate only.

4. Results

4.1 Physical parameters

4.1.1 Grüntopf and Kneippklamm

The water temperature in both cave streams is largely invariant but generally higher in the Kneippklamm stream. The mean value for the Grüntopf stream is 4.3 °C ± 0.7 and for the Kneippklamm stream 5.5 °C ± 0.3. In contrast, EC varies strongly in both systems, in response to snowmelt and precipitation events. The Grüntopf stream has a mean value of 160 µS/cm ± 43 and the Kneippklamm stream of 186 µS/cm ± 46. In both systems the maxima are due to heavy precipitation, snowmelt or a combination of both.

During a water level rise caused by precipitation the Grüntopf stream reacts with a slight increase in EC of approximately 10–20 µS/cm before the water level reaches its maximum. During the rise of the water level also the water temperature increases by 0.1–0.2 °C, followed by a drop in EC (Fig. 3a). The Kneippklamm stream reacts differently: water temperature and EC show a minimum prior to the maximum of the water level (Fig. 4a). Snowmelt causes diurnal fluctuations of the water level and results in a strong drop of the EC. Depending on the thickness of the snowpack these fluctuations dominate the stream behavior between May and June and in some years even until August. This regime affects the Grüntopf stream longer than the Kneippklamm stream. The former shows symmetrical water level changes with a daily maximum at 17:00–18:15 (Fig. 3b), whereas the Kneippklamm stream reacts with a fast increase in water level reaching the maximum between 12:00 and 14:00, followed by a slow decrease (Fig. 4b).

4.1.2 Kneippklamm lifter system

Since 31 July 2014 the data logger in the Kneippklamm stream recorded regular, asymmetrical fluctuations of the water level, the EC, and the water temperature with a higher frequency than the daily fluctuations caused by snowmelt (Fig. 5). On 31 July 2014 the water level reached its maximum for the entire observation period (2007–2017) (Höfer-Öllinger et al., 2016). To verify that these

