sciendo
Austrian Journal of Earth Sciences | Vienna | 2022 | Volume 115 | 199 - 212 | DOI: 10.17738/ajes.2022.0010

Hydrogeology of alpine lakes in the Northern Calcareous Alps: a comparative study on the role of groundwater in Filblingsee and Eibensee

Sylke Hilberg[1]*, Florian Sändler[1], Florian Fürlinger[1]

[1)] Paris Lodron University of Salzburg, Department Environment and Biodiversity, Hellbrunner Str. 34, 5020 Salzburg

[*)] Corresponding author, ?????

KEYWORDS

alpine lake, Northern Calcareous Alps, hydrogeology, lake classification, karst

Abstract

In the Northern Calcareous Alps (NCA) there are countless small lakes with small orographic catchments that are often located only slightly below the respective summit regions. On the one hand, the lakes are located in karstable aquifers and their existence is likely to be related to karstification. Then, they are expected to be directly connected to the karst water body. These lakes are classified as karst lakes. On the other hand, the alpine environment is also influenced by glacial processes and lakes might be related to glacial erosion and deposition. For these glacial lakes, the share of groundwater inflow and outflow is regarded as subordinate even within high permeable karst lithologies. Here we compare two alpine lakes of potentially different origin in the NCA in Salzburg with the aim to provide a basis for an aerial survey of the numerous small alpine lakes in the NCA region and their characterization using the guiding parameters elaborated here. We consider (a) the lake geometry, (b) potential inflow and outflow systems, and (c) physicochemical parameters and hydrochemistry of the Filblingsee and the Eibensee, both located in the Fuschlsee region. Filblingsee was initially considered as a typical karst lake and Eibensee as a moraine-dammed glacial lake. Some clear differences arise in lake geometry, which in the karst lake shows a nearly round surface and concentric depth profile, while the glacial lake is elongated in the direction of glacier flow and has the deepest areas just upstream of the moraine dam. Both lakes show very little to no surficial inflow. Inflow and outflow occur in groundwater in both cases but are not directly tied to a highly permeable karst system. The depth profiles of the field parameters of the two lakes differ only slightly and show a dominant groundwater inflow in mid-depth regions but no flow through at the lake bottom. Water chemistry in both lakes and their potential outflows correspond to the respective aquifer in terms of solution load. Filblingsee can be characterized as a hanging lake in a secondarily sealed doline, Eibensee lies in a glacially excavated depression sealed by glacial sediments. While the inflow and outflow conditions and the hydrochemistry of both lakes are very similar, the lake geometry is a clear distinguishing feature that can be attributed to the different genesis of the two lakes. This can therefore be used as a guiding parameter for the classification of the numerous small alpine lakes in the NCA.

1. Introduction

Lakes in the alpine region play a major role as water reservoirs, serve as water supply for alpine agriculture, represent special ecosystems (Bartels et al., 2021) and offer valuable tourist attractions (e.g., Roy and Hayashi, 2008; Senetra et al., 2020). On the other hand, alpine lakes represent potential risks of natural hazards (Emmer, 2018; Mergili and Schneider, 2011). It is therefore of great importance to have a good understanding of the hydrological and hydrogeological processes that lead to the formation and persistence of alpine lakes. There is however no clear and generally accepted definition of alpine lakes. In general, lakes above a certain altitude (defined differently depending on the respective mountain region) are classified as alpine lakes. Another definition includes those natural water reservoirs that are directly related to mountains or mountain-related processes independent of their altitude. The formation of lakes can be attributed to surface processes, glacial developments or can be karst related. Surface processes, such as landslides, lead to the formation of lakes that are often temporary. Argentin et al. (2021) describe landslide-dammed lakes and their formation processes as well as their hazard potential in Austria.

Numerous studies on alpine lakes understand them to be primarily glacial lakes, although a wide variety of definitions are given here (Yao et al., 2018). Buckel et al. (2018), as well as many authors cited therein, discuss under the term glacial lakes mainly young formations in the forefront of still existing glaciers. This consideration is currently the focus of climate change research because these glacial formations make current developments clearly visible and quantifiable. Detached from current developments, Yao et al. (2018) and numerous citations therein generally consider glacial lakes as those formed by glaciation regardless of their current relation to a still existing glacier. Chen et al. (2010) refers to water bodies in basins that have been formed since the last glacial maximum and are fed by meltwater or rainwater without mentioning groundwater. A classification of glacial lakes is given by Yao et al. (2018) according to the type of dam or glacial process that led to lake formation. In doing so, they distinguish lakes due to glacial erosion from moraine-dammed lakes and present examples where remote sensing, and thus lake geometry, has been used to classify them. Emmer and Curin (2021), on the other hand, who see hazard potential primarily in moraine-dammed young glacial lakes, state that the different dam types do not necessarily lead to different lake geometries and therefore an interregional classification based on remote sensing is not possible without restrictions. Most studies of glacial lakes consider surface inflow and outflow systems, and ignore groundwater influence (e.g., Chen et al., 2010). However, the few studies on groundwater flow in glacial lakes show that groundwater contribution to the water budget can be substantial even in moraine-dammed lakes (Winter, 1999; Gurrieri and Furniss, 2004; Hood et al., 2006). Roy and Hayashi (2008) discussed groundwater flow in two alpine lakes in the Canadian Rockies and found that it can even be the dominant component in the water budget of alpine catchments.

In karst research, in contrast, groundwater flow plays a major role, while surface runoff is considered to occur only temporarily and acts as a feeder to the often selectively formed swallow holes. This is due to the distinct system of karst conduits resulting in high rock permeability. Lakes in karst are generally considered to be temporary phenomena during flood periods (Ravbar et al., 2021). Poljes, known mainly from the Slovenian Dinarides, are terrain depressions within karstified lithologies that are dry or flooded depending on the karst water table. Their diameter can be in the kilometer range. Such poljes are also known in the Austrian NCA, but they are not comparable in extent to those in Slovenia. Smaller karst hollow forms, such as swallow holes, are widespread in Austria and are mostly associated with transition zones between lithologies that are well karstified and those that are not karstable (Plan, 2016). These karst hollow forms are mostly funnel-shaped dolines, i.e., surface water is collected in them and infiltrated pointwise into a mostly extensive system of karst conduits and caves in the epiphreatic zone. Only when the karst water level rises above the level of the bottom of a swallow hole the funnel is filled with water. The fact that the construction of artificial water reservoirs in karst is highly problematic and risky (Milanovic, 2021) also reflects that permanent lakes can rarely form in karst. However, one famous exception is Kozjak Lake in the Plitvice Lakes National Park in Croatia. Biondic´ et al. (2010) identified it as hanging lake without direct connection to the karst aquifer. In this case karst conduits are filled with tufa which leads to a significant reduction of the permeability of the lake´s bottom and prevents direct interaction between lake and aquifer. Hartmann et al. (2014) describe numerous epikarst features in their review of karst water as a global resource. Permanently existing karst lakes are not among them. One example of a permanently present lake within karst cavities is given by Vrsalovic et al. (2022) with the Red Lake in Croatia which is directly connected to the groundwater body since its depth extends below the deepest karst water level.

In our study, we consider two small alpine lakes on the northern edge of the NCA, both of which appear to contradict the common view of generally groundwater related karst lakes and surface water dependent glacial lakes. The overview survey of both lakes aims to find out similarities and differences between these two types of alpine lakes. For this we considered hydrological and hydrogeological catchment conditions, in- and outflow, lake geometry, and physicochemical water parameters to define guiding parameters for an in-depth classification of alpine lakes. Since there are numerous small lakes in the NCA, comparable in location and size to those presented here, we intend to provide the impetus for a detailed classification of the NCA lake inventory.

2. Study area

The two study sites are located on the northern edge of the NCA in the federal state of Salzburg in Austria, approximately 20 km east of the city of Salzburg (Fig. 1a) and near the much larger lake Fuschlsee in Salzkammergut (Fig. 1b). Both lakes are only a few kilometers apart within the Tyrolian nappes of the Austroalpine (Pestal et al., 2009).

