Is hydrotectonics influencing the thermal spring in Eisensteinhöhle (Bad Fischau, Lower Austria)?

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Abstract

Eisensteinhöhle is a 2 km long crevice cave that is significantly overprinted by hydrothermal karst processes. It was opened during quarrying in the Fischauer Vorberge, at the western margin of the Vienna Basin. This pull-apart basin cuts the eastern foothills of the Alps and is formed by a major NE-SW striking, sinistral transform fault. The western margin consists of NNE-SSW striking normal faults creating paths for thermal water to rise from the central basin. The deepest part of the cave, 73 m below the entrance, hosts a pond with 14.6 ±0.2 °C warm water that occasionally acts as a spring. The water level and temperature fluctuate and at a certain level, water visibly discharges into a nearby narrow fissure. As sporadic observations of the water level since 1992 gave no obvious connection to precipitation events, the connection to an aquifer and the origin of the water remained unknown. A pumping test, conducted on 13/7/2016, yielded a volume of the spring/pool of about 2.8 m³ that is fed by a very small inlet at the sandy bottom. At the time of the pumping test, the discharge was only 4.5 l/h but during previous overflow events, discharge values of up to 289 l/h were recorded.

Water temperature and hydrochemistry hint towards a mixture of an old thermal component and a young meteoric component. During continuous monitoring of water level and temperature from October 2015 until November 2018, the water level was almost stable with few periods of high level (almost at overflow) that lasted for about 3 to 4 weeks each. The water temperature increased during most high stands and is positively correlated with the water level. Correlation of the high-resolution data on water level and temperature fluctuations with precipitation measurements at the nearest meteorological stations show a relation of water level to certain rainfall events and the sporadically taken long time records show a correlation with annual precipitation sums. Long-term observations also indicate a connection to groundwater levels in the Vienna Basin with a delay of about 8 weeks in Bad Fischau. In July 2017, the water level dropped suddenly and then recovered simultaneously in the time of several weak earthquakes in the vicinity. The data suggest that the spring in Eisensteinhöhle is influenced by precipitation. For one seismic event, there is a correlation with unusual water level changes at Eisensteinhöhle, but the rareness of earthquakes demands for a longer time series to confirm this observation.

Die Eisensteinhöhle ist eine etwa 2 km lange Spalthöhle, deren Morphologie von hydrothermalen Karstprozessen überprägt wurde. Sie wurde 1855 während Steinbrucharbeiten in den Fischauer Vorbergen am Westrand des Wiener Beckens angefahren. Im tiefsten Abschnitt der Höhle, 73 m unter dem Eingangsniveau, liegt ein fast immer wassergefüllter Quellsiphon mit auffällig schwankendem Wasserstand, der ab einem bestimmten Niveau in den nebenliegenden Raum abläuft. Insbesondere die Quelle weckte aufgrund der schwankenden Schüttungsrate und der mit 14,6±0,2 °C, im Vergleich zu normalem Grundwasser, signifikant erhöhten Temperatur immer wieder Interesse.

Bei einem Pumpversuch am 13.7.2016 konnte die Form des wassergefüllten Hohlraumes vermessen und dessen Volumen bestimmt werden. Während des Pumpversuchs konnte eine Schüttung eines eintretenden Gerinnes von lediglich 4,5 l/h gemessen werden; Frühere Messungen am Überlauf ergaben Werte bis zu 289 l/h.

Weil kein offensichtlicher Zusammenhang zwischen Pegelschwankungen und Niederschlägen bestand, wurden seit 1992 sporadische Messungen vorgenommen. Diese Messreihe wurde ergänzt durch Pegel- und Temperaturmessungen, die von Oktober 2015 bis November 2018 mit einem automatischen Datenlogger durchgeführt wurden.

In diesen 3 Jahren lag der Wasserstand relativ konstant bei 307,0 m ü.A. mit Ausnahme einiger Perioden in denen der Pegel fast den Überlauf erreichte. Diese Phasen dauerten je 3-4 Wochen an. Die Wassertemperatur stieg parallel dazu mit einer Verzögerung bis zu 15 Tagen. Die Korrelation der hochaufgelösten Pegel- mit Niederschlagsmessungen der umliegenden Messstationen zeigt einen Zusammenhang zwischen der Schüttung und Starkniederschlagsereignissen, die Langzeitbeobachtungen korrelieren jedoch mit der jährlichen Niederschlagssumme. Durch die

Langzeitbeobachtungen konnte auch eine klare Verbindung der Quelle mit dem Grundwasser im Wiener Becken nachgewiesen werden, wo an einem Pegel in Bad Fischau Schwankungen mit einer Verzögerung von 8 Wochen aufgezeichnet werden.

Ein Hinweis auf eine Beeinflussung der Quellschüttung durch tektonische Prozesse konnte im Juli und August 2017 gewonnen werden, als ein plötzliches Absinken des Pegels in der Eisensteinhöhle, gefolgt von einem Anstieg auf das vorherige Niveau zeitgleich mit mehreren schwachen Erdbeben in der Nähe, gemessen wurde.

Die gesammelten Daten legen nahe, dass die Quelle in der Eisensteinhöhle sowohl durch Thermalwässer als auch durch Niederschlag beeinflusst wird. Ein Erdbeben korreliert mit ungewöhnlichen Wasserspiegelschwankungen in der Eisensteinhöhle, aber aufgrund der geringen Anzahl an seismischen Ereignissen bedarf es einer längeren Zeitreihe um diesen Zusammenhang zu bestätigen.

1. Introduction

To the south of Vienna, a zone of numerous faults forms the margin of the Vienna Basin (VB). This fault system accounts for the steep drop of the Alpine units towards the centre of the basin and thermal water uses it as a pathway through layers of impermeable sediments and sedimentary rocks (Wessely, 1983). On the surface, this groundwater discharges at several lukewarm springs.

The southernmost thermally influenced spring at the western margin of the VB is a spring with fluctuating discharge in the deepest part of the 2 km-long show cave Eisensteinhöhle (EISE). EISE is a crevice cave with, in some parts, significant overprint by hypogene karst processes.

The spring fills a pond that rarely overflows into a neighbouring gallery through a fissure. This particular discharge behaviour initiated sporadic observations from 1968 on (Winkler, 1992). A stick gauge was installed in 1992 and since then the measurements have been taken during every visit to the cave by the cave guide Gerhard Winkler.

Recently, evidence of active tectonics was found while measuring the fault displacement inside EISE and Emmerberghöhle (a 135 m-long cave, 3.5 km SW of EISE) using a 3D moiré extensometer (Baroň et al., 2016). In November and December 2013, displacement was recorded in both caves prior to a magnitude 3 earthquake in Bad Fischau. The total cumulative displacement vector at the fault in EISE amounted to 0.051 mm between November 2013 and September 2016 and comprised of five particular displacement events during that time. The eastern (hanging) block moved approximately by 0.026 mm/year along a vector 106/61° in accordance with the regional active-tectonic pattern and the observed crevice character of the cave indicating eastward opening and subsidence towards the VB (Baroň et al., 2019).

Within more than 30 years of sporadic observations no clear link between the water level (including the rare overflows) at EISE and precipitation at nearby meteorological stations could be established. These latest findings raise the question if the discharge behaviour could be influenced by tectonics. Active tectonics and earthquakes have an influence on the environment in many ways including effects on groundwater that range from liquefaction and mud volcanoes to changes in groundwater levels, temperature and composition (e.g. Wang and Manga, 2010; Cox et al., 2015).

The aim of this study was to examine the processes influencing the thermally influenced spring in EISE and to shed light on the question if tectonic activity plays a role. This was done by statistical analysis and evaluation of sporadic long-term observations, combined with data on water level and temperature sampled every 15 minutes from 7/10/2015 to 13/11/2018. A pumping test was performed to characterise the connection of the spring to an aquifer. Hydrological and meteorological data as well as the Austrian Earthquake Catalogue were also analysed.

1.1 The thermally influenced spring in Eisensteinhöhle (EISE)

The thermal springs in the VB have been used as spas by the Romans already 2000 years ago (Zötl, 1997). The spa around the lukewarm springs (ca. 19 °C) in Bad Fischau was built in 1872 and in Brunn an der Schneebergbahn an ephemeral pond, filled by two lukewarm springs (up to 23 °C), is used as a bath.

EISE attracted the interest of researchers since its opening in 1855 and from its deepest parts the Austrian poet F.J. Leitner described a water flow causing *a mumbling, ripple and swoosh* in 1909 (Winkler, 1992). The thermally influenced spring that caused these sounds was then found in 1919 when a new gallery was opened by blasting (Winkler, 1992).