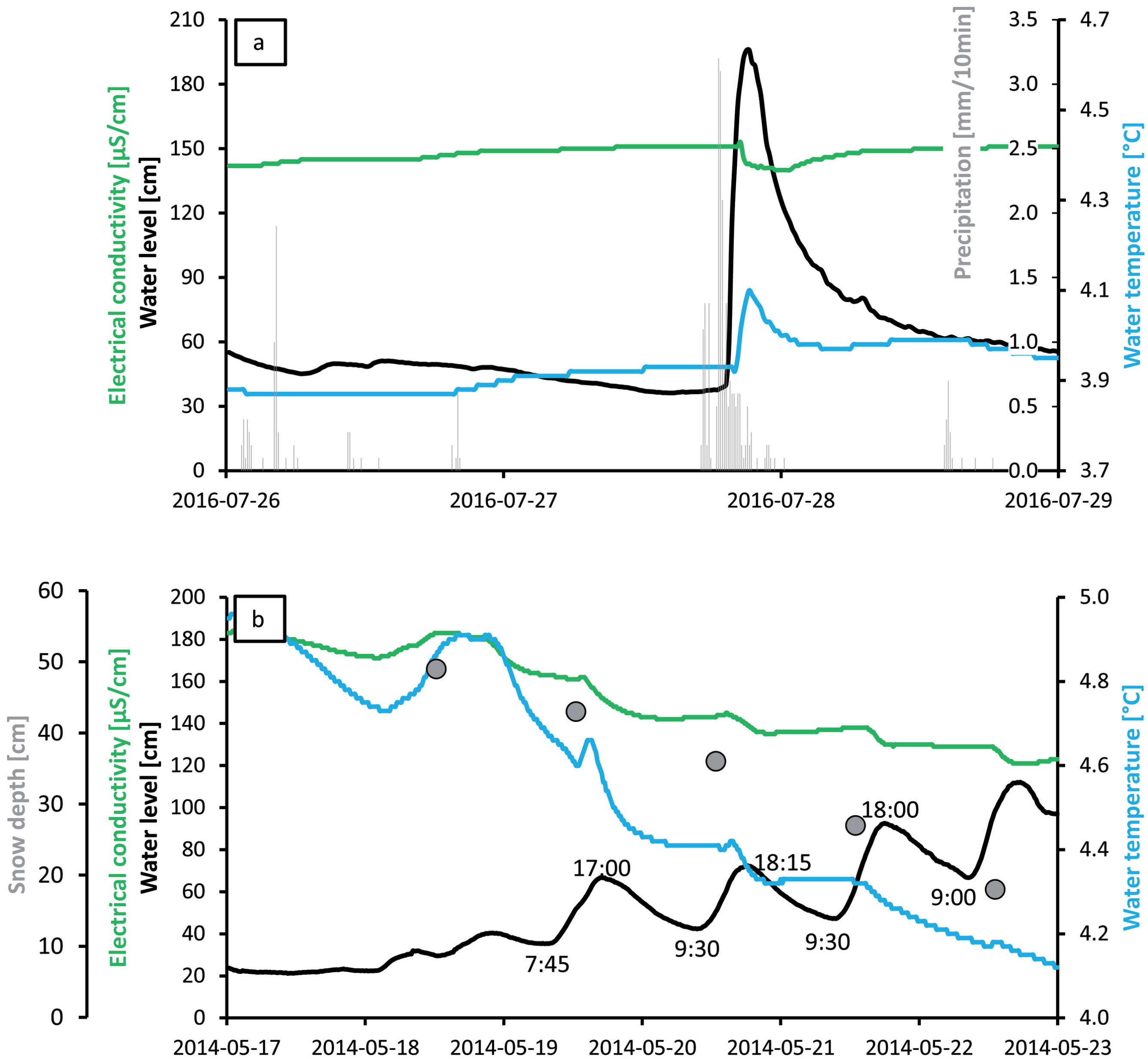

Figure 3: Examples of the response of the Grüntopf stream to a major precipitation event (a) and snowmelt (b). Grey dots represent the mean snow depth (cm) for one day.