Filblingsee is located at an altitude of 1,064 m asl with an area of appr. 12,000 m^2. The highest elevation in the catchment is the summit Filbling with 1,307 m asl WNW of the lake. A second summit in the catchment is the Schmiedhorn E of the lake, 1,223 m asl. The lake lies less than 300 m below the summit region and has a rather small catchment of approximately 0.23 km^2. The region within the Osterhorn Tyrolicum is a part of the tyrolean nappe system within the NCA (Pestal et al., 2009). The lake is surrounded by NW-SE-striking calcareous and dolomitic lithologies of Jurrassic and Triassic age, respectively. Based on Egger and van Husen (2003) three NW-SE striking fault zones cross the study area. One of them, called Filblingsee fault, straddles the lake on its NE side and separates fractured and low karstified Triassic

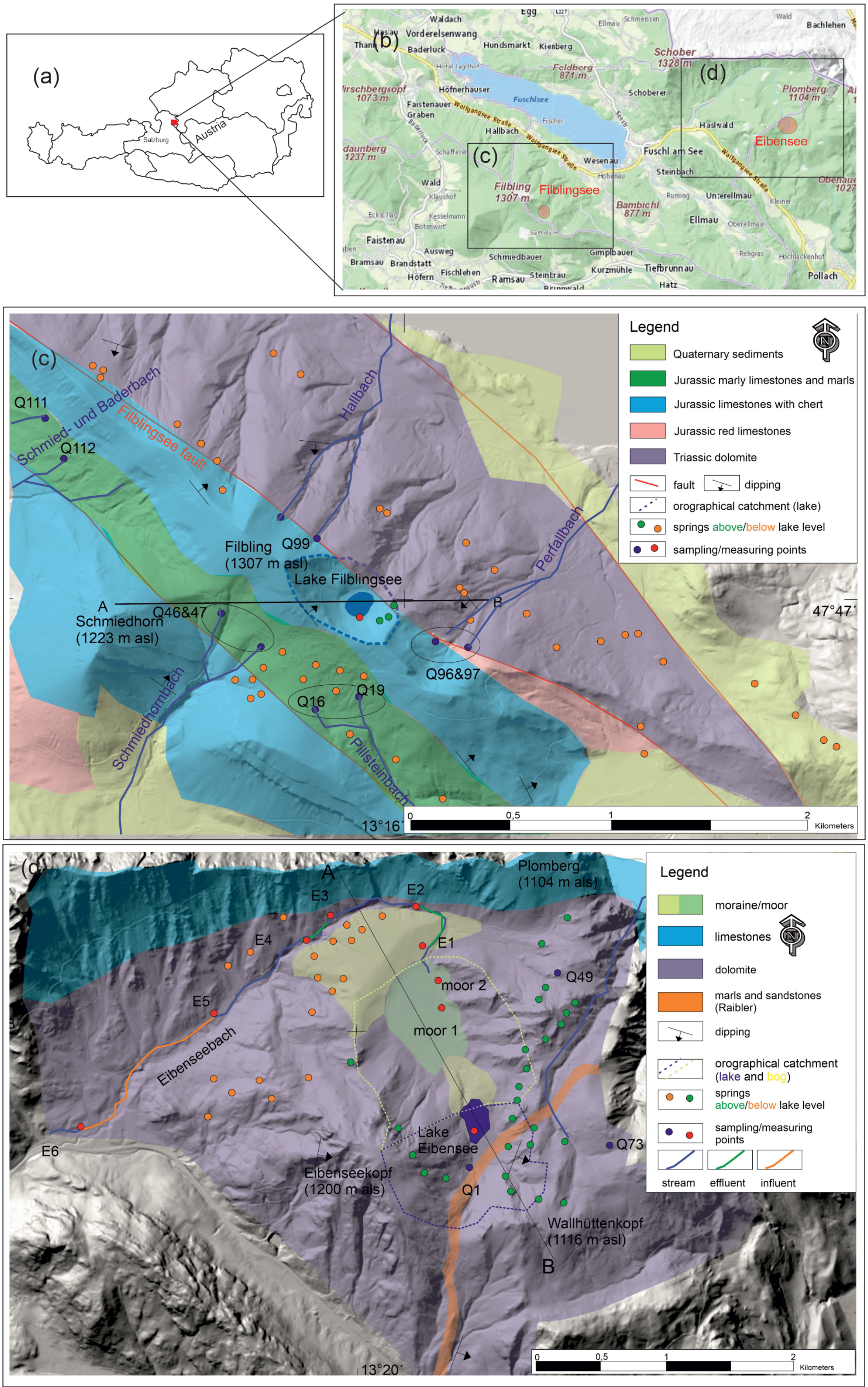

Figure 1: Overview of the study areas Filblingsee and Eibensee. (a) location of the study area in the northern part of Salzburg, Austria. (b) Position of the lakes and delineation of the investigated catchments. (c) Study area Filblingsee and (d) study area Eibensee. Black lines (A-B) in (c) and (d) mark the position of the profile sections in Figure 7.

dolomites (Hauptdolomit) from karstified Jurrassic (Oberalm) limestones. While the dolomite dips to the SW, the Jurrasic limestones are dipping to NE. The lake itself lies in a nearly round hollow shape within the karstified limestones (Fig. 1c). It has no permanent surficial inflow or outflow, thus, at first it is interpreted as a swallow hole directly connected to the limestone karst aquifer. However, the lake water level shows only small seasonal fluctuations, and the permanent lake level is well above the karst water level of its surroundings, which can be derived from springs (Sändler, 2019).

Eibensee is about 5 km away from Filblingsee in ENE direction, just at the border to the federal state of Upper Austria (Fig. 1b) but also on the territory of Salzburg. With an area of 32,000 m^2 the lake is more than twice as big as Filblingsee. Its catchment has an area of 0.53 km^2. The highest elevations in the catchment are Wallhüttenkopf (1,116 m asl) in the S, Plomberg with 1,103 m NE, and Eibenseekopf with 1,198 m asl W of the lake which lies at an altitude of 960 m asl, around 240 m below the highest elevation of the catchment. Between Filblingsee and Eibensee the Wolfgangsee fault divides Osterhorn Tyrolicum in the S from the Stauffen-Höllengebirgs nappe in the N in which Eibensee is located (van Husen, 1989). The lake is located completely within fractured and low karstified Triassic dolomitic units (Wettersteindolomit and Hauptdolomit), which are dipping to the E. Limestones are only present in the very northern part of the lake´s catchment. Based on van Husen (1989) the lake is moraine dammed and thus, can be classified as glacial lake. The moraine dam separates the lake from an extensive marshland lying about 50 m below to the N (Fig. 1d). As glacial lake groundwater influence is expected to be subordinate, however, a first view on the hydrological conditions shows that Eibensee has obviously no permanent surficial inflow or outflow (Fürlinger, 2019).

3. Methodology

3.1 Geological and hydrogeological mapping

In summer 2018 hydrogeological maps of both catchments were prepared. This period was characterized by a comparatively dry phase with monthly precipitation totals in July and August 2018 amounted to only about 60% of the long-term average in the study area. Therefore, low water conditions are considered here, the transferability of some results to other hydrological conditions was not investigated within the framework of this study. Geological and hydrogeological outcrops were recorded at a scale of 1:10.000. The mapping was based on the existing geological maps of the area (van Husen, 1989; Egger and van Husen, 2003). In addition to springs, the inventory of wetting zones, infiltrations and streams were documented over the entire study areas of Filblingsee and Eibensee. The field parameters temperature, electrical conductivity, oxygen, and pH of springs and streams were measured using a WTW

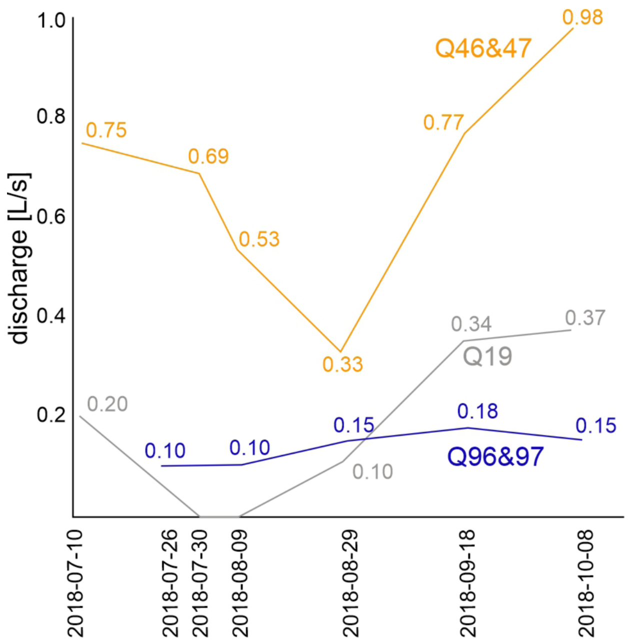

Figure 2: Discharge measurements at selected springs (in L/s) in the vicinity of Filblingsee indicate karst springs (Q46&47, Q19) and springs from fractured aquifers (Q96&97). The date of the measurements is plotted on the x-axis. See Figure 1c for the location of the springs.

Multiparameter instrument 350i. Stream discharge of the surface run-off of the Eibenseebach was measured at several positions by means of the salt dilution method using a Sommer TQ-Trace mobile instrument with two independent conductivity sensors. Discharge was measured once at each detected spring and repeatedly at the few permanently active springs in both catchments with the vessel-vs.-time method.