Most of the time, this spring forms a pool with irregularly fluctuating water level that discharges through a crack into the neighbouring gallery only during high water. Due to its peculiar discharge behaviour, it has attracted attention ever since its discovery. It has been described as a *perennial trickle* (German: *perennierender Riesel;* Mühlhofer, 1923) and a *thermal spring of very poor quality and quantity* (Hock, 1948). Pirker (1950) described it as a *small spring with strongly fluctuating discharge*, but neither the hydrothermal origin nor the reason for the discharge fluctuations were explained.

Winkler (1992) described erratic water level fluctuations and rare overflows until the spring ran dry in 1971. Excavations of mud at the bottom of the spring reached the water table 1.8 m below its initial level before it dropped even further. In 1979, the spring became active again and a new, on average lower water level was established. Nevertheless, the peculiar water level fluctuations continued and occasionally during high discharge when the

water level reached the overflow, a discharge of up to 240 l/h was measured (Winkler, 1992).

1.2 Hydrotectonics, earthquake-induced hydrological phenomena and hydrodynamic earthquake precursors

Earthquakes cause a variety of effects. The best known are ground shaking and related damage to buildings (e.g. Grünthal et al., 1998). Less familiar are effects on the environment, which are listed in the Environmental Seismic Intensity Scale (Michetti et al., 2007). Besides rock fall, tsunami waves and surface ruptures, also effects on groundwater and surface waters are known. Water level changes, variations in spring discharge or pore pressure in aquifers and changes of chemical and physical properties such as the amount of dissolved solids, temperature and turbidity are summarised by the term *earthquake-induced hydrological phenomena* (Muir-Wood and King, 1993; Rojstaczer et al., 1995; Roeloffs, 1996; Wang and Manga, 2010; Cox et al., 2015).

These phenomena can appear in many ways and can be observed up to several 100 (sometimes 1000) km from the earthquake's epicentre. They play an important role in estimating the intensity of earthquakes (Michetti et al., 2007) and can provide an insight into local tectonics and earthquake generating processes (Roeloffs, 1988).

Variations in spring discharge and the emergence of new springs seem to be related to groundwater that was stored in the aquifer and released due to enhanced permeability caused by the earthquake (Wang and Manga, 2015). Changes in ground water levels can appear as step-like, co-seismic changes in the near-field of the ruptured fault (at distance of about the rupture length of the earthquake-causing fault), as more gradual changes lasting several days or weeks in the intermediate field, or as water level oscillations in the far-field (distances of many ruptured fault lengths; Wang and Manga, 2010). Several different mechanisms underlying variations of groundwater levels have been proposed: One mechanism in the near-field is the enhancement of permeability mentioned above. This is caused by mobilisation of colloidal particles in porous aquifer, by unblocking fractures through shaking of the seismic waves, or by opening of fractures due to co-seismic static strain (Rojstaczer et al., 1995).

Another mechanism changing groundwater levels is the shaking-induced consolidation of young sediments (e.g. alluvial fans or basin sediments), whereby a volumetric decrease leads to an increase of pore pressure and therefore to a rising water level (Wang et al., 2001).

On the other hand, the earthquake-induced static strain can change aquifer properties depending on the location to the epicentre. In regions of compressive strain, water levels tend to increase during earthquakes while they decrease in dilatational settings (Lai et al., 2016). According to Larsson (1972), who studied the influence of the tectonic regime on fractured aquifers in granites of the Baltic Shield, shear faults show low permeability, while tension faults are open and have a high permeability.

In the far-field, water level oscillations in wells coincide with the ground motion generated by earthquakes (Brodsky, 2003). Depending on well properties and aquifer characteristics, these oscillations can be used as hydroseismograms (Cooper et al., 1965; Wang and Manga 2010).

All earthquake-induced changes in spring discharge and groundwater levels are related to the seismic energy density, which is a function of earthquake magnitude and distance of the observed site to the epicentre (Montgomery and Manga, 2003). A certain threshold of energy must be reached to induce hydrological effects, which in turn means that the hydrological effects can occur only within a certain distance.

Coseismic temperature changes in thermal springs are related to the increase of permeability of fractures (Mogi et al., 1989) enhancing water flow from the heat source to the spring, while temperature changes in wells may often be caused by the turbulent mixing of stratified water (Shi et al., 2007).

Hydrologic phenomena can also occur before earthquakes (i.e. precursor phenomena). As a reaction of aquifers to crustal strain, they are potential tools for earthquake prediction. However, their variability and the difficulty to distinguish them from other factors (e.g. precipitation, snowmelt or barometric influences) limit their application (Roeloffs, 1988; Wyss and Jackson, 1997).

2. Study site

2.1 Geographic setting

The study area is located at the transition of the Northern Calcareous Alps to the southern VB (Figure 1). To the west, it is marked by the Hohe Wand, a rugged, mountainous karst plateau with elevations up to 1134 m a.s.l. A steep cliff terminates the plateau towards the Neue Welt Basin (NWB) in the southeast. To the east, the NWB is confined by the Fischauer Vorberge, a ridge with elevations of up to 605 m a.s.l. marking the western margin of the southern VB and separating it from the NWB.

The climate in the study area is rather dry with annual precipitation between 599 mm at Wiener Neustadt (270 m a.s.l.) and 897 mm Puchberg am Schneeberg (580 m) and a mean temperature of 9.4 and 7.5 °C, respectively (ZAMG, 2019). Even though the precipitation maxima occur during summer, the main period of groundwater recharge is during the winter months given the lower evapotranspiration (Fenzl, 1977).

2.2 Geological setting

2.2.1 Regional stratigraphy

Several lithological units of Triassic to Neogene age as well as Quaternary sediments are present in the study area (Figure 2). The oldest rocks are Hallstätter Kalk, Wandriffkalk as well as Wettersteinkalk and –dolomit (Plöchinger, 1967). These Triassic carbonate rocks form
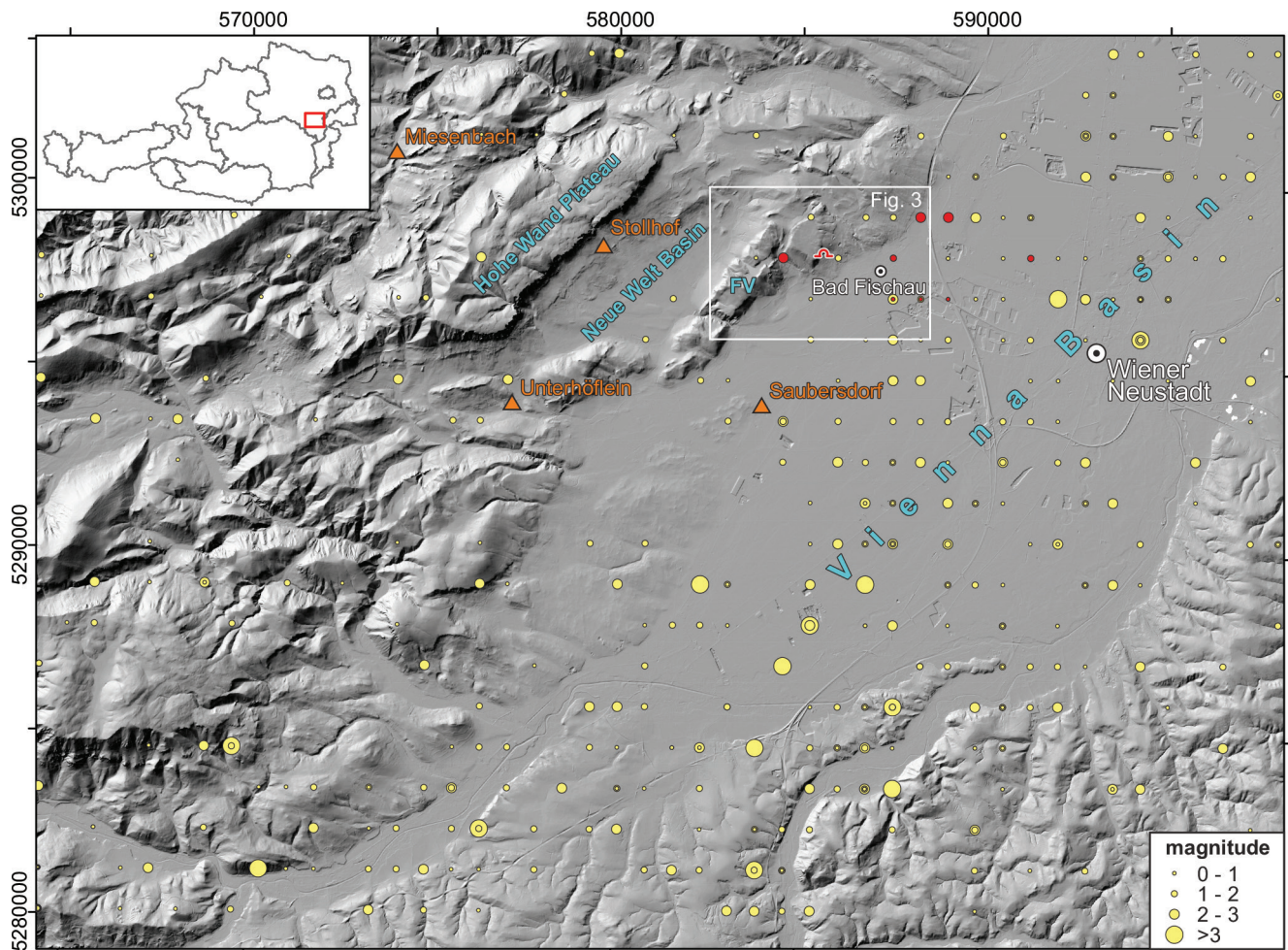
Figure 1: Hillshade of the southern Vienna Basin with the location of EISE (red omega), meteorological stations (orange triangles), and the location of Figure 3. Yellow circles are earthquakes between 1992 and 2018 (AEC, 2019); red circles mark the earthquakes near EISE between July and August 2017 (seismic data: courtesy of ZAMG). FV: Fischauer Vorberge; Coordinates: UTM 33N.