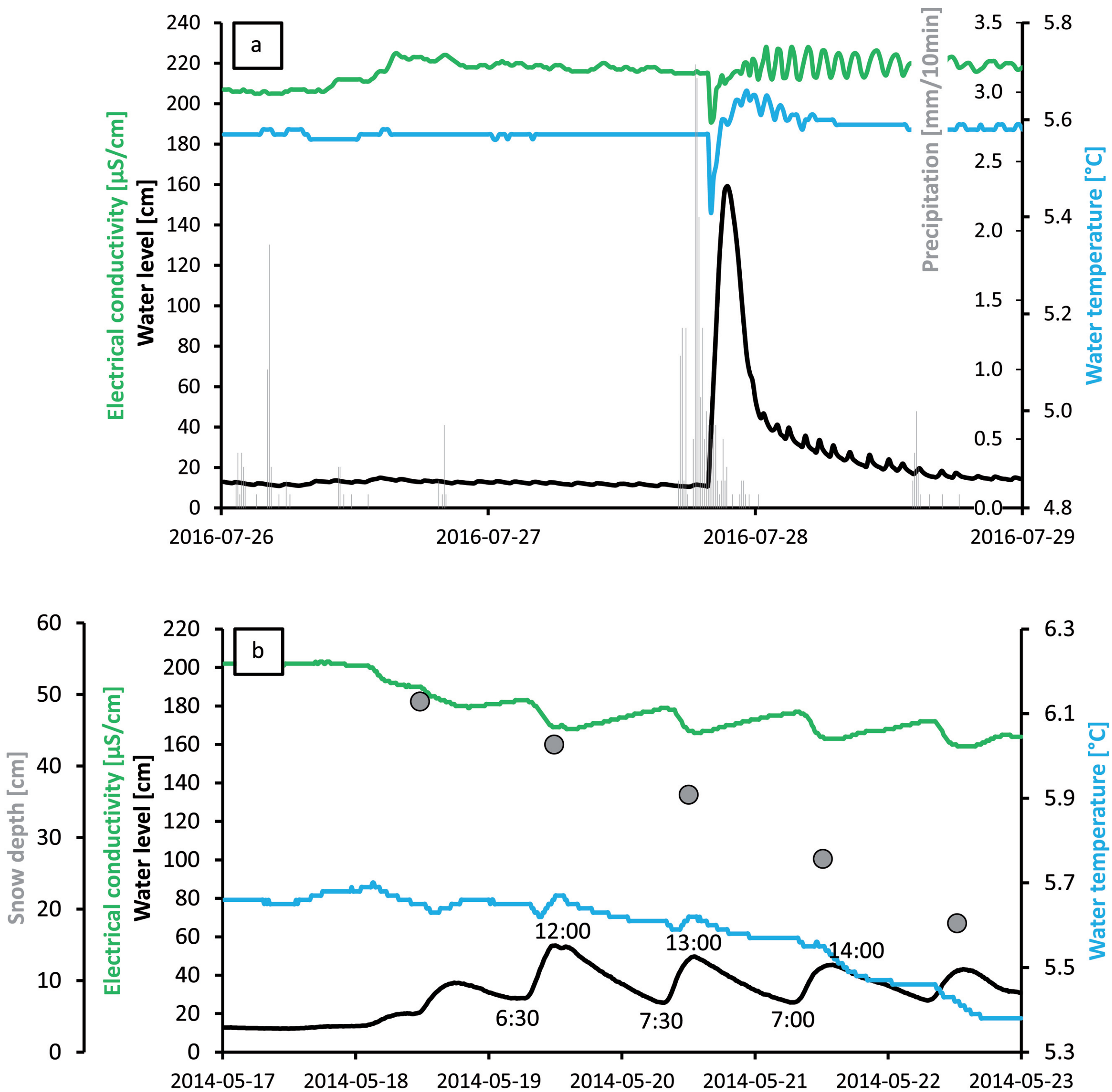

Figure 4: Examples of the behavior of the Kneippklamm stream to a major precipitation event (a) and snowmelt (b). Grey dots represent the mean snow depth (cm) for one day.

fluctuations reflect a hydrological phenomenon rather than instrumental misbehavior, a second data logger was installed in 2016. Both data loggers show the same asymmetrical changes of the three parameters. The amplitudes of the fluctuations in the water level are up to 5 cm and the increase lasts 15 min, while the decrease takes up to 1 hour.

4.1.3 Comparison of the four streams at Lamprechtsofen

Evaluating the data recorded by the different loggers permits to trace individual flood events across the northern part of the cave system. As an example the flood event from 29 August 2016 was taken (Fig. 6). The first precipitation signal was recorded at the meteorological station Vorderhorn at 13:20. About 5 hours later the maximum of the flood was recorded at the Forscherteil stream, i.e. leaving the karst system. This illustrates the high transmissivity of this karst aquifer. The underground streams react within less than 4 hours to a rainfall in the catchment. Floods typically arrive at the Kneippklamm stream first and 1 hour later at the Grüntopf. 1 hour after the water level reached its maximum at the Grüntopf the flood arrives at Walterhalle, i.e. close to the lower cave entrance.

4.2 Isotope data

All karst water samples plot on the Global Meteoric Water Line and show little seasonal changes. Because the purpose of the isotope analysis was to determine the altitude of the catchment only the mean $\delta^{18}O$ values are discussed here. The mean $\delta^{18}O$ value of the