3.2 Lake surveying

The geometry of the lakes was recorded three-dimensionally. The lateral and vertical extent of the lakes was recorded along longitudinal, and transverse transects. For this purpose, the depth and physicochemical field parameters were sounded at numerous locations along the transects (Fig. 3) in both lakes from a boat using a 300 m tape and a SEBA KLL-Q2 electric contact meter equipped with a plummet on September 11th 2018, in Filblingsee and on September 12th 2018, in Eibensee, respectively. The water levels of the lakes were furthermore monitored continuously during and after a precipitation event between October 21st and November 21st 2018. Therefore, pressure probes (SEBA dipper PT) were installed in both lakes. Unfortunately, the data logger in Eibensee was lost and thus, the variations of water level can only be presented for Filblingsee.

3.3 Physicochemical field parameters and hydrochemistry

The physicochemical field parameters of the lakes were measured depth stepped (Filblingsee 1 m step, Eibensee 2 m steps) by using a SEBA multi parameter probe MPS

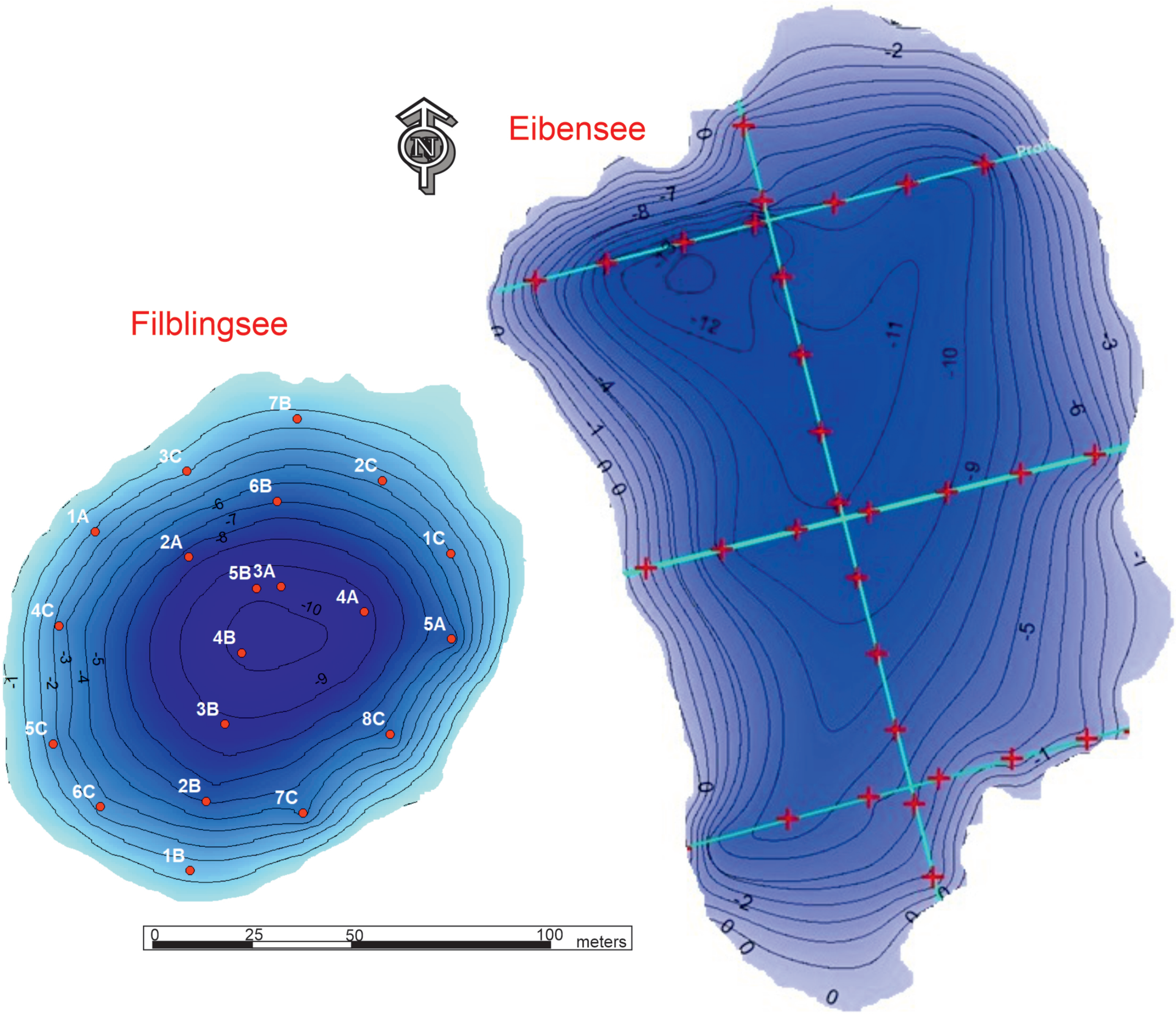

Figure 3: Geometry of Filblingsee with its nearly round shape and concentric depth profile and Eibensee, elongated in the direction of glacial flow with the deepest part at the northern edge. Red dots and crosses, respectively mark the transects and the position of the measuring points in the lakes.

D8 (equipped with sensors for pressure, temperature, electrical conductivity, pH, and oxygen) once in September 2018. Rodriguez-Rodriguez et al. (2018) showed that these parameters are expected to provide information on groundwater-surface water interaction in shallow lakes. In our study these data were also used to compare the hydrochemical characteristics of the two lakes.

Temperature, electrical conductivity, pH-values, and oxygen were also measured several times during the field campaign using a WTW 350i Multi parameter instrument at springs and streams in both catchments. Before each use, a two-point calibration of the pH-probe was conducted, and the oxygen probe was calibrated with an air calibration device. Water samples from springs, streams and the lakes were taken once between October 9th and 11th 2018 in the Filblingsee catchment and on November 1st 2018 in the Eibensee catchment. Samples were collected in new PE bottles, pre-rinsed three times with sample water. The samples were filtered directly in the field with a 0.45 µm membrane filter and partly (for cation analysis) acidified with HNO_3. The samples were analyzed in the Hydrogeology laboratory of the University of Salzburg. The parameters sulfate, nitrate, potassium and chloride and total hardness were measured with an Aqualytic Spectral Photometer AL800. Alkalinity, which is assumed to be equivalent to bicarbonate at circumneutral pH-values, was measured with an automatic titration device (TitroLine 5000) and 0.1 molar HCl. Sodium was measured with an ionoselective sensor pH/Ion 3310 by WTW. Calcium and magnesium contents were measured titrimetrically using the procedure after Merck (1980). Field parameters pH and electrical conductivity were cross-checked in the lab with an WTW inoLab 740. Hydrochemical data of all samples were processed in a Schoeller diagram using the software Aquachem by Waterloo Hydrologic.

3.4 Water balance

The water balance of Filblingsee was quantified for a single precipitation event and the subsequent dry period (recorded by the climate station Hintersee, station no. 103846, 727 m asl, (Land Salzburg, 2019)). For the water balance based on this single event precipitation (P_{lake}) and evaporation (E_{lake}) related to the lake area, surficial (Q_{sur}) and groundwater (Q_{gw}) in- and outflow and changes in water volume of the lake (ΔV) were considered. P_{lake} was derived from the climate station Hintersee. E_{lake} was calculated after Haude (1954) based on data from the climate station Salzburg Airport. Q_{sur} represents the sum of surficial flow (positive values = inflow, negative values = outflow). However, Q_{sur} can be widely neglected since no surfical flow or even signs for temporary in- and outflow was observed during the field campaign. ΔV was calculated from the lakes surface geometry and the water level data assuming that the lake´s area does not change significantly with the change in water level. This assumption seems plausible with respect to the steep shore zones of the lake. Finally, Q_{gw} as the sum of groundwater flow ($Q_{gw\ in} - Q_{gw\ out}$) is what we aimed to estimate.

This leads to the following equations (1) for surficial flow, (2) for groundwater flow and the combination of both in equation (3):

$$\Sigma Q_{sur} = P_{lake} + Q_{stream\_in} - Q_{stream\_out} - E_{lake} \quad (1)$$

$$\Sigma Q_{gw} = Q_{gw\_in} - Q_{gw\_out} \quad (2)$$

$$\Delta V = P_{lake} + Q_{stream\_in} + Q_{gw\_in} - Q_{stream\_out} - Q_{gw\_out} - E_{lake} \quad (3)$$

A similar procedure for determining ΣQ_{gw} was not possible for Eibensee because of the lost data logger.

4. Results

4.1 "Karst lake" Filblingsee

The Filblingsee catchment is built by lithologies of the Osterhorn Tyrolicum, which forms a NW-SE-striking syncline in the study area (Fig. 1c and 7a). Karstified limestones build up the Filbling summit as the highest elevation in the area. The center of the syncline is built by marls and marly limestones that can be characterized as aquitards. Parallel to the fold axis three fault zones cross the limb of the syncline. The Filblingsee fault which is directly connected to the lake separates karstified limestones on the SW side from fractured dolomites on the NE side. Thus, the NE edge of the lake is delineated by a fractured aquifer since karstification plays a subordinate role in this lithology (Hilberg and Schneider, 2011).

