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# Statistical analysis of karst springs in Lower Austria

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## Abstract

Karst springs play a central role in Austria's water supply. This paper aims to provide an overview of the karst springs of Lower Austria, analysing statistical correlations of spatial distribution, discharge, electrical conductivity (EC), and temperature. As part of a project with the provincial government of Lower Austria, older data from numerous studies have been combined with the self-generated data in a GIS database. This database contains data on 2056 karst springs. Most of the recorded springs are located in the Northern Calcareous Alps, although karst springs also occur in the Central Alpine Permomesozoic, the Waschberg zone and the Bohemian Massif, some of which are also of regional importance for drinking water supply. Chemical analyses show that limestone, dolomite and mixed springs are widespread in Lower Austria and occur with similar frequency. Gypsum springs, which are characterised by a significantly higher total mineralisation, are also of regional importance. The statistical analysis shows that spring water temperatures correlate well with the mean annual air temperature at the mean catchment elevation. The temperature decrease with increasing elevation corresponds to the air temperature gradient in the Eastern Alps (0.47 °C/100 m). In addition, the springs show a negative correlation of the EC with the mean catchment elevation, which can be explained by a decrease in soil cover and thus reduced $CO_2$ uptake of the water, as well as dilution by rainwater. This leads to less carbonate dissolution, which is also reflected in less $HCO_3^-$ contents. Corrected for the elevation effect, the investigated dolomite springs, have on average a 2.7% higher EC than limestone springs. A difference was also found between the Hauptdolomit and the Wettersteindolomit rock types, which are widespread in Lower Austria, with the latter displaying higher values on average by 2.2%. This indicates longer residence times of the spring water due to less karstification of the Wettersteindolomit.

## 1. Introduction

Karst springs are essential sources of drinking water in Austria, where about half of the population is supplied with karst water, including major cities such as Salzburg, Graz and Innsbruck (Benischke et al., 2016). For the capital Vienna, Europe's largest karst water supply system provides high quality drinking water for almost 2 million people from several springs at the foot of karst massifs in Styria and Lower Austria (Stevanovic, 2019). Due to the great importance of karst water resources, knowledge about the distribution, characteristics and the catchment of karst springs is not only important for researchers, but also for authorities and water providers in Austria.

Within the project "Digital Karst Morphological Map of Lower Austria" (NÖ-Karst) a comprehensive GIS-based dataset of karst phenomena was provided for the Federal Government of Lower Austria (Plan et al., 2019). Also, karst springs were in the scope of the project. A characterisation of the most important springs including the analysis of long-term data series is published in Schmalfuss et al. (2021). The core of the hydrological aspect of the project is a database containing information on location, discharge, electrical conductivity (EC), water temperature, and hydrochemistry was compiled from pre-existing as well as newly mapped data. The aim of this paper is to present an analysis of this dataset. The regional distribution of karst springs in Lower Austria is considered as well as their hydrochemical classification. Geostatistics are used to show a dependence of the water temperature and EC on the mean catchment elevation of the spring. Furthermore, an attempt is made to find statistical deviations of temperature and EC for major karst lithologies.

## 2. Definition of the term "karst spring"

An exact delimitation of the term karst spring is not trivial and contradictory definitions can be found in the literature. First, we look at both parts of the term. (1) For karst, the most common definition refers to a landscape with characteristic subsurface drainage and landforms (e.g. caves, dolines, ponors) resulting from a high solubility of the rock and a well-developed secondary porosity (Ford and Williams, 2007). (2) A spring is defined as "spatially limited, natural outlet of underground water", in Austria (ÖNORM B 2400, 2015, p. 28).

However, the combination of these two definitions is problematic in several aspects, since springs in karst areas, for example, do not necessarily carry karst water. Furthermore, springs in areas with predominantly crystalline rocks may also have been formed by dissolution of carbonate fissure fillings and thus be classified as karst springs (Benischke et al., 2016). According to Bögli (1980), karst springs are water seeps from karst hydrologically active cavities in water-soluble rocks, both on the earth's surface and underground. This definition also includes cave springs, which are not considered by many other definitions. Parameters such as ionic content, temperature, or flow characteristics can serve as indicators for karst springs, but they are not unique features and therefore not useful for a definition of the term (Bögli, 1980). High discharge variations can be observed in many karst springs, but are not limited to them. The defining element is rather the origin of the water from cavities created by rock dissolution.

In general, a spring in the field can only be clearly identified as a karst spring if the spring outlet is recognisable as a karst cavity. Dolomite rocks are characterised more by narrow fractures than by larger karst cavities. However, it is difficult to distinguish between springs from fractured, non-karstified but karstifiable rocks and springs from karstified rocks, as there is no clearly defined boundary (Benischke et al., 2016). In this study, the definition was interpreted generously in such borderline cases. Springs from karstifiable rocks whose degree of mineralisation indicates significant solution processes were classified as karst springs.