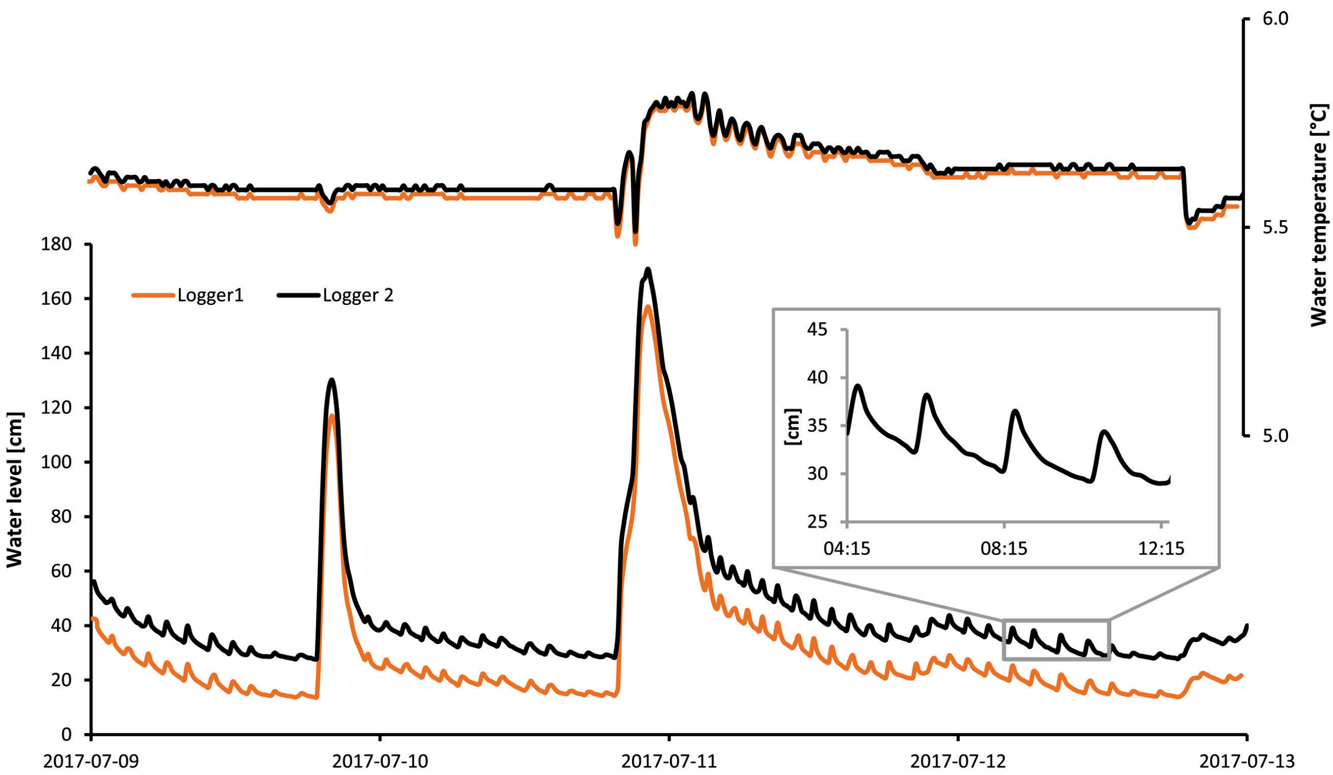

Figure 5: Small-scale oscillations of the water level (enlarged in the inset) and the water temperature in the Kneippklamm stream recorded by two instruments.