The Filblingsee study area is characterized by numerous small, mostly intermittent springs. Most of the spring outlets were dry or showed only very little discharge during the field campaign. However, the position of the springs, even the dry ones, helps to interpret the hydrogeological situation. In Figure 1c the mapped springs are documented. In total 148 springs were mapped. For a clear presentation, springs close to each other were displayed as spring group with only one point and only the further discussed springs are labeled. However, the hydrogeological map (Fig. 1c) shows that regarding the geological setting there are three areas in which springs occur condensed: (1) along the Filblingsee-fault, (2) within the debris covers of marls or marly limestone in the center of the syncline and (3) in or at the origin of the trenches within the dolomites. Main drainages to the S and W orginate in type (2) springs (Schmiedhornbach, Pillsteinbach, Schmiedbach, Baderbach) whereas the drainage systems to NE are bound to type (3) springs (Perfallbach und Hallbach).

Compared to the total amount of spring outlets very few permanently active springs with discharges of more than 0.2 L/s were found in the transition zone between karstified limestones and unkarstified marls (type 2) on the SW slope (Q46&47 and Q16&19) and along the fault between limestones and dolomite on the NE slope (type 1) (Q96&97, Q99). The discharge of these spring groups was measured five to six times between July 10th and October 18th 2018 (Fig. 2). The springs with the highest discharge can be found at the origin of the Schmiedhornbach (Q46&47). They also show the highest discharge variations between 0.33 L/s and 0.98 L/s. The springs at Pillsteinbach (Q19) show also strong variations with dry periods with no discharge and 0.37 L/s in maximum. These strongly fluctuating springs can be classified as karst related springs draining the limestone aquifer (Oberalmer Kalke). In contrast spring group Q96&97 has a low but stable discharge in the range of 0.1 to 0.2 L/s which is a clear indication that these springs drain the dolomitic fractured aquifer.

Only three and during the field campaign dry spring outlets were mapped in the orographic catchment of Filblingsee above the lake level. The lake is in the center of the hollow shape. High, steep embankments border it to NW, W and SW, an about 10 m high less steep elevation forms the border to NE where the fault zone penetrates the lake. However, no surficial outflow of the lake or evidence for direct surface near groundwater outflow to the following trench was observed. Thus, due to the results of the mapping, surficial flow (in and out) can be neglected for Filblingsee.

As shown in Fig. 3 Filblingsee has a nearly round lake area (110 m EW, 140 m NS-direction) and shows a fairly symmetrical concentric depth profile with the deepest sections in the center. In the deepest areas the lake has a water column of more than 10 m. In all directions, the bottom of the lake rises steeply with an average gradient of approximately 20 % (Fig. 3). This is the typical morphology of a swallow hole (Plan, 2016).

To investigate the hydraulic system of Filblingsee, especially to estimate the groundwater share in the

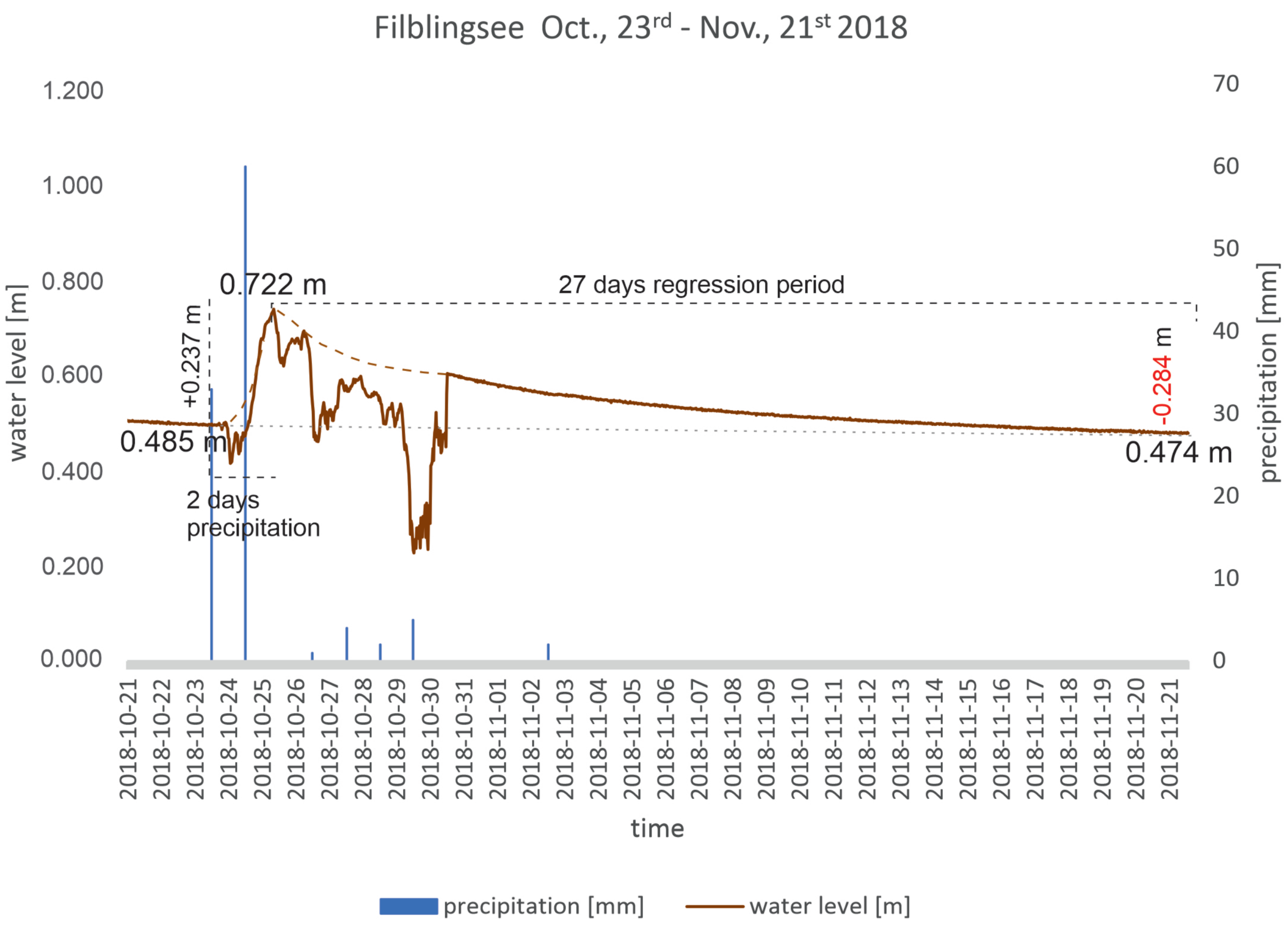

Figure 4: Lake level (in m) evolution during and after a rain event in October and November 2018. After two days of heavy rain with a precipitation amount of approximately 100 mm and a following dry period of 27 days the water level of the lake varies in the range of 0.28 m. Fluctuations in the lake level are probably due to a defect of the data logger, which was repaired on October 30th 2018.

system, the water level was continuously observed during a heavy rainfall event between October 23rd and 25th 2018 which was followed by a one-month almost dry period. The time series is shown in Fig. 4. Table 1 shows the calculation according to equation 3. Since no evidence for surficial runoff was found in the field, Q_{stream_out} is generally set to zero. On the other hand, there are signs of surficial inflow from temporally active trenches in the catchment. Thus, Q_{in} can only be determined as the sum of $Q_{stream\ in}$ and Q_{GWin}. Since these trenches were always found inactive during the dry periods $Q_{stream\ in}$ can be set to zero during the regression period. It is further assumed that evaporation is zero during the storm event. ΔV_1 (in Tab. 1) represents the precipitation event and thus, the sum of surface and groundwater inflow. ΔV_2 (in Tab. 1) in the dry period event represents the sum of groundwater inflow and groundwater outflow, i.e., the groundwater turnover which was the focus of the water budget calculations. The regression period shows that the basic groundwater turnover in the Filblingsee system is at least 1.4 L/s.

Water temperature, electrical conductivity, pH, and oxygen content of the lake water were detected every meter below water surface along two crossing transects A and B and around Filblingsee about ten meters from the shore (transect C) (transects shown in Fig. 3, for depth oriented median values see Fig. 5a-d). Each parameter shows a significant change in the depth of 5 m. Temperature decreases from 15°C at the surface to 7°C in 9 m depth with a moderate reduction between 0 and 5 m and a significant decrease between 5 and 9 m. Electrical conductivity and oxygen content are nearly stable between 0 and 5 m. Between 5 and 9 m conductivity increases from 200 µS/cm to 300 µS/cm in the deepest parts of the lake. The oxygen content is rapidly decreasing between 5 and 7 m from 10 mg/L to nearly zero. pH-values decrease from around 8.2 in the upper 5 m to circumneutral values between 6 m and the lake bottom. The development of the field parameters with depth is nearly symmetric over the lake, which implicates that there is a complete mixing of the lake water to the depth of 5 m while no appreciable flow movements take place below it. That also proofs that groundwater inflow and outflow are in the range of 5 m below water level. The depth profiles are symmetrical along the transects. There is no evidence for point like groundwater inflow or outflow.