the Hohe Wand Plateau and the ridge of the Fischauer Vorberge as well as the basement of the VB and the NWB.

The limestones are karstified and several caves, dolines and karren occur on Hohe Wand and Fischauer Vorberge. In the latter, the morphology of many caves indicates a hydrothermal origin (Spötl et al., 2017).

Sedimentary rocks of the Cretaceous Gosau Group overlie these Triassic carbonates with a transgressive contact and constitute the fill of the NWB and of a graben-like structure in the Fischauer Vorberge. These are mostly clastic sediments with basal breccias and conglomerates containing clasts of carbonate, quartz, and chert and higher up sandstone and shales (Plöchinger, 1967).

On the eastern slope of the Fischauer Vorberge, Neogene sediments crop out. Particularly interesting is the so-called Wurstmarmor (*sausage marble*; named after the coarse bright clasts embedded in reddish matrix), a carbonate breccia of unclear stratigraphic position. Plöchinger (1967) suggested that this unit was deposited during the lower Badenian, about 16 million years ago, in a coastal-marine environment as one of the oldest sediments in the VB and considered it as a variety of the Gainfarner Brekzie. The Wurstmarmor is generally poorly sorted in terms of mineralogical composition, size and

shape of clasts. Clasts sizes vary from few millimetres to several centimetres and are sub-angular to rounded.

While most clasts consist of limestone, dolomite and marine fossils, few are silicate-bearing Gosau-sediments. The matrix is a reddish micrite. The mineralogical composition of the grains points towards a source area in the Northern Calcareous Alps that formed the hinterland during sedimentation.

The Badener Konglomerat overlies the Wurstmarmor, a grey conglomerate with rounded clasts of light grey carbonate with grain sizes of few millimetres, followed by the Brunner Konglomerat.

The cave is situated in the transition zone from the tectonic regions of the Northern Calcareous Alps to the VB. While the exposed Triassic carbonates of Hohe Wand Plateau and Fischauer Vorberge belong to the Hohe Wand Nappe, which is part of the Mürzalpen Nappe System, the Neogene units are sediments of the VB (Plöchinger, 1967; Wessely, 2006).

2.2.2 Regional tectonic setting

Several major faults coin the area. The left-lateral Salzach-Ennstal-Mariazell-Puchberg (SEMP) fault system extends for about 300 km through large parts of the Eastern
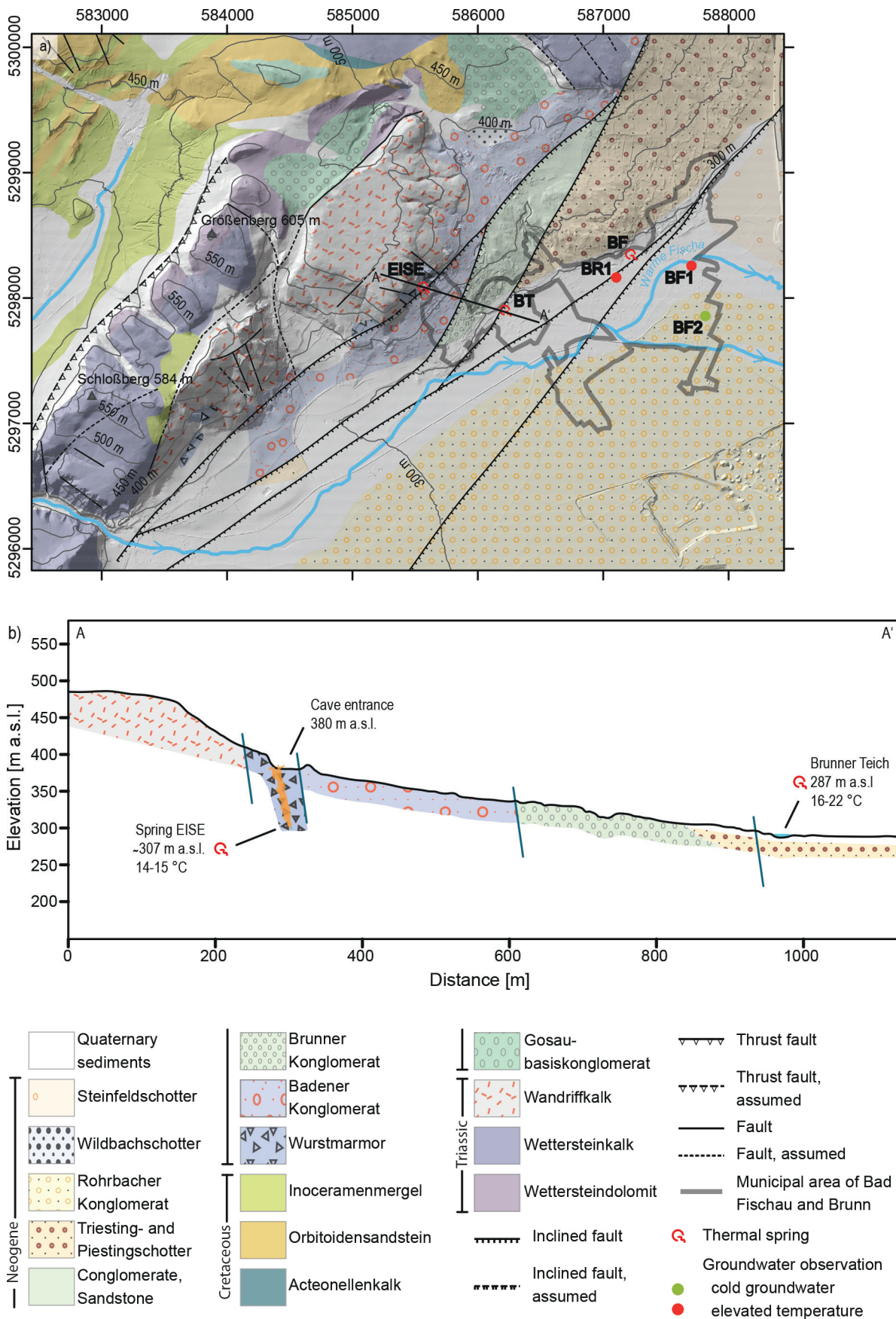
Figure 2: a) Geological map of the Fischauer Vorberge shown on 1 m – hillshade. Thermal springs: **Eise**nsteinhöhle, **B**ad **F**ischau, **B**runner **T**eich; Groundwater observation points: **B**ad **F**ischau **1**, **B**ad **F**ischau **2** and Bad Fischau **Br**unnen. Coordinates: UTM 33N.
b) Cross section through the western margin of the VB cutting EISE and the Brunner Teich in Brunn an der Schneebergbahn. (after Brix and Plöchinger, 1982; Plöchinger, 1964; topographic data: courtesy Government of Lower Austria); No vertical exaggeration.