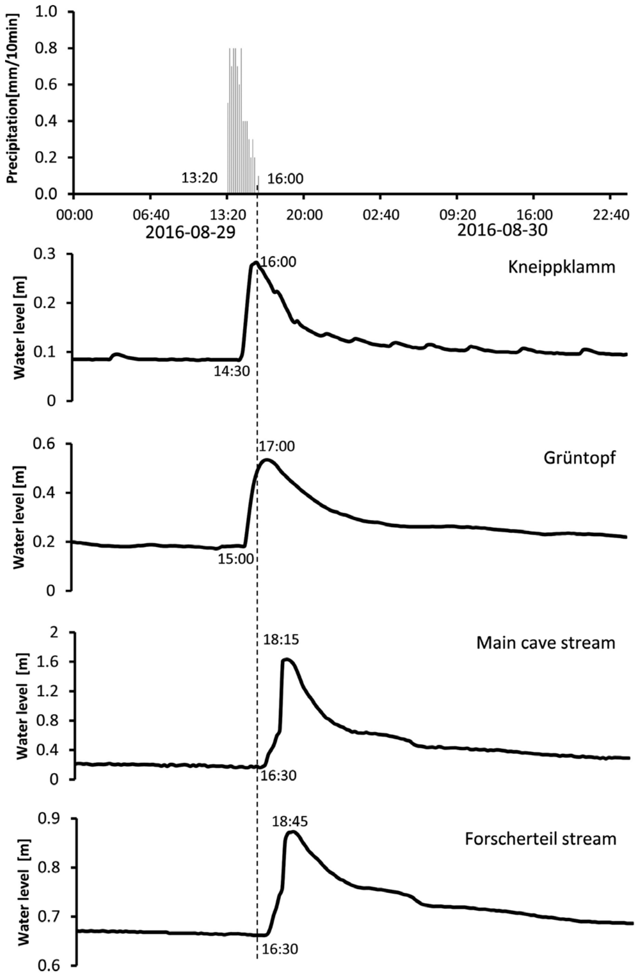

Figure 6: Time series of a flood wave moving from the Kneippklamm and Grüntopf to the Forscherteil stream.

snow profile (January–March) is -14.66 ‰ and the mean weighted value of water collected by the rain gauge (July-September) is -10.56 ‰. The weighted isotopic summer value of the station Saalfelden is -6.81 ‰ and -13.72 ‰ for the months January–March. The resulting mean annual $\delta^{18}O$ altitude gradient is 0.19 ‰/100m. This value is only slightly higher than the gradient of 0.14 ‰/100m obtained by Reischer et al. (2015) for the Untersberg massif northeast of the Leoganger Steinberge. Using Saalfelden as a reference point (748 m a.s.l.) the mean elevations of the different catchments were determined (Fig. 7). The Grüntopf stream shows the highest catchment, which is in agreement with its daily fluctuations of the water level until August caused by long-lasting snowmelt and the low EC values. The Stainerhallen stream has the lowest catchment (1400 m a.s.l.). The catchments of the other two streams are at intermediate elevations (1770–1920 m a.s.l. – Table 1).

4.3 Discharge and catchment area

In 2016 the Forscherteil stream had a maximum discharge of 2500 l/s and fell dry during the winter months. The calculated size of the catchment is between 7.8 and 9.8 km^2. The highest discharge in the Walterhalle at a water level of 11 m was 2000 l/s, the minimum around 40 l/s and the catchment comprises 8.4–10.6 km^2. Even though the water level maxima of the main cave river were not recorded, this stream has a higher discharge than the Forscherteil stream. The higher the discharge the larger the difference of both streams, i.e., overflow pathways are activated. Because the Forscherteil stream fell dry during low water in contrast to the main cave stream, probably not all the water leaves the karst system via the Forscherteil stream. This could be an indication that some water infiltrates directly into the porous aquifer of the valley fill. Calculations for the catchment size and height of the two measurement sites (Walterhalle and Forscherteil) yielded slightly contrasting results.

The maximum discharge in the Kneippklamm stream is around 1200 l/s and the minimum around 20 l/s. The peak discharge of the Grüntopf stream is not known, but the minimum is around 20 l/s. The catchment of the Grüntopf stream is approximately six times larger than the Kneippklamm stream, so the former dominates the main cave stream (Table 1).

5. Discussion

5.1 Physical parameters

In a water-active cave both the water temperature and the air circulation control the temperature distribution of the vadose homothermic zone which underlies the near-surface heterothermic zone affected by seasonal temperature changes. Temperature gradients between the main phreatic conduits and the top of the phreatic zone are very small and below the main phreatic system the temperature gradient is close to the regional geothermal gradient (Luetscher and Jeannin, 2004).