		ΔV [m³]	P_{lake} [m³]	$Q_{stream\ in}$	Q_{GWin}	Q_{GWout}	$Q_{stream\ out}$ [m³]	E_{lake} [m³]
precipitation event	ΔV1 (23.-25.10.18)	2.844	1.116	Σ 1.728 m³ = 16.5 L/s		unknown	0	0
dry period	ΔV2 (26.10.-21.11.18)	3.408	168	0	**Σ3.236 m³ = 1.4 L/s**		0	340

Table 1: Estimation of the water balance of Filblingsee (Calculations based on: ΔV_1: lake area 12,000 m², precipitation 93 mm, 2 days, level increase 0.237 mm; ΔV2: lake area 12,000 m², precipitation 14 mm, 27 days, level decrease 0.284 mm).

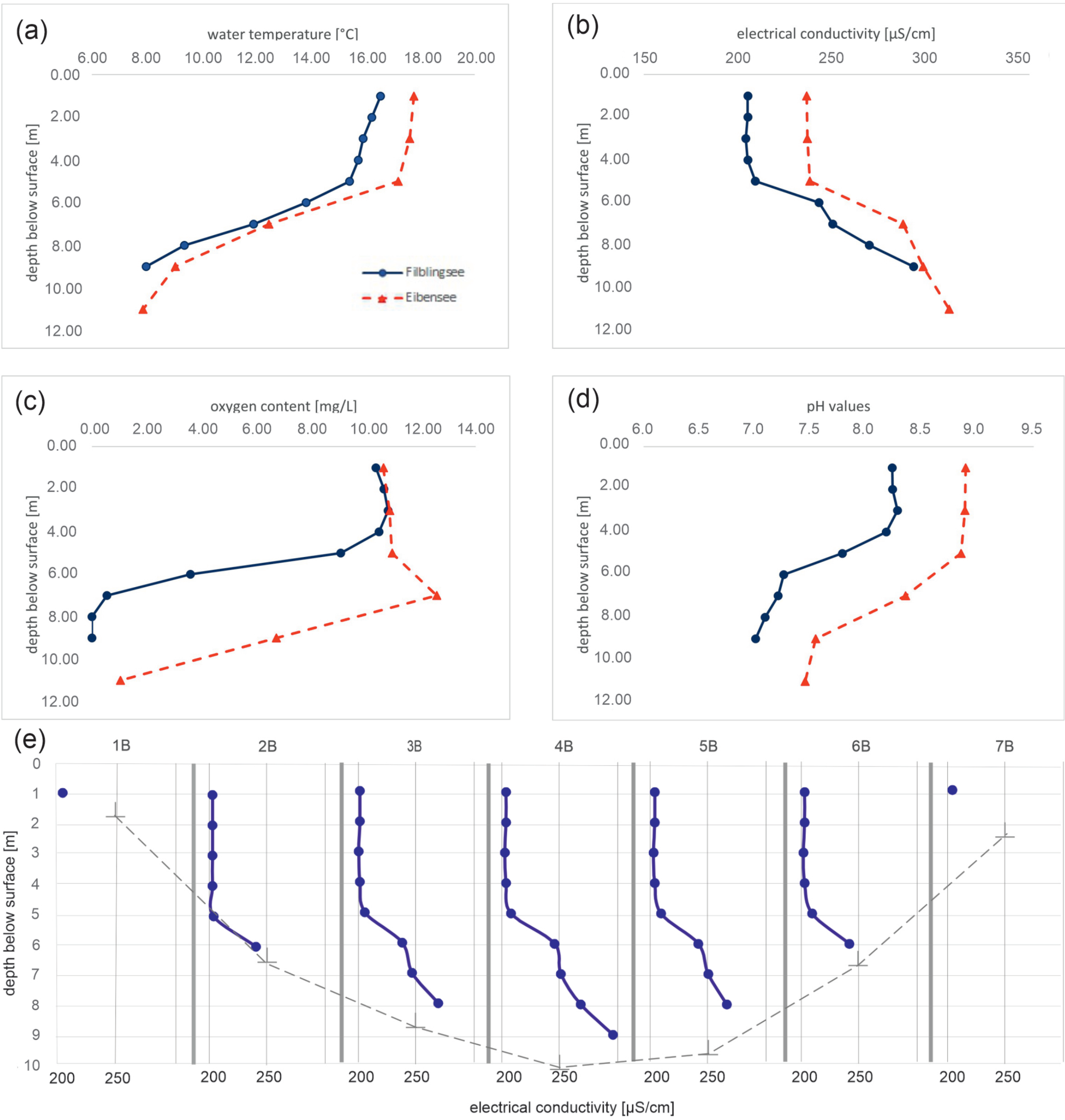

Figure 5: Depth profiles of physicochemical parameters in Filblingsee and Eibensee. (a) Temperature, (b) electrical conductivity, (c) oxygen content and (d) pH values. Blue dots (Filblingsee) and red triangles (Eibensee) represent median values of all measuring points along the transects (see Fig. 3). (e) The values and their development in depth are very uniform within the lakes, as the example of conductivity in Filblingsee transect B shows. The dashed line symbolizes the respective water depth at the measuring points and shows the symmetrical depth profile of Filblingsee.

sample	temp	cond.	pH	O_2 (Lab)	HCO_3	Ca	K	Na	Cl	SO_4	Mg	NO_3	ion balance error
	[°C]	[µS/cm]		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	[%]
Filblingsee	10.8	208	7.166	6.42	142	52.1	1.4	0.228	0.8	2.1	3.5	n.n.	5.23
Q16	9.8	382	8.152	7.43	253	84.2	2.6	0.827	3.5	3.1	4.9	n.n.	4.58
Q19	8.3	303	7.836	7.23	191	68.1	2.6	0.125	1.6	3.2	2.5	n.n.	3.50
Q46 & Q47	8.9	255	8.223	8.04	157	54.1	1.4	0.133	1.3	4.0	2.5	n.n.	0.79
Q61	8.0	344	7.089	6.82	218	68.1	1.6	0.631	3.5	2.1	4.9	n.n.	1.96
Q96 & Q97	6.7	267	7.343	7.86	166	60.1	1.5	0.365	1.6	2.5	4.5	6	-3.08
Q99	6.8	292	8.265	7.71	190	64.1	2.1	0.251	1.9	2.6	2.5	n.n.	0.75
Q111	9.5	297	8.205	9.76	184	68.1	2.3	0.298	1.8	5.2	3	5	-0.94
Q112	10.9	355	8.191	8.00	226	72.1	1.4	0.772	2.1	6.8	8.5	n.n.	5.86
Eibensee	9.7	239	8.04	5.98	169.02	32.08	2.2	0.151	0.9	2.4	12.65	4	-2.59
Q1	7.3	318	8.34	7.74	197.08	40.08	3.4	0.094	2	1	22.7	9	0.49
Q49	8.1	337	8.3	6.69	226.37	44.08	1.2	0.056	0.5	1	25.3	7	1.09
Q73	10.3	365	8.41	8.82	245	44.08	1.3	0.065	1.2	2.3	25.3	5	-1.62
Moor1	8.6	281	7.73	5.47	187.87	44.08	2	0.227	9.5	1	17.71	4	5.33
Moor2	8.4	395	7.86	7.06	255.05	48.09	2.7	0.114	8.4	4.4	25.3	7	-4.84
E1	10.6	413	8.16	7	266.64	52.1	3.3	0.102	1.9	5.6	27.83	9	-2.79
E2	9.6	350	8.36	8.01	233.7	52.1	1.7	0.091	14.1	2.1	22.7	4	2.93
E3	8.6	347	8.35	8.46	235.53	52.1	1.3	0.076	1.9	2.8	21.3	8	-0.38
E4	8.5	360	8.46	8.25	237.35	48.09	1.5	0.07	1.4	2.3	25.2	6	-1.09
E5	8.2	354	8.46	7.21	242.23	48.09	3.3	0.075	6.7	n.n.	22.7	8	-4.2
E6	8.2	363	8.05	6.66	240.4	48.09	1.9	0.094	8.5	2.7	21.6	6	-3.85

Table 2: Hydrochemistry of lakes, springs, and streams.

Seven springs or spring groups in the Filblingsee study area were sampled and analyzed for the main hydrochemical parameters. Additionally, the Filblingsee itself was sampled on its shore zone. Hydrochemical data are presented in Table 2. Figure 6a shows that the springs and the Filblingsee are of Ca-HCO_3 water type after Furtak and Languth (1967). Low Mg contents indicate that the dolomite aquifer on the NE side of the lake has no significant influence on the upper part of the water column, which was sampled here. In deeper areas, the higher electrical conductivities, which are very similar to those in Eibensee indicate that more highly mineralized waters are flowing in. An inflow from the dolomite aquifer in depth zone of 5 to 6 m therefore seems likely. However, springs on the NE slope (Q96&97, Q99) also show no dolomite characteristics, suggesting that their catchments are SW of the Filblingsee fault. When comparing the Filblingsee sample to the composition of the springs, all springs that could potentially represent a lake discharge are higher in mineralization. This can be attributed to the fact that sampling in the uppermost part of the lake´s water column does not represent the water composition of the groundwater discharge from the lake, since this occurs at a depth of 5 to 6 m from the more highly mineralized area.