## 3. Study area

With an area of 19 186 km², Lower Austria is the largest federal state of Austria. The area comprises all major geological units of the Eastern Alps as well as the southern Bohemian Massif. The vast majority of karst areas is located in the Northern Calcareous Alps (NCA). The most widespread lithostratigraphic units are Triassic carbonates such as Hauptdolomit, Wettersteindolomit and -kalk, Dachsteinkalk and Gutensteiner Kalk. The tectonically higher nappes in the south of Lower Austria are characterised by large karst plateaus mainly consisting of Dachstein- and Wettersteinkalk (e.g., Dürrenstein, Schneeberg) while the lower units are lithologically more diverse and mostly dominated by dolomites (Wessely, 2006). Figure 1 shows the distribution of carbonate rocks, which constitute by far the largest part of the karst areas. Outside of the NCA, karstified metamorphic carbonates can be found in the Central Alpine Permo-Mesozoic and the Bohemian Massif. Mesozoic limestones of the Waschberg Zone and various Neogene sediments of the Vienna Basin should also be mentioned as karst rocks of local significance (Schubert, 2006).

Evaporite karst is a regionally important phenomenon in Lower Austria, mainly in the NCA, with the gypsum-bearing Haselgebirge and the Werfen Formation (which are often hard to distinguish), as well as the Opponitzer Rauhwacke. In some areas, these deposits can present serious geotechnical challenges due to their high solubility (Grösel, 2018). Large rock salt occurrences in the Haselgebirge, similar to the economically important deposits of the Salzkammergut area (central NCA), are absent in Lower Austria. Only one brine spring, "Salzerbad" northeast of Kleinzell, is known and used for balneological purposes (Elster et al., 2018). According to calculations by Chauveau (2021) 12% of Lower Austria are built up of karst rocks.

The climatic conditions in the Lower Austrian parts of the NCA show great variability, with mean annual precipitation ranging from around 600 mm at the edge of the Vienna Basin to over 1800 mm in the more mountainous southwest, where a significant part of the precipitation falls as snow. Average annual temperatures range from 10 to 0 °C, with extremes of -25 °C in winter and 40 °C in summer (ZAMG, 2022).

## 4. Materials and Methods

### 4.1 Data collection

A comprehensive GIS database of karst springs in Lower Austria was compiled from literature data and complemented by field measurements conducted during the NÖ-Karst project, which focused on areas with sparse pre-existing data coverage (see Supplemental Material for a table summarizing this dataset). Chemical data (concentrations of $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $HCO^{3-}$, $SO_4^{2-}$, $Cl^{-}$) were available for 716 out of 2056 total springs. For springs with multiple measurements or data series, mean values of the parameters were calculated. Table 1 gives an overview of the data sources. 3D-positions of the springs were determined from a 1 x 1 m airborne laser scan derived digital elevation model (ALS-DEM) in combination with handheld GPS and sometimes aerial photographs. On the basis of a digital geological map at the scale of 1:50 000 (NÖ Landesregierung, Geologischer Dienst, 2013) each spring was manually assigned a 'main lithology', which is assumed to be the predominant lithology in the catchment area.

In the field, EC and temperature were measured using regularly calibrated PCE-PHD-1 and Myron Ultrapen PT2 devices. EC was automatically corrected to 25 °C. Discharge of major springs was determined using either the