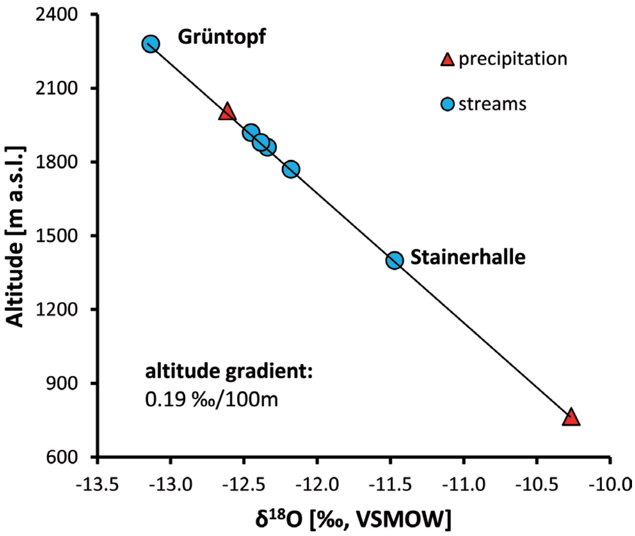

Figure 7: Mean $\delta^{18}O$ values of cave streams and selected springs and the weighted $\delta^{18}O$ value of precipitation plotted against the mean altitude of the catchment.

Our observations at the Kneippklamm stream are consistent with this concept showing a drop in EC and water temperature prior to the water level maximum. During a rain event comparably warm water with low EC enters the karst and flows preferentially along subvertical high-capacity pathways in the vadose zone and thereby cools (Fig. 8). The cooling occurs because the water flows through conduits with free surfaces, where heat exchange takes place via radiation through the air (Luhmann et al., 2015). This water reaches the Kneippklamm stream within approximately 1 hour and causes a drop in EC and water temperature. Host rock dissolution (and hence the increase in EC) is slower than heat exchange (Luhmann et al., 2015). Therefore the arrival of the event water at the hydrograph is reflected by a drop in EC. Meanwhile rainwater has also reached the phreatic zone higher up in the cave. The hydraulic response of this rise in the karst water level arrives at Kneippklamm with some delay compared to EC and water temperature. This dual flow pattern also explains the asymmetrical changes of the water level during snowmelt: the fast event water flows directly through vadose pathways to the measurement site, whereas the hydraulic (phreatic) response is delayed. Cave exploration and tracer tests have shown that the Kneippklamm stream is recharged autogenically in Ebersbergkar and during high flow the water preferentially uses large conduits. Consequently, drops in temperature and EC at the Kneippklamm stream are caused by high flow velocities during high flow conditions via large conduits with free surfaces in the vadose zone (Covington et al., 2012).

The Grüntopf stream, although not far from the Kneippklamm, shows a different behavior, because it only reacts to changes of the karst water table. At the Grüntopf stream the water level therefore reaches its maximum mostly 1 hour after the Kneippklamm stream. During snowmelt this delay reaches up to 6 hours.

The slight increase of EC in the Grüntopf stream before the water level maximum can be explained by the piston flow-model, i.e., a rainwater pulse causes deeper water with a longer mean residence time and a slightly higher EC to be hydraulically pushed out of the karst conduits

		$\delta^{18}O_{prec}$ = -10.27 ‰ [VSMOW]		Catchment area [km²]	
	Altitude of measurement point [m a.s.l.]	$\delta^{18}O_{water}$ [‰, VSMOW]	Mean elevation [m a.s.l.]	2% Evapotranspiration	22% Evapotranspiration
Forscherteil	660	-12.5	1920	7.8	9.8
Eis spring	665	-12.2	1770		
Hacker spring	665	-12.3	1860	2.9	3.7
Stainerhalle	675	-11.5	1400		
Walterhalle	665	-12.5	1920	8.4	10.6
Grüntopf	886	-13.1	2280	7.2	9.1
Kneippklamm	875	-12.4	1880	1.2	1.6

Table 1: Mean catchment elevation and size of the different cave streams and selected springs (with the altitude of the measurement points). The catchment size was calculated assuming two different values for evapotranspiration.