4.2 "Glacial lake" Eibensee

The Eibensee catchment is located within the Tyrolean nappe system and is dominated by the upper Triassic Hauptdolomit formation (Fig. 1d). In the area, Raibler layers and limestones of the Wetterstein limestone formation can be found subordinately. On the SW edge of the study area the NW-SE striking Wolfgangsee fault is present but does not penetrate the Eibensee catchment. The main fracture directions within the dolomite are N-S-oriented, but subordinate are also NW-SE and NE-SW oriented fissures. On the S, N and E side the lake is surrounded by dolomites. Only the NW edge is delineated by a moraine dam. Thus, Eibensee can be characterized as a glacial lake.

In the Eibensee catchment springs are bound to fissures within dolomite and emerge mainly in morphological depressions and trenches. Since karstification is a subordinate process in dolomites and no appreciable epikarst structures were found in the catchment the surrounding of Eibensee can be characterized as a fractured aquifer. As it is typical for the closely fractured dolomite (Pfleiderer et al., 2006) numerous small and randomly distributed springs characterize the catchment. In total 69 springs or spring groups were mapped in the entire study area. During the field campaign only three springs were permanently active (Q1, Q49 and Q73), only they are labeled in Figure 1d with discharge values in the range of 0.2 L/s in maximum. 14 spring outlets were found on a position topographically in the lake´s catchment. They could potentially form stream inflow to the lake. However, only 6 (incl. Q1) were partially active with maximum discharge in the range of less than 0.2 L/s during the field campaign. An important hydrological element is a marshland area, about 50 meters in altitude below the lake. It forms the origin of the main drainage channel, the Eibenseebach. A hollow in the damming moraine on the N side of the lake forms a potential overflow into this moor, but this was never found active during the field campaign. The trench between lake and moor can be classified as a wetting zone that implies a

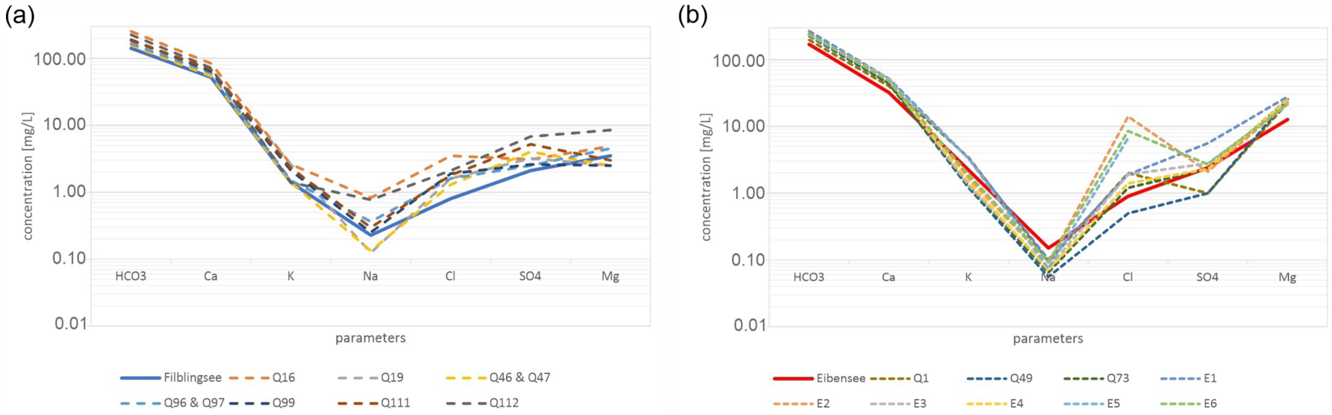

Figure 6: Water chemistry of the lakes, springs and streams of (a) Filblingsee and (b) Eibensee, indicating Ca-HCO_3 and Ca-Mg-HCO_3 water types, respectively. Elevated chloride concentrations in E4, 5, and 6 are likely due to the adjacent forest road and diffuse inputs of road salt to the stream.

near surface flow from the lake to the moor also in dry periods. Thus, lake Eibensee also has only temporal surficial inflow, no permanent surficial outflow but obviously perennial surface near outflow from the lake to the moor. To quantify the base flow of the Eibensee catchment the discharge of Eibenseebach was measured after a three-week dry period in October 2018 six times along the stream. In the upper section of the stream, the numerous small spring outlets dope the stream and cause it to rise from 3 L/s at the marshland outflow to 7 L/s. In the lower section of the stream, the discharge then decreases significantly, and the stream dries up completely (shown as effluent and influent sections of the creek in Figure 1d).

Eibensee (Fig. 3) has an elongated area with 220 m in N-S and 145 m in E-W direction. The deepest section is in the northern most part of the lake with more the 13 m, while the major part has a maximum depth of 11 m. The northern and western slopes are with 26% rather steep. The southern and eastern slopes are with 11% comparably flat (Fig. 3). A wetting zone S of the lake and the very flat southern shore indicate silting processes due to sediment supply from the south side. On the northern edge a moraine dams the lake. Here is the lowest point of the shore zone, which potentially forms a lake overflow.

A comparative consideration of the water balance, as it was carried out for the Filblingsee, can unfortunately not be presented for Eibensee due to the lost data logger. However, some qualitative statements about the water budget are possible. From the hydrogeological mapping it is known that several springs in the catchment of the lake are temporally active and provide an unknown amount of stream inflow ($Q_{stream\ in}$). Only one spring with a maximum discharge of 0.2 L/s was detected during the field work. In times of high water level there is surficial outflow to the northern adjacent moor area. Wet zones in the ditch underneath the overflow indicate that in times of low lake levels a near-surface runoff through the moraine takes place and, in this way, the adjacent moor area is doped. The baseflow of the moor area was measured during the dry period in November 2018 at the measuring point E1 (Fig. 1d). The lowest discharge quantities with 3 L/s were detected on Nov. 22nd 2018. Assuming that near surface runoff to the moor is the only groundwater outflow from the lake means that the basic groundwater turnover in Eibensee is approximately 3 L/s. Compared to the observed stream inflow, outflow is more than ten times higher, which is strong evidence for significant groundwater inflow to Eibensee.

Depth oriented measurements of field parameters temperature (Fig. 5a), electrical conductivity (Fig. 5b), oxygen content (Fig. 5c), and pH (Fig. 5d) were also conducted in Eibensee to localize potential groundwater inflow zones. Here we found constant values of all parameters between surface and 6 m in depth. Below 6 m a significant change in the physicochemical parameters was detected in each measurement point along the transects. Temperature decreases from 18°C to 10°C, conductivity increases from about 230 µS/cm to nearly 300 µS/cm, oxygen content shows a remarkable increase between 6 and 8 m from 10 to 12 mg/L, followed by a rapid decrease to nearly zero at the lake bottom, rather high pH values of 9 in the upper part of the water column decrease to 7.5 between 6 and 8 m depth. As observed in Filblingsee the development of the field parameters with depth is very uniform over the lake without any evidence for point like groundwater inflow or outflow. The tipping point for the water quality change implicates a complete mixing of the lake water to the depth of 6 m while no appreciable flow movements take place below it. Water temperature and electrical conductivity are slightly higher than those of Filblingsee which is due to the 150 m lower altitude and the dolomitic catchment regime, respectively.

In the Eibensee region the lake, three springs (Q1, Q49 and Q73), the moor outflow (E1) and the main drainage Eibenseebach (E2 to E6) were sampled and analyzed (Tab. 2 and Fig. 6b). To find out differences between lake and moor outflow and groundwater outflow from the dolomite aquifer the Eibenseebach was sampled 6 times along the flow path. For sampling points see Figure 1d. The analyzed waters are of Ca-Mg-HCO_3 type regarding to Furtak and Langguth (1967) which reflects the dolomitic catchment. As Filblingsee, Eibensee has, in comparison to springs and streams in the catchment, the lowest total mineralization and the lowest contents of the main parameters Ca, Mg, and HCO_3. The springs that are located above the lake level also have higher total concentrations which confirms that they drain the fractured aquifer after a significant residence time. E1 as direct outflow from the moor shows the highest total mineralization while the stream water in the further course of the stream is in turn diluted by tributaries. Elevated chloride concentrations in E4, 5, and 6 are likely due to the adjacent forest road and diffuse inputs of salt to the stream.