Alps in W-E direction and terminates in the southern VB. With its origin in the central Eastern Alps, the left-lateral Mur-Mürz-Fault System (MM) enters the VB in the south and extends in SE-NW direction through the VB and Moravia into the Outer Carpathians (Hinsch and Decker, 2003). Both, the SEMP and the MM developed during the lateral extrusion of the Eastern Alps in the Miocene, resulting in the opening of the VB along the Vienna Basin Transform Fault (VBTF), a fault segment of the MM (Royden, 1985; Decker, 2005). The western margin of the VB is marked by the Vienna Basin Marginal Fault and several other normal faults are known from the Alpine basement of the VB as well as in the Neogene sediments (Decker et al., 2005; Wessely, 1983).

Recent tectonic activity along these faults is documented as seismic activity (Figure 1). Most of the stress is released along the VBTF as earthquakes in the southern part of the VB with most hypocentres clustering at around 7 km depth (Hinsch and Decker, 2003; Reinecker and Lenhardt, 1999). Hinsch and Decker (2003) calculated a slip rate of up to 0.5 mm/a along some segments of the MM and VBTF which is the highest one recorded in Austria.

2.3 Hydrogeology

The VB has been studied extensively during exploration for hydrocarbons and as consequence, comprehensive data also exists on the basin's hydrogeology. The transition from the Northern Calcareous Alps with its karstified limestones and dolomites to the VB with its mainly clastic sediments substantially influences the groundwater regime. Borehole data from the fault zone along the western basin margin show temperature anomalies with warm, highly mineralized groundwater overlying colder water of deeper aquifers (Wessely, 1983).

To explain the temperature anomalies as well as the occurrence of numerous thermal springs along the western margin of the VB, a model of groundwater flow was proposed by Wessely (1983). According to this model, precipitation infiltrates in the Northern Calcareous Alps, migrates along fractures and faults in these carbonate-dominated rocks towards deeper parts of the VB. On its flow path to depths of up to 6 km, the groundwater heats up and rises along faults towards the surface. Fractures and impermeable Neogene sediments channel the groundwater back towards the margin of the VB where the water often mixes with colder groundwater and discharges at several thermal springs.

According to Fenzl (1977), who investigated the hydrogeology of Hohe Wand and Fischauer Vorberge, groundwater within the Triassic units of the Hohe Wand Nappe follows fractures and karst conduits in NW-SE directions that result from Neogene tectonics. Based on hydrochemical and Tritium analysis Fenzl (1977) concluded that precipitation infiltrates in the Hohe Wand area, flows beneath the Neue Welt Basin within the limestones of the Hohe Wand Nappe and discharges at springs and rivers east of the Fischauer Vorberge near the margin of the VB.

For the thermal spring in Bad Fischau, (1.6 km east of EISE), Pavuza et al. (1985) suggested a model similar to that of Wessely (1983) but on a smaller scale. Groundwater flows eastward through the karstified rocks of the
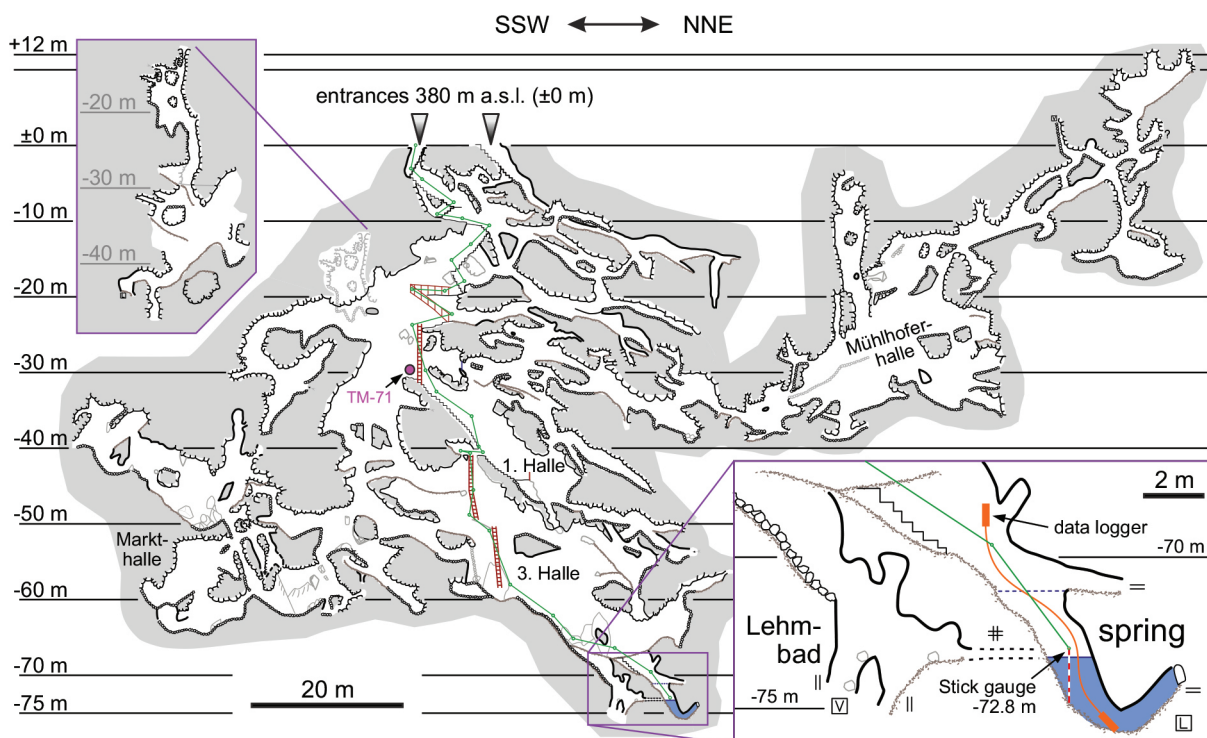

Figure 3: Profile of EISE with details (longitudinal section) of the lowest parts near the spring. Green lines show survey shots from the entrance along the tourist trail to the reference point, as well as an anchor bolt at the upper end of the stick gauge at 307.2 m a.s.l. The highest observed water level is marked with a blue dashed line; the overflow from the spring to the Lehmbad is marked by two black dashed lines (map after Nagl and Plan, unpublished).

Fischauer Vorberge towards the VB. Sediments in the VB are less permeable and force the groundwater to flow upwards along the marginal faults, eventually emerging as thermally influenced water.

Elster et al. (2016) suggested this model for all local thermal and subthermal springs (several springs at the spa Bad Fischau, subthermal pond in Brunn and others). Compared to other thermal waters in the VB the mineralisation in thermal waters near Bad Fischau is low (0.5 mg/l). $\delta^{18}O$-values of -8.82 to -10.81 ‰ and δD-values of -64.8 to -76.9 ‰ correspond to recent water in the catchment, but a contribution of older groundwater cannot be excluded (Elster et al., 2016).

2.4 Eisensteinhöhle

2.4.1 General description

EISE was discovered in 1855, during quarrying the Wurstmarmor, the host rock of the cave. Shortly after, many parts of the cave were explored and in 1919 the thermally influenced spring in the deepest part of the cave was discovered (Winkler, 1992).

The cave extends over 87 m in altitude with two entrances at 380 m a.s.l. (located at UTM 33N 585571/5298094). The lowest measured point is at -73 m and the highest at +14 m related to the entrance. The maximum horizontal extent is about 150 m in SW-NE direction and the total length is 2.3 km (Hartmann and Hartmann, 2000).

Big boulders and collapsed ceilings dominate the cave morphology in most parts and form a confuse network of galleries (Baroň et al., 2016). However, as characteristic morphologic features like cupolas, ceiling half tubes formed by condensation corrosion, and extremely weathered rock surfaces can be found in some parts, hypogene speleogenesis played a role and at least overprinted the morphology (Spötl et al., 2017).

The cave climate is dominated by the hydrothermal activity in the lower parts, leading to air temperatures around 13 °C with the highest temperatures near the lukewarm spring. The air in the cave shows elevated CO_2 concentrations of occasionally up to 2 % (Plan et al., 2006; Plan and Spötl, 2016).

EISE developed in Miocene sedimentary rocks. The main outcropping unit inside the cave is the Wurstmarmor and probably towards the upper parts of the cave, the Badener Konglomerat. Strongly weathered rock surfaces, the heterogeneity of the Wurstmarmor itself, clay and speleothems (i.e. coralloids, frostwork) covering the walls make it hard to define bedding planes or layer boundaries. Cracks permeate the host-rock in multiple orientations. They are present as closed fissures or as wide as 25 cm and are open, filled with euhedral calcite crystals or partially filled with euhedral calcite and/or laminated, sandy to loamy sediments. Wessely et al. (2007) described similar cracks lined by calcite spar in Miocene conglomerates and Triassic carbonates in the borehole "Vöslauer 7" (ca. 10 km NNE of EISE) and identified them as pathways of thermal water.