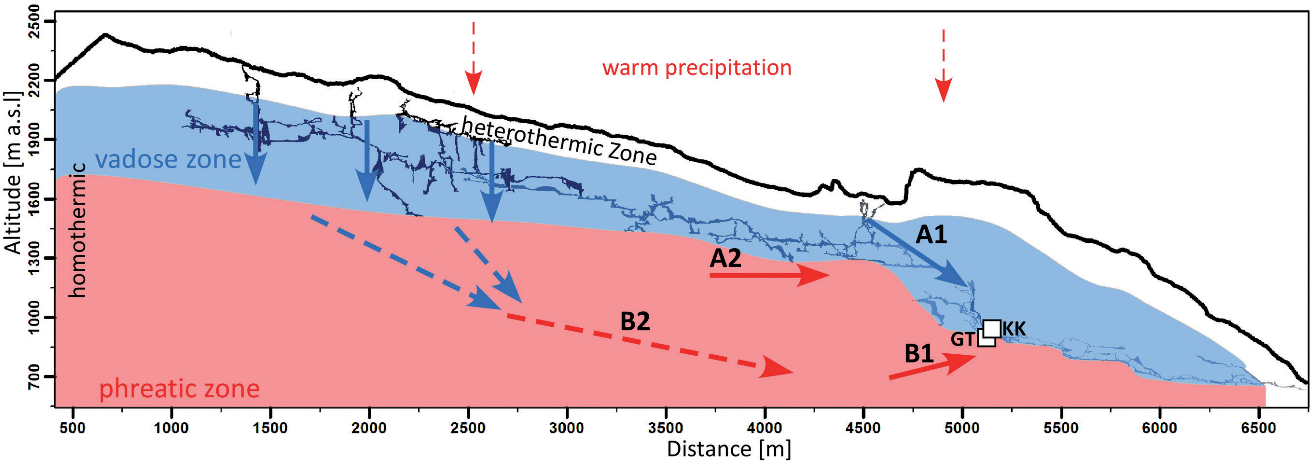

Figure 8: Hydrological model of the Lamprechtsofen illustrating flow routes to the monitoring sites at Kneippklamm (KK) and Grüntopf (GT) during summer. A1 and A2 represent the behavior of the Kneippklamm stream. First event water with a low EC which cooled off in the vadose zone (A1) and then slightly warmer water from the phreatic zone arrives (A2). At the Grüntopf measurement site first "older" and slightly more mineralized water from the deeper parts of the aquifer arrive (B1) and then rain water mixed with the phreatic water causes a water level maximum (B2).

(Drew and Goldscheider, 2007 - Fig. 8). This "older" water arrives at the measurement site prior to the maximum in water level. Interestingly, the slight increase in EC is only observed when the water level at Grüntopf is higher than 120 cm, i.e., the piston flow requires a certain threshold to become active. Another potential explanation for the increase in EC in karst systems is based on the epikarst concept. According to Ford and Williams (2007) the increase in EC during a rain event can be caused by water displaced rapidly from the epikarst and is therefore caused by fast event water. The catchment of the Grüntopf stream mostly comprises bare rock with little vegetation and soil cover and the epikarst is poorly developed. The recharge at the Leoganger Steinberge occurs preferentially via dolines and not by diffuse recharge. In addition, the increase in EC at the Grüntopf stream occurs only when a certain threshold discharge is exceeded. Therefore the increase in EC does not represent water from the epikarst, but rather older water which is hydraulically pushed out of the karst conduits (piston flow-model).

The lower water temperature in the Grüntopf system compared to the Kneippklamm stream can be ascribed to a higher flow rate of the Grüntopf stream and/or a higher catchment. Cool water infiltrates at high altitudes into the karst system, thereby reducing the local thermal gradient. Due to high flow rates the water does not reach thermal equilibrium with the surrounding rock (Covington et al., 2012). The low EC in the Grüntopf stream reflects the dependence of the dissolution capacity of water on the CO_2 partial pressure. The degree of carbonate dissolution is a function of the amount of dissolved CO_2 in the infiltrating water. Rainwater can dissolve more CO_2 in the soil than on bare rocks, due to higher pCO_2 in the soil. Consequently if rainwater infiltrates into the karst system through a soil cover, the dissolution capacity of water increases dramatically (Wisotzky, 2011). The catchment of the Grüntopf stream comprises bare rock with little soil and vegetation, whereas the catchment of the Kneippklamm stream is at lower altitude and consists of soil-covered rock with little vegetation. Consequently, the higher EC of the Kneippklamm stream does not reflect the characteristics of the aquifer rock, but the presence of a soil cover in the catchment, which is related to the altitude of the catchment.