5. Interpretation and Discussion

5.1 "Karst lake" Filblingsee

Filblingsee is located in a karst hollow reaching to the Filbling summit within Oberalm limestones. It is bordered on its NE side by a fault zone and bounded by a dolomitic rock dam that is much lower than the surrounding area. A few intermittent springs emerge in the catchment area and feed the lake for a short time during periods of heavy precipitation or high karst water levels. However, no overflow is activated even during flood events. There is no evidence of temporary surface runoff from the lake. The lake has an approximately round surface and exhibits a nearly concentric depth profile with a 20% steep slope to the maximum depth of about 10.5 m in the center of the lake. Therefore, the geometry of the lake implicates that it is a doline. However, fieldwork conducted during a dry period revealed numerous mostly inactive springs in all directions well below the lake water table. Springs indicate the position where groundwater leaves the subsurface driven by the position of the groundwater table in relation to the land surface (Toth et al., 2022), especially in karst regimes. Thus, it can be inferred that the lake cannot be directly related to a contiguous karst water table. This is also supported by the relatively slow and low response of the lake level to heavy precipitation and dry periods, as shown by the continuous observation of a rain event.

Depth-oriented measurements of the physicochemical parameters temperature, electrical conductivity, oxygen content, and pH show that inflow and outflow do not occur selectively, but apparently at numerous points in the lake at a maximum depth of 5 m to 6 m, and thus in the upper part there is good mixing of water inflowing from the fractured aquifer or from the vadose to epiphreatic zone of the karst aquifer. Oxygen-free conditions under a depth of 7 m prove that the deeper areas are not flowed through and that the outflow does not occur at the lake bottom, as would be expected in a doline (e.g. Ravbar et al., 2021). The hydrochemical composition of the lake water indicates an inflow from the limestones. Low Mg-contents, even compared to those of Eibensee, rule out an inflow from the adjacent dolomite. However, since the deeper sections of the lake were not sampled, this assumption needs to be proved in a follow-up study with depth-oriented sampling.

The topographic depression of Filblingsee is the result of an exokarst process by which, starting from the Filblingsee fault, an extensive doline was created within the karstable Oberalm limestones. However, the originally open flowpaths at the bottom of the doline were then apparently secondarily sealed. Sealing of a doline may be caused by fine grained sediments or, as described by Biondic´ et al. (2010) by tufa. In Filblingsee the cause of this sealing can be assumed to be the proximity to the fault zone, its potential barrier effect (Caine et al., 1996) and fine-grained material from the fault zone. That the fault zone in this specific case acts as a hydraulic barrier can be clearly inferred from the numerous small spring outlets occurring along the fault (Fig. 1c). Inflow and outflow therefore take place in higher vadose karst areas, whereby outflow can occur both along karst structures in the limestone and along the fault zone in the transition area between limestones and dolomite. Based on hydrochemical characteristics inflow seems to come exclusively from the Oberalm limestones from SW to SE. However, significantly higher electrical conductivity in the deeper parts of the water column indicate a dolomitic influence. The low minimum flow rate of 1.4 L/s, which can be derived from dry weather observations, shows that it is a lowly permeable system, resulting in a lake level that is unusually stable for the karst environment. A conceptual model of Filblingsee is given in Figure 7a.

5.2 "Glacial lake" Eibensee

Eibensee occupies a total area about twice as large as that of Filblingsee, but the maximum depth with 13 m is only slightly larger, with the deepest areas near the north shore, i.e., in the outflow area. This corresponds to the process of excavation of a glacial basin. Its catchment area is dominated by dolomitic rocks. As shown in Figure 7b the lake is dammed on its northern side by a moraine, which temporarily represents the overflow and thus a surface runoff. Despite the lack of permanent surface inflow, a siltation zone lies on the south side, suggesting temporarily productive stream inflow. As expected Eibensee exhibits water chemistry typical for dolomites. Depth-graded measurements of temperature, electrical conductivity, pH, and oxygen show common summer to fall stratification typical of a lake fed by surface water and near-surface groundwater. The base flow measured at the main drainage system Eibenseebach is at least 3 L/s, which is much more than the surface inflow observed during the field campaign. This is an indication for a significant amount of groundwater inflow. Thus, Eibensee is a further example for the significant share of groundwater on the hydrological system of a glacial lake which is to date widely neglected (e.g. Chen et al., 2010).

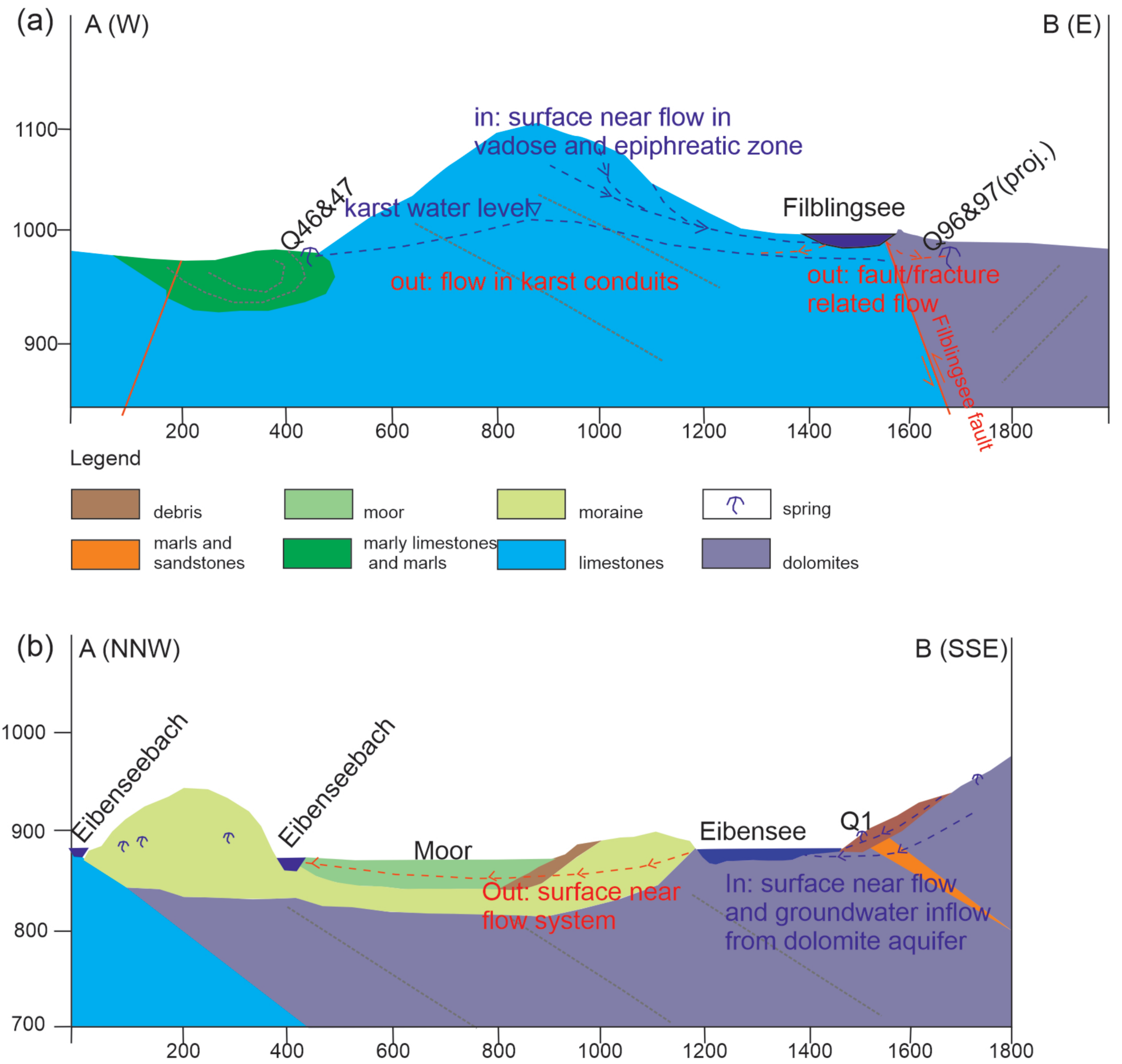

Figure 7: Hydrogeological conceptual models of (a) Filblingsee and (b) Eibensee. The position of the profile lines can be seen in Figure 1. Both profiles are twofold exaggerated. It shows that Filblingsee is a hanging lake with inflows from the vadose zone of the karstified catchment and a diffuse outflow via karst conduits and along the fault zone. Eibensee, on the other hand, is fed by near-surface tributaries from the dolomitic fractured aquifer and drains via surface runoff into the underlying marshland.

6. Conclusions

The study shows that the common basic characterization of karst lakes and glacial lakes requires differentiation. With the two lakes presented here it was shown that karst lakes, such as Filblingsee, do not necessarily have to be directly connected to a well permeable karst aquifer and that, on the other hand, the hydraulic system of a glacial lake can be considerably influenced by groundwater. Since both lakes show very similar hydrochemical and hydrodynamic properties despite completely different genesis, among the aspects considered in this study, only lake geometry has clearly proven suitable as a guiding parameter for large scale study to classify small alpine lakes.