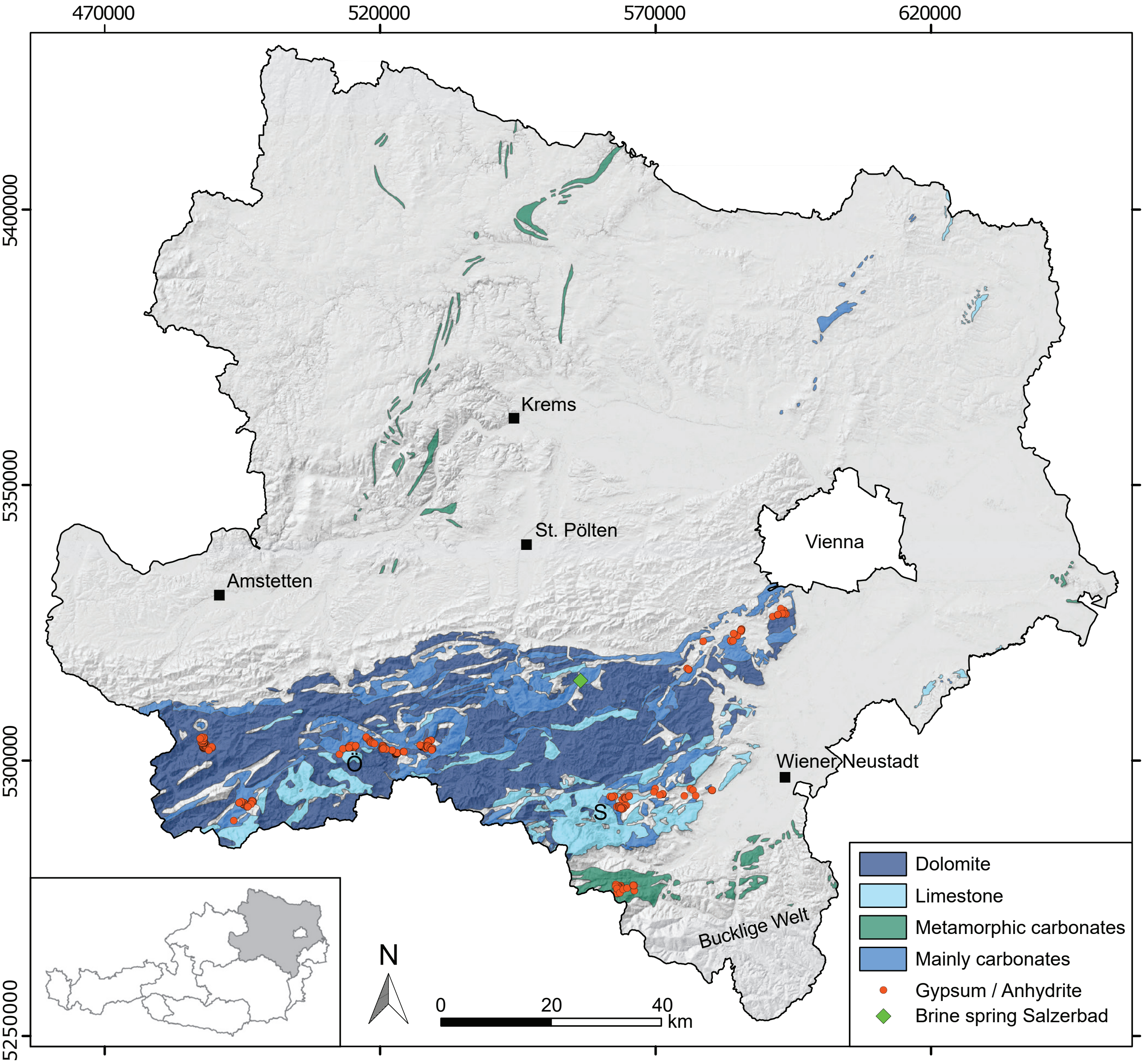

**Figure 1:** Distribution of karst rocks in Lower Austria (modified after Schubert, 2003; gypsum/anhydrite locations from Winkler, 2019; topographic data: courtesy Government of Lower Austria; coordinates: UTM 33N). Insert: Location of Lower Austria within Austria.

salt dilution or the bucket-and-stop-watch method while for many springs only an estimated value was used.

Water samples were taken from 63 selected springs. These were of particular interest due to their geological setting, high discharge, or unusual EC or temperature values. Concentrations of $Ca^{2+}$ and $Mg^{2+}$ were determined using complexometric titration (Merck, 1973). The $Na^{+}$ concentrations were measured with an ion-selective electrode. $HCO_3^-$ concentrations were determined using an acidimetric titration with hydrochloric acid (HCl). $SO_4^{2-}$ concentrations were calculated from the ion-balance under the assumption that other ions can be neglected. A major presence of $Cl^-$ was considered unlikely as $Na^+$ measurements did not indicate significant contributions from rock salt dissolution. Therefore, the calculated $SO_4^{2-}$ concentrations are likely to be only slight overestimates.

### 4.2 Estimation of mean catchment elevation

An attempt was made to determine an estimated value for the mean catchment elevation (MCE) for each spring. For this purpose, the assumption was made that this value is a function of the elevation of the spring outlet ($Z$), the maximum elevation in the catchment ($Z_{max}$), and a constant K whereby the following relationship applies:

$$MCE = Z + (Z_{max} - Z) \cdot K \qquad (1)$$

| **Data source and Project name** | **number of springs** |
|---|---|
| Plan et al. (2019): field mapping during the NÖ-Karst project | 923 |
| Pfleiderer et al. (2005): Hydrogeologische Grundlagen in den Kalkvoralpen im SW Niederösterreichs | 375 |
| Hacker and Spendlingwimmer (1989): Hydrogeologie im Einzugsgebiet der Erlauf und des Ötschers: Detailprojekt 1983 | 274 |
| Beyer (2008): Karsthydrogeologische Untersuchungen im oberen Erlauf- und Salzagebiet, Niederösterreich. | 117 |
| Haseke (2014): Wildnis Dürrenstein: Projektbericht Quellaufnahme 2013 | 90 |
| Verband Österr. Höhlenforscher (2022): Karstverbreitungs- und Karstgefährdungskarten Österreichs - Blätter 61, 70, 72, 73, 4329 | 71 |
| Fink (2004): Hydrogeographische Untersuchungen im oberen Erlaufgebiet | 70 |
| Fink et al. (2005): Daten zur Karstverbreitung und Karstgefährdung in den östlichen Kalkhochalpen | 57 |
| Elster et al. (2016): Thermalwässer in Österreich | 20 |
| EHYD (2022): Spring surveillance network of the Hydrographic Service of Lower Austria | 14 |
| Salzer (1997): Erkundung unterirdischer Wasservorkommen in NÖ: Hydrogeologie der Karbonate zw. Wien-Fluß und Schwechat - Fluß im Wienerwald Bereich | 11 |
| BMLRT (2022): Wasserinformationssystem Austria | 8 |
| ÖBB Infra (2015) - Quellmonitoring Semmeringbasistunnel | 7 |
| Stadler et al. (2008): Hydrogeologie Schneeberg/Rax | 7 |
| Narany et al. (2019): Spatial and temporal variability in hydrochemistry of a small-scale dolomite karst environment | 5 |
| Pfleiderer et al. (2017; 2019): Hydrogeologische Grundlagen Bucklige Welt | 4 |
| Christian Böck (Pers. comm. 2019) Stadt Wien, MA 31 - Wiener Wasser | 2 |
| Elster et al. (2018): Österreichs Mineral- und Heilwässer | 1 |
| **total** | **2056** |

**Table 1:** Sources of the karst spring database.

To determine the values for $Z_{max}$, first a broad estimation of the highest point of the orographic catchment of each spring was made manually. The maximum elevation in this area was then extracted from the ALS-DEM using ArcGIS. In order to obtain a value for $K$, the model was calibrated with 44 MCE values calculated on the basis of oxygen isotope analyses from various data sources (Spendlingwimmer, 1984; Salzer, 1997; Pfleiderer et al., 2005; Stadler et al., 2008). We used the R-function 'optim' on the isotope-derived MCE-model to minimise the sum of squared errors, which resulted in $K = 0.43$. This is reasonable and means that it is slightly below the mean value of $Z_{max}$ and $Z$ where $K$ would be 0.5.

In order to check the plausibility of the model, the data from isotope analysis were compared with the MCE-model values. Figure 2 shows the good correlation ($R^2 = 0.78$) between the two. Therefore, the model values were considered to be a reasonably good approximation and were used for further statistical evaluations. Inaccuracies may result from deviations between the orographic and real catchment or from precipitation variations with elevation.

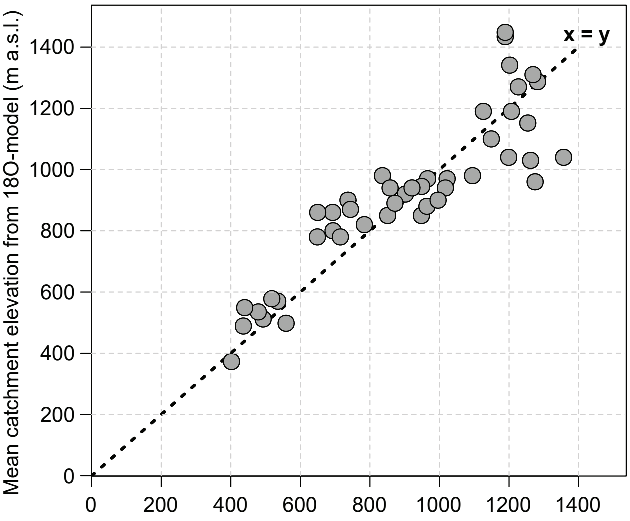

**Figure 2:** Correlation of MCE-values calculated from oxygen isotope data with MCE estimation from equation (1).

## 5. Results and Interpretation

### 5.1 Overview

Figure 3 illustrates the spatial distribution of all 2056 karst springs in the database. The vast majority (98%) is located in the NCA. The remaining springs are mostly found in the Central Alpine Permo-Mesozoic units. Only a couple of springs associated with metamorphic carbonates of the Bohemian Massif, Jurassic limestones of the Waschberg Zone and Neogene sedimentary rocks (limestone and carbonate breccias and conglomerates) of the Vienna Basin are included. However, it has to be mentioned that data coverage is not homogeneous and