2.4.2 Thermally influenced spring and water level fluctuation

In the deepest part, the cave splits up into two galleries. While the Lehmbad, the lowest lying part of the cave, is usually dry, the spring pond in the neighbouring gallery is almost constantly filled with water (Figure 4). The wall that separates these two galleries is only few meters thick and a few centimetre-wide crack serves as an overflow when the water rises high enough. This overflow discharge can be measured in the Lehmbad, where the water finally disappears in a narrow impenetrable fissure. The water temperature fluctuates between 14.4 and 14.8 °C.

3. Materials and Methods

3.1 Time Series Data

3.1.1 Water level and temperature data

In 1992, a stick gauge of 2 m length with 10 cm intervals was installed and the water level was recorded during each visit. At rare occasions of overflow, the discharge was measured as the amount of water that reached the neighbouring gallery, but as the water probably drained through other smaller cracks as well, these values are only approximations.

The position of the upper end of the stick gauge was referenced at -72.8 m, relative to the cave entrance (380 m a.s.l.) during a cave survey. The accuracy of the stick gauge measurements was checked after the automated data logger was installed in October 2015 and found accurate to ±1 cm.

For automated measurements, a Dipper-PT data logger by SEBA-Hydrometrie was installed into the spring (Figure 3) (accuracy ±5 mm for water level and ±0.1 °C for temperature). Air pressure variations are compensated using an integrated pressure-compensation tube. The sampling interval was 15 minutes.

3.1.2 Seismic data

Seismic data were taken from the Austrian Earthquake Catalogue (AEC 2019) including all recorded earthquakes from 1992 onwards. The catalogue includes date and time, epicentre location, depth, magnitude and epicentral intensity of the earthquakes. The spatial resolution of the calculated epicentre is 0.01 degree, which corresponds to roughly 1 km.

3.1.3 Hydrological data

Hydrologic datasets for four meteorological stations and three groundwater heads closest to the cave were provided by the Hydrological Service of Lower Austria (see Table 1, Figure 1 and 2). Precipitation at the stations Miesenbach, Stollhof - Hohe Wand (hereafter just Stollhof), Saubersdorf, and Unterhöflein was recorded as daily total.

Groundwater levels at wells 313973 Bad Fischau Br. (BR1), 322560 Bad Fischau Bl238 (BF1) and 326900 Bad

Figure 4: Thermally influenced spring with stick gauge and data logger.

Measured parameter	Name	Coordinates UTM 33N E	Coordinates UTM 33N N	Distance to EISE [km]	Altitude [m a.s.l.]	Annual mean [mm/a] or [m a.s.l.]	Annual mean temperature [°C]
Precipitation	Stollhof-Hohe Wand	580242	5298028	5.3	446	882	8.3
	Saubersdorf	583966	5293635	4.7	320	654	8.9
	Unterhöflein	577301	5294065	9.2	441	860	8.2
	Miesenbach	573474	5298739	12.1	480	933	7.6
Groundwater level	Bad Fischau BR1 *	587127	5298184	1.6	286.5	284.1	11.6
	Bad Fischau BF1 *	587813	5297861	2.3	280.5	266.6	13.4
	Bad Fischau BF2	587724	5298260	2.2	280.7	267.8	–

Table 1: Overview of observation stations. Thermally influenced groundwater observation wells are marked with an asterisk (*). Annual mean temperatures refer to air temperature at meteorological stations and to groundwater temperature for observation wells.

Fischau BI293 (BF2) were recorded irregularly. Records of groundwater temperatures of thermally influenced observation wells unfortunately are too fragmented to be used for a detailed study.

3.2 Pumping Test

To estimate the reservoir capacity of the pond as well as to determine the spring discharge a recovery test was performed in EISE on 13/7/2016, starting from an initial water level of 305.82 m a.s.l. Using an immersion pump, the pumping rate was calculated by taking the time it needed to fill a bucket. The spring pond was emptied completely, and a small water inlet appeared in the sandy sediment at the bottom. Its discharge was determined using a measuring cup. During the pumping test, the data logger was set to a 2-minute sample interval.

3.3 Data analysis

Raw data were prepared using Excel and then processed and analysed using MATLAB (after Trauth, 2006; Menke

and Menke, 2012). The time series data were interpolated using a shape-preserving spline to reduce noise but preserve short-term changes of water level and temperature and were then resampled with a sampling interval of 1 day for automatically logged data (7/10/2015 – 13/11/2018) and a sampling interval of 14 days for long-term observations (1992 – October 2015). This was done to reduce the amount of data for further analysis and visualisation and to synchronize data from different sources. Data from groundwater wells were treated the same way.

As daily precipitation data between each water level sampling point would not have been considered in the calculations, it was found unsuitable for correlation within the first sampling period. Therefore, moving sums for different time intervals (14, 30, 90, 365 days) were calculated and resampled in the same sampling interval as water level data from EISE. Correlations (r-values) and corresponding levels of significance (significant $p \leq 0.05$; highly significant ≤ 0.01) were calculated with the MATLAB function 'corrcoef' (Schönwiese, 2006). Periods of higher correlations were identified with the MATLAB function 'movcorr' that applies a correlation using a moving window of data points.

Peak ground velocities (PGV) were calculated from seismic data for the location of EISE using the equation by Weginger et al. (2017) adapted for the Eastern Alps.

4. Results

In the first phase (1992-2015), when 267 water level values were collected manually, the sampling rate ranges from one measurement per year to more than one in two weeks. The average sampling rate was about one sample per month. In the second phase (October 2015 – November 2018) the sampling rate was much higher (108,908 data points) and therefore, time series data is split into two sections for further analysis.

4.1 Period of manual water level observations (1992 – 2015)

4.1.1 Water level changes

During the first observation period a drying-up as well as several overflow events into the

neighbouring gallery were observed. The record of water level shows fluctuations within a range of 3.9 m with 304.8 m a.s.l. as minimum and 308.7 m as maximum values (Figure 5). Certain stages can be considered as recurring, such as levels around 306.0 m a.s.l., which were observed on 47 occasions and around 307.1 m with 93 counts. Levels around the average water level of 306.5 m a.s.l. were observed only few times. A bimodal frequency distribution of observed water levels is evident (Figure 6).

The lowest level was observed over several months in 2001 when only a small amount of water remained in the spring pond. During overflow conditions, 21 discharge measurements were taken that ranged from 4.2 to 289 l/h. Discharges higher than ca. 300 l/h led to a flooding of the Lehmbad and prevented discharge measurements. This situation was observed five times. The highest level was reached on 29/6/2009 after the capacity of the overflow was exceeded and a back-flooding of 1.5 m above the upper end of the stick gauge occurred.

4.1.2 Correlation with precipitation data

The correlation of water level at EISE and 14-day precipitation sums is weak for all stations. By increasing the number of days over which precipitation is integrated (Figure 7), the correlation increases to moderate (see Table 2). The strongest correlation was found for Stollhof ($r = 0.63$; $p \leq 0.01$) followed by Miesenbach ($r = 0.62$; $p \leq 0.01$) for precipitation sums of 365 days. The precipitation at these stations is very similar in distribution ($r = 0.89$; $p \leq 0.01$) and therefore only data from Stollhof were further used.

Correlation using a moving window indicates a change of the degree of correlation between precipitation and water level at EISE over time (Figure 8).