However, the study leaves numerous specific questions around both lakes unanswered, which are to be clarified in a follow-up project. For example, the actual discharge areas need to be identified by means of tracer experiments and a detailed hydrochemical characterization of the lake water column. A continuous observation of the lake level over a hydrological year in combination with climate observations and continuous observations at selected springs and thus, the consideration of seasonal variations can also support the description and quantification of the hydrogeological system in detail.

The general question arises as to whether the compared lakes are special cases or whether others of the numerous small lakes near the summits in the NCA are traceable to a similar geological setting, thus justifying the introduction of additional types of alpine lakes or at least a more detailed differentiation within existing classifications. In any case a more detailed examination of the widely distributed small lakes within the NCA is required. Our study showed that a comprehensive investigation of alpine lakes, primarily based on the guiding parameter lake geometry (possibly extended by additional hydrogeological-hydrochemical parameters) can contribute to an improved classification of alpine lakes.

Acknowledgements
The authors would like to thank the Austrian Federal Forests for permission and support during field work in the Filblingsee area. Many thanks to Steffen Birk, Dorothee Hippler, and Kurt Stüwe for their valuable recommendations which helped a lot to improve this manuscript.

References

Argentin A-L., Robl, J., Prasicek, G., Hergarten, S., Hölbling D., Abad, L., Dabiri, Z., 2021. Controls on the formation and size of potential landslide dams and dammed lakes in the Austrian Alps. Natural Hazards Earth System Science, 21, pp. 1615-1637. https://doi.org/10.5194/nhess-21-1615-2021

Bartels, A., Berninger U.-G., Hohenberger, F., Wickham, S., Petermann, J.S., (2021) Littoral macroinvertebrate communities of alpine lakes along an elevational gradient (Hohe Tauern National Park, Austria). PLoS ONE 16:e0255619

Biondic´, B., Biondic´R., Measki H., 2010. The conceptual hydrogeological model of the Plitvice lakes. Geologia Croatica, 63/2, pp. 195-206. https://doi.org/104154/gc.2010.17

Buckel, J., Otto, J.C., Prasicek, G., Keuschnig, M., 2018. Glacial lakes in Austria – Distribution and formation since the Little Ice Age. Global and Planetary Change, 164, pp. 39-51. https://doi.org/10.1016/j.gloplacha.2018.03-003

Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. Geology (Boulder) 24, pp. 1025–1028.

Chen, Y.N., Xu, C.C., Chen, Y.P., 2010. Response of glazial-lakes outburst floods to climate change in the Yarkant River basin on northern slope of Karakorum Mountains, China. Quarternary International. 226 (1/2), pp. 75-81.

Egger, H., van Husen, D., 2003. Geologische Karte der Republik Österreich, Blatt 64 Strasswalchen. Geologische Bundesanstalt, Wien.

Emmer, A., 2018. GLOFs in the WOS: bibliometrics, geographies and global trends of research on glacial lakes outburst floods (Web of Science, 1979-2016). Natural Hazards Earth System Science, 13, pp. 813-827. https://doi.org/10.5194/nhess-18-813-2018

Emmer, A., Curin, V., 2021. Can a dam type of an alpine lake be derived from lake geometry? A negative result. Journal of Mountain Science. 18/3, pp. 614-621. https://doi.org/10.1007/s11629-020-6003-9

Fürlinger, F., 2019. Hydrogeologische Konzeptstudie im Einzugsgebiet eines Bergsees am Rande der Nördlichen Kalkalpen. Unpublished Masterthesis, Paris Lodron University of Salzburg, 67 pp.

Furtak, H., Langguth, H-R., 1967. Zur hydrochemischen Kennzeichnung von Grundwässern und Grundwassertypen mittels Kennzahlen. Mem. IAH Kongress, 7, pp. 89-96.

Gurrieri, J.T., Furniss, G., 2004. Estimation of groundwater exchange in alpine lakes using non-steady mass-balance methods. Journal of Hydrology, 297, pp. 187-208. https://doi.org/10.1016/jhydrol.2004.04.021.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M., 2014. Karst water resources in a changing world: Review of hydrological modelling approaches. Review of Geophysics. 52, pp. 218-242. https://doi.org/10.1002/2013RG000443

Haude, W., 1954. Zur praktischen Bestimmung der aktuellen und potentiellen Evaporation und Evapotranspiration. Mitteilungen des Deutschen Wetterdienstes, Bad Kissingen, 8 pp.

Hilberg, S., Schneider, J.F., 2011. The Aquifer Characteristics of the Dolomite Formation – a new Approach for providing Drinking Water in the Northern Calcareous Alps Region in Germany and Austria. Water Resource Management, 25, pp. 2705-2729. https://doi.org/10.1007/s11269-011-9834-x

Hood, J.L, Roy, J.W., Hayashi, M., 2006. Importance of groundwater in the water balance of an alpine headwater lake. Geophysical Research Letters, 33, L13405, https://doi.org/10.1029/2006GL026611

Husen van, D., 1989. Geologische Karte der Republik Österreich, Blatt 65 Mondsee. Geologische Bundesanstalt, Wien.

Land Salzburg, Hydrographischer Dienst, 2019. Meteorologie Station Hintersee/Almbach, No. 103846. https://www.salzburg.gv.at/wasser/hydro/#/Meteorologie?station=103846 (accessed on 14. July 2022)

Merck, 1980. Komplexometrische Bestimmungsmethoden mit Titriplex. Reagenzien Merck, 3. Auflage.

Mergili, M., Schneider J.F., 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Natural Hazards Earth System Science, 11, pp. 1447-1462. https://doi.org/10.5194/nhess-11-1447-2011

Milanovic, P., 2021. Dams and reservoirs in karst? Keep away or accept the challenges. Hydrogeology Journal, 29, pp. 89-100. https://doi.org/10.1007/s10040-020-02273-0

Pestal, G., Hejl, E., Braunstingl, R., Schuster, R., 2009 Geologische Karte von Salzburg 1:200.000, Erläuterungen. Geologische Bundesanstalt, Wien.

Pfleiderer, S., Klein, P., Reitner, H., Heinrich, M., 2006. The Hydrogeology in the Northern Calcareous Alps between the Rivers Enns and Ybbs. Austrian Journal of Earth Sciences, 99, pp. 4-10.

Plan, L (2016): Oberflächenkarstformen. In: Spötl, Ch., Plan, L. Christian E. (Hrsg.) Karst und Höhlen in Österreich. -Linz Oberösterreichisches Landesmuseum, pp. 11-22.

Qin, D.H., Yao, T.D., Ding, Y.J., 2016. Glossary of Cryosphere Science. Beijing: China Metropol Press.

Ravbar, N., Mayaud, C., Blatnik. M., Petric, M., 2021. Determination of inundation areas within karst poljes and intermittent lakes for the purposes of ephemeral flood mapping. Hydrogeology Journal, 29, pp. 213-218. https://doi.org/10.1007/s10040-020-02268-x

Rodriguez-Rodriguez, M., Fernández-Ayuso, A., Hayashi, M., Moral, F., 2018. Using water temperature, electrical conductivity, and pH to characterize surface – groundwater relations in a shallow ponds system (Doñana National Park, SW Spain). Water, 10, 1406. https://doi.org/10.3390/w10101406

Roy, J.W., Hayashi, M., 2008. Groundwater exchange with two small alpine lakes in the Canadian Rockies. Hydrological Processes, 22, pp. 2838-2846. https://doi.org/10.1002/hyp.6995

Sändler, F., 2019. Filblingsee – Entwicklung eines konzeptionellen hydrogeologischen Modells. Unpublished Masterthesis, Paris Lodron University Salzburg, 94 pp.

Senetra, A., Dynowski, P., Cieslak, I., Zrobek-Sokolnik, A., 2020. An Evaluation of the Impact of Hiking Tourism on the Ecological Status of Alpine Lakes – A Case Study of the valley of Dolina Pieciu Stawow Polskich in the Tatra Mountains. Sustainability, 12, 2963. https://doi.org/10.3390/su12072963

Toth, A., Kovacs, S., Kovacs, J., Madl-Szonyi, J., 2022. Springs regarded as hydraulic features and interpreted in the context of basin-scale groundwater-flow. Journal of Hydrology, 610, 127907. https://doi.org/10.1016/jhydrol2022.127907

Vrsalovic A., Andric, I., Bzjak, N., Bonacci, O., 2022. Karst Lake´s Dynamics Analysis as a Tool for Aquifer Characterization at Field scale, Example of Cryptodepression – Red lake in Croatia. Water, 14, 830. https://doi.org/10.3390/w14050830

Winter T.C., 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal, 7, pp. 28-45.

Yao, X., Liu, S., Han, L., Sun, M., Zhao, L., 2018. Definition and classification system of glacial lake for inventory and hazards study. Journal of Geographical Science, 28(2), pp. 193-205. https://doi.org/10.1007/s11442-018-01467-z

Received: 23.8.2022
Accepted: 13.12.2022
Editorial Handling: Kurt Stüwe