The small-scale oscillations in the physical parameters of the Kneippklamm stream showing a frequency of a few hours could be explained by a lifter system (Höfer-Öllinger et al., 2016). This phenomenon was described by Bögli (1978) and is based on two karst cavities connected by an elbow pipe. When the water level in the upper cavity reaches a certain level the connecting pipe gets filled and the entire water volume is then pulled out of the first cavity. This process repeats itself regularly as long as the water flow into the first cavity is constant. This lifter system has been observed since the water level reached its maximum for the entire observation period on 31 July 2014. This could be an indication that during this high flood the geometry of the conduits changed thereby activating the lifter system.

5.2 Comparison of catchment analyses and tracer tests

Völkl (1974) proposed that the water infiltrating in the Dürrkar and Hochgrub flows to the Birnbachloch spring in the south. Our study suggests that the catchments of the Grüntopf stream and main cave stream are located in the Ebersbergkar and also extend to the cirques in the east. This assumption is based on the calculated catchment size and the mean altitude of the catchment. For example, the catchment of the Grüntopf stream (7.2 km^2, mean altitude of ca. 2200 m a.s.l.) extends to the cirques in the east to match the local topography. The calculated elevation of the catchments (around 1800 m a.s.l.) of the Hacker and Eis springs is in agreement with the tracer tests and provides an independent check for the isotope analysis. In 1971 the tracer reappeared 18 hours later at the Forscherteil stream. The data loggers show the water flow following a precipitation event can even be faster. Generally speaking, the tracer tests reflect the hydrological regime of a certain water level only. Alpine karst aquifers, however, are highly dynamic systems. During high water supply the water level rises, new flow paths are activated and the watershed may move laterally.

6. Conclusions

Based on hydrographs, monitoring the different cave streams, the systematics of the Lamprechtsofen karst system were analyzed. The origin of the main cave stream, whose water level highstand causes partial flooding of the show cave, was the first time verified based on the hydrographs at the Grüntopf and Kneippklamm streams and the isotope data. The Grüntopf stream has a higher catchment than the Kneippklamm stream and reacts, based on the piston flow-effect, slower to precipitation events and snowmelt. The high altitude of the catchment of the Grüntopf stream is not only confirmed by the isotope data, but is also reflected by the low EC and water level rises until August caused by snowmelt. The lower mineralization of the Grüntopf stream reflects the higher catchment elevation.

Grüntopf and Kneippklamm stream merge to form the main cave stream. Because the Grüntopf stream has a higher discharge than the Kneippklamm stream, most of the water of the main cave stream origins from the Grüntopf system. The calculated higher discharge rate of the Grüntopf stream is also reflected by higher flow rates and the lower water temperatures compared to the Kneippklamm stream. The assessment of the catchment size suggests that the catchment of Grüntopf and therefore also of the main cave stream is higher and larger than shown by the tracer tests, which is relevant for understanding floods in the show cave and in the valley bottom (Höfer-Öllinger et al., 2016).

The Kneippklamm stream shows evidence of a lifter system, first recorded during a flood event. Until now it is unclear where the lifter system is located.

The Lamprechtsofen drains a strongly karstified alpine catchment and reacts fast to precipitation events (ca. 5 hours) and snowmelt, which can last until August. The continuous monitoring of this study provides for the first time insights both into the long-term behavior of this major karst system as well as into its high-frequency dynamics.

Acknowledgements

Gerhard Völkl provided unpublished information. Karoline Glitzner (Höhlenforscherclub Salzburg) and the Landesverein für Höhlenkunde in Salzburg allowed and enabled us access to the cave. Michal Ciszewski (KKTJ-Krakowski Klub Taternictwa Jaskiniowego) is thanked for the discussion and for providing cross sections of the cave. The first author would also like to thank the team of the Passauer hut, Hubert Hirschpichler, Albert Haitzmann and the Bavarian Forest Administration. The authors are grateful to an anonymous referee and Lukas Plan who provided constructive criticism to an earlier version of the manuscript.

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Received: 24 11 2018
Accepted: 07 05 2019

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