The poor correlation of short-term precipitation data and water level is inconsistent with observations during manual measurements, when extreme rainfall preceded the highest measured water level on 29/6/2009. Several days of intense rainfall with 156.3 mm within 10 days and a maximum of 40 mm/d occurred at the Station Stollhof.
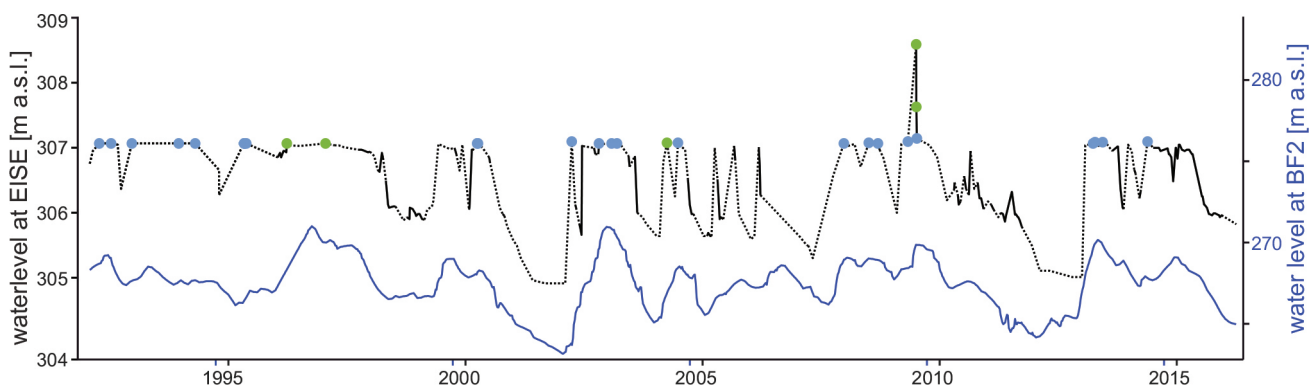

Figure 5: Water level of the spring at EISE between 1992 and 2015. Blue dots indicate overflow into the Lehmbad, green dots indicate flooding of the Lehmbad, dotted lines indicate a sampling interval of more than 21 days: the full line indicates sampling intervals of 21 days or less. The level in well BF2 (blue graph) shows the highest correlation if a delay of 14 weeks is applied as in the figure (R increased from 0.68 to 0.78).
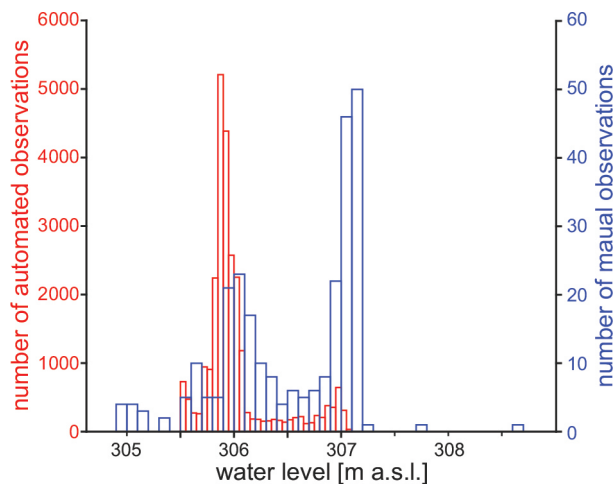
Figure 6: Frequency distribution of hourly-observed water levels during automated measurements (in blue) and sporadic measurements from 1992 until 2015 (in red). Data measured during the pumping test are excluded. The higher number and resolution of automated measurements compared to the sporadically collected data allow smaller class sizes.
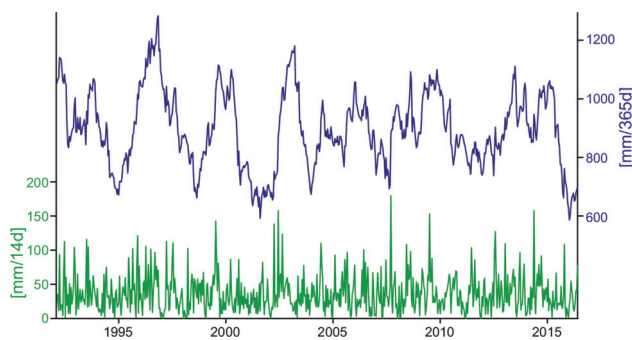

Figure 7: Precipitation at Stollhof: 14-day sums and sum during the last 365-days, both resampled in the same two weeks interval as the water level in EISE.

	14 days	**90 days**	**365 days**
Stollhof	0.13	0.30	**0.63**
Miesenbach	0.13	0.27	0.62
Unterhöflein	0.11	0.24	0.44
Saubersdorf	0.11	0.17	0.35

Table 2: Correlation coefficients for water level at EISE and total precipitation over the previous 14, 90 and 365 days for each sampling date.

4.1.3 Correlation with groundwater levels in nearby wells

The water level at EISE is about 24 m above the groundwater at well BR1 and about 40 m above groundwater at wells BF1 and BF2. Although the latter two are further away and the difference in head is higher, the correlation is stronger than for BR1. A time lag of about 14 weeks yielded the highest correlation (r = 0.78; p ≤ 0.01; Figure 5).

4.2 Period of automated measurements October 2015 to November 2018

4.2.1 Water level and temperature

During this measurement period, the water level remained fairly stable, apart from six events of water
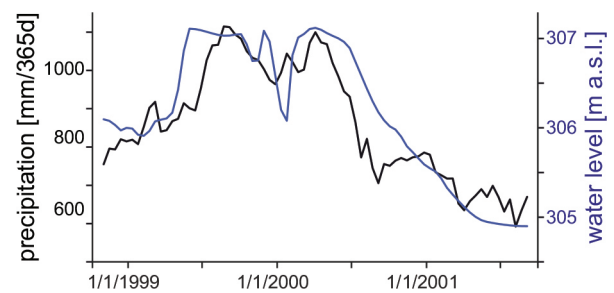

Figure 8: Time window with strong correlation of cumulative precipitation of the previous 365 days for each sampling date (black) and water level at EISE (blue) from 11/1998 until 9/2001.

level increase and one period of a significantly lower level between 8/1 and 12/4/2018 (Figure 9). The data, from the start of the pumping test until the previous water temperature was reached again, were analysed separately. The natural water level fluctuated around 306 m a.s.l. with events of sudden rises to 307.1 m a.s.l. The frequency distribution of measurements differs from that during manual measurements (Figure 5 and 10). The maxima of the bimodal frequency distribution are close to the same values of the period of manual measurements (Figure 6). During the high discharge events, the water level stagnated for a short time just below the visible overflow.

The temperature ranged between 14.4 °C and 14.8 °C. During high discharge events temperature increased. At the first five events, this happened with a delay between 4 and 15 days after the water level started to rise and at the last event (16/6/2018) it happened almost simultaneously. Cooling to the previous temperature took longer than for the water level to decline to the previous value. From March 2017 to September 2017 three of these high discharge events were recorded (Figure 11). While the water level dropped significantly between each event, the temperature decreased slightly before it rises again with the next water level increase.

4.2.2 Pumping test

On 12/6/2016 a pumping test was performed at the spring of EISE. The determined pumping rate was about 1.7 ± 0.1 l/s which emptied the spring in 28 minutes leading to a pumped volume of about 2.8 m³ (±0.16 m³).

The lowest measured water level of 304.58 m a.s.l. was reached during the pumping test when the water level dropped slightly below the lowest measurable head. After the spring had been emptied completely, a small outlet in the sandy bottom appeared. In the following 3 hours 5.7 l/h were discharged. This rate is rather low compared to discharge measured during overflow events. Using above-mentioned volume and assuming a constant discharge, the spring would have been filled to the same level within ca. 20 days.

During the pumping test, the water temperature fell from 14.51 °C to 14.17 °C, the lowest temperature of the entire record.
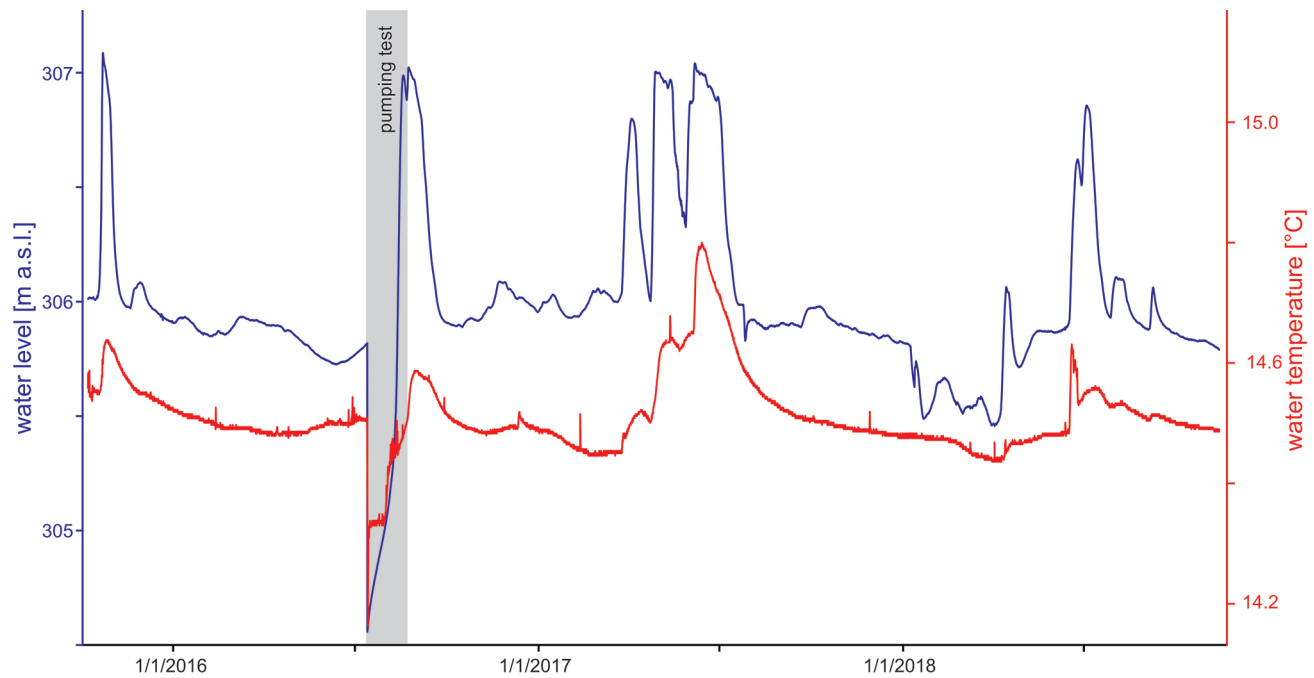
Figure 9: Observed water level (in blue) and temperature (in red) at EISE from October 2015 until November 2018. The data presumably influenced by the pumping test (13/7 to 22/8/2016) are marked in grey.
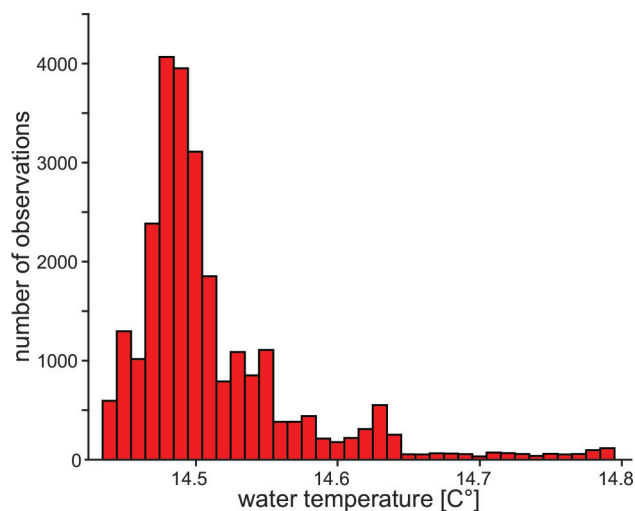

Figure 10: Frequency distribution of observed hourly water temperatures from Oct. 2015 until Nov. 2018. Data influenced by the pumping test are excluded.
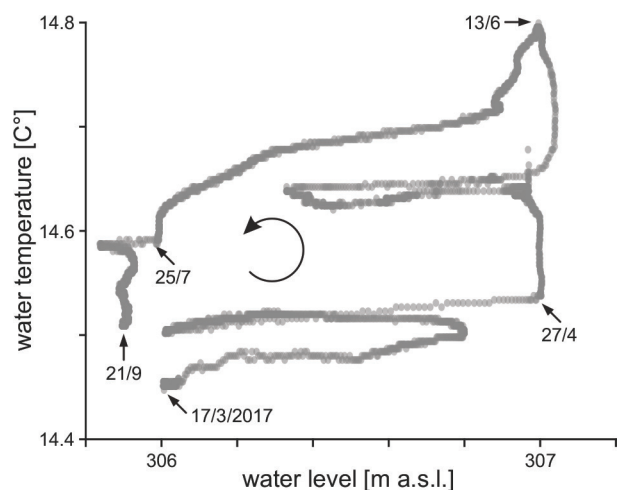

Figure 11: Scatterplot of hourly measured water levels and corresponding temperatures for the period of 17/3/2017 until 21/9/2017.

4.2.3 Correlation of the spring level with precipitation

No significant correlation between the automatically recorded water level at EISE and precipitation was found. However, all major and some minor water level increases followed days with precipitation of 15 mm or more at the station Stollhof. In turn, not all days with precipitation of 15 mm or more were followed by distinct water level changes (Figure 12).

4.2.4 Correlation with groundwater in the Vienna Basin

For nearby groundwater wells, no correlation of the water level at EISE was found for the short-term observations.

4.2.5 Comparison of water level and temperature with seismic data

Comparing the water level with seismic data, only few events causing considerable PGV at EISE are relevant. One remarkable water level change at the end of July 2017 stands out, which cannot be related to precipitation (Figure 13). The water level dropped 20 cm in one day before it recovered simultaneously with several earthquakes of magnitude ≤ 2.4 within a radius of 2 km (Figure 1).

The epicentres of most of these earthquakes were located in Bad Fischau, but the strongest one with a magnitude of 2.4 was located further west only 1 km from the cave at a depth of 5.1 km.
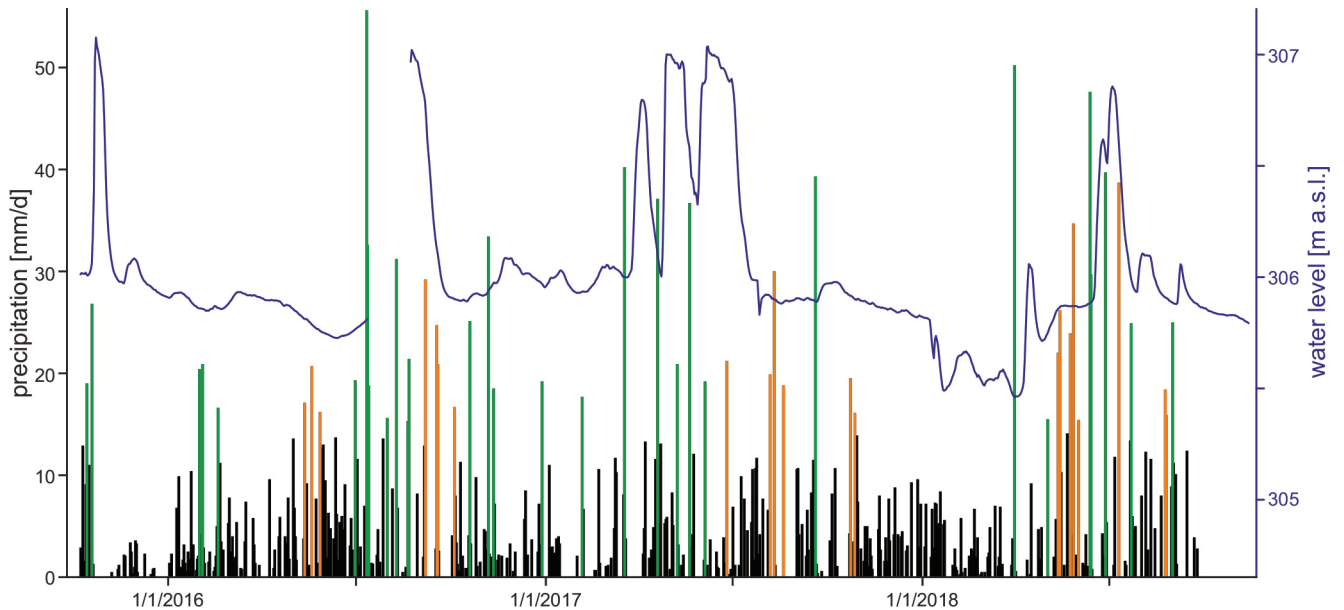
Figure 12: Daily precipitation at station Stollhof (black bars) and water level at EISE (blue). Green bars indicate rain events with more than 15 mm per day that were followed by a water level increase. Orange bars indicate events not followed by an increase. Note that there are also distinct peaks without preceding rain events.
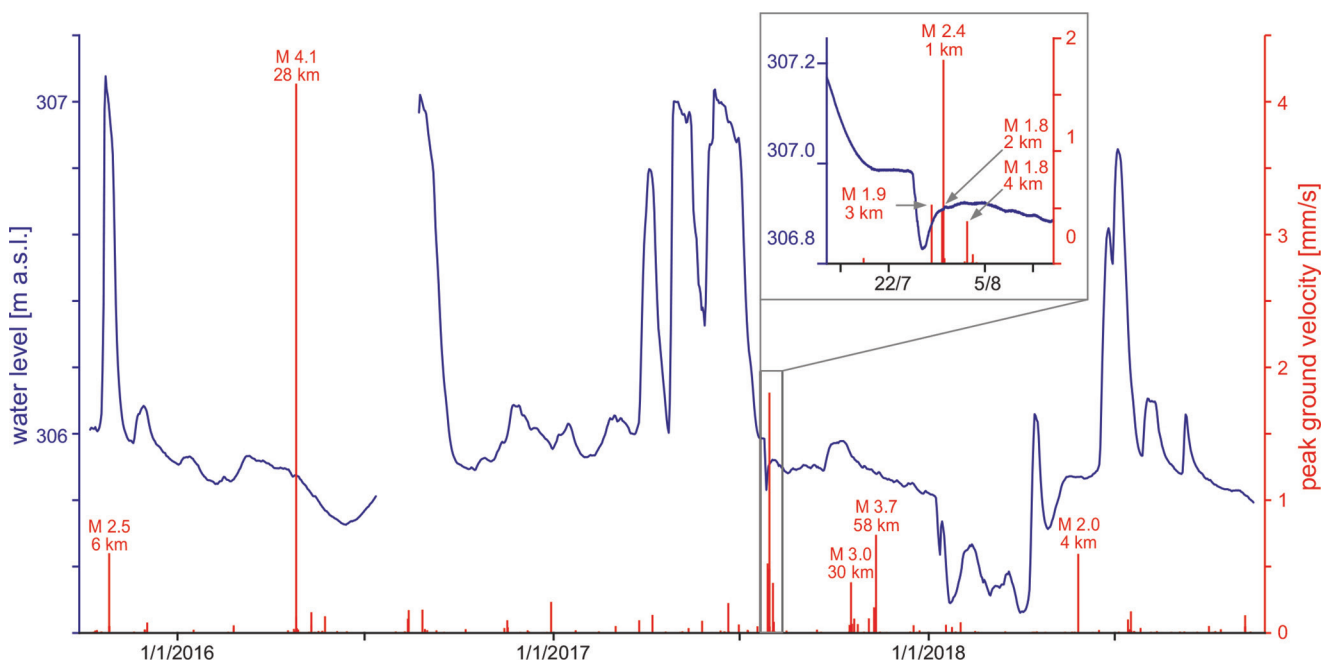

Figure 13: Peak ground velocities calculated for the location of EISE (red bars; including magnitude and distance to the epicentre) and the recorded water level (blue). Only few earthquakes caused noteworthy ground motion at EISE.
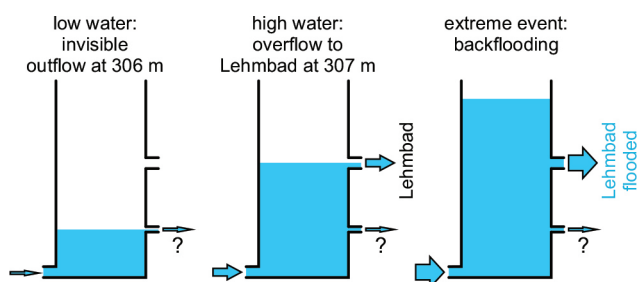
Figure 14: Schematic section of the spring in EISE explaining the water levels (approximate elevations in m a.s.l.).

5. Interpretation and discussion

5.1 Water level and temperature records

The quality of both datasets is generally suitable for time series analysis and manual measurements, taken during the automated logging, showed a precision of ±1 cm. However, the scarcity of data points during some intervals of manual measurements complicates the correlation with other datasets and even makes it useless for correlations with seismic data that consist of single points

in time. Data interpolation often results in repetitive values or linear trends (e.g. periods 1992-1994, 2006-2008). This is also reflected in the correlation of the interpolated data with short-interval precipitation data (Table 2).

Furthermore, manual measurements show a bias towards higher water levels than during the period of automated measurements (a U-test rejected the hypothesis of equal medians). This could mean, either that a sustained change of the water level occurred or that the cave was visited more often during higher water levels. No influence of seasonal variations of the frequency of measurements was found. Comparing the two records it becomes apparent that peaks of water level of only few weeks in the record of automated measurements are probably represented as plateaus of several months during manual observations. Especially when high water levels are interpolated, the bias introduced by the measurement is amplified by interpolation.

The high-water levels show plateaus, indicating that the pool drains through unknown outlets (Figure 14). Consequently, discharge measurements made during overflow conditions underestimate the actual discharge to an unknown extent, which confirms the assumption by Winkler (1992).

Water level and temperature are coupled temperature lagging up to 15 days. This delay is interpreted as the time it takes for the warm water to flow through conduits, initially filled by colder water and to warm up the surrounding rock. The observation that not all water level changes are followed by increasing temperature hints towards multiple water sources feeding the spring.

5.2 Pumping test

The pumping test revealed the geometry of the spring-pool and helped to identify a diffuse outlet in the sandy bottom of the spring as the water inflow. However, it gave no exact insights into aquifer properties.

The fact that the neighbouring normally dry Lehmbad reaches below the elevation of the spring indicates that the spring is fed by a small, vadose conduit and is not directly connected to a larger body of karst water of the Fischauer Vorberge. The actual water level of the spring is determined by the balance of discharge and outflow through several small, unknown fissures (Figure 14).

5.3 Correlations with other datasets

The comparison with meteorological stations reveals a major influence of precipitation on water level changes at EISE. In particular, the cumulative precipitation at the stations west of EISE show a robust correlation with the spring's water table.

Combining both long-term and short-term observations lead to a model with a reservoir that, when filled to a certain level, responds to individual precipitation events as it was observed during automated measurements.

Hydrogeological models by Wessely (1983) and Pavuza et al. (1985) describe a northeast- to east-directed groundwater flow in the Fischauer Vorberge. This is in agreement with the 8 weeks delay of groundwater signals at BF1 relative to EISE and indicates that both locations are part of the same thermally influenced aquifer.

For the southern VB no recent evidence for earthquake-related hydrologic phenomena has been reported so far. On 27/2/1768, there was an earthquake in Wiener Neustadt (sometimes Bad Fischau is mentioned as epicentre) with an intensity of 7 (Hammerl and Lehnhardt, 2013). After that event, Nagel (1768) described increased discharge, turbidity, and temperature for the thermal springs in Baden and for the Ursprungsquelle in particular (21 km north of EISE). Schenk (1805: 170) further reported the emergence of red sand at Ursprungsquelle.

The comparison with seismic data suggests that there are earthquakes relevant for inducing hydrogeological effects at EISE, but also that they do not occur very often. Given the rare and irregular occurrence of earthquakes that cause enough strain or ground shaking at EISE to induce hydrogeological effects, it is currently impossible to prove earthquake-spring relationship.

6. Conclusions

The thermally influenced spring in the lowest part of Eisensteinhöhle shows fluctuations in discharge resulting in water levels between 304.8 and 308.7 m a.s.l. The observed overflow discharges at Lehmbad ranged from 4.2 to 289 l/h. The highest water level was observed on 29/6/2009, after a period of intense rainfall with 156.3 mm in 10 days. A complete drying-up occurred only for several months in 2001.

The water level of the spring is determined by the interplay of discharge and outflow through cracks and fissures. The most prominent elevations in the frequency distribution of water levels reflect the position of cracks or more permeable rock. Certain recurring water levels like 306 and 307.1 m a.s.l. indicate the position of these partially unseen outlets.

Between 7/10/2015 and 13/11/2018, water temperature ranged between 14.4 and 14.8 °C and was positively correlated with discharge. During high discharge events, the increase of water temperature followed the increase of water level with a delay of up to 15 days.

A pumping test revealed the basal inlet of the spring and helped to interpret water level as well as discharge data.

Our analysis showed that the spring discharge is controlled by several factors. The amount of annual precipitation plays a dominant role. However, observations showed that only a couple of rainfall events gave rise to an increase in water level. The magnitude of influence of individual factors remains uncertain and probably changes over time.

Based on the comparison of the water level at Eisensteinhöhle and at observation wells nearby, it was also shown that the aquifer feeding the thermally influenced spring is in contact with the aquifer in the nearby wells

in the Vienna Basin or is at least influenced by the same factors. As water level changes at Eisensteinhöhle are more abrupt, the spring is probably closer to the common catchment.

The correlation of the groundwater level at Eisensteinhöhle with seismic data revealed a first earthquake-induced hydrologic event. To confirm this relation and for further quantitative analysis a higher number of earthquakes that cause ground motion at Eisensteinhöhle and its surroundings and therefore a much longer observation period would be necessary.

Acknowledgments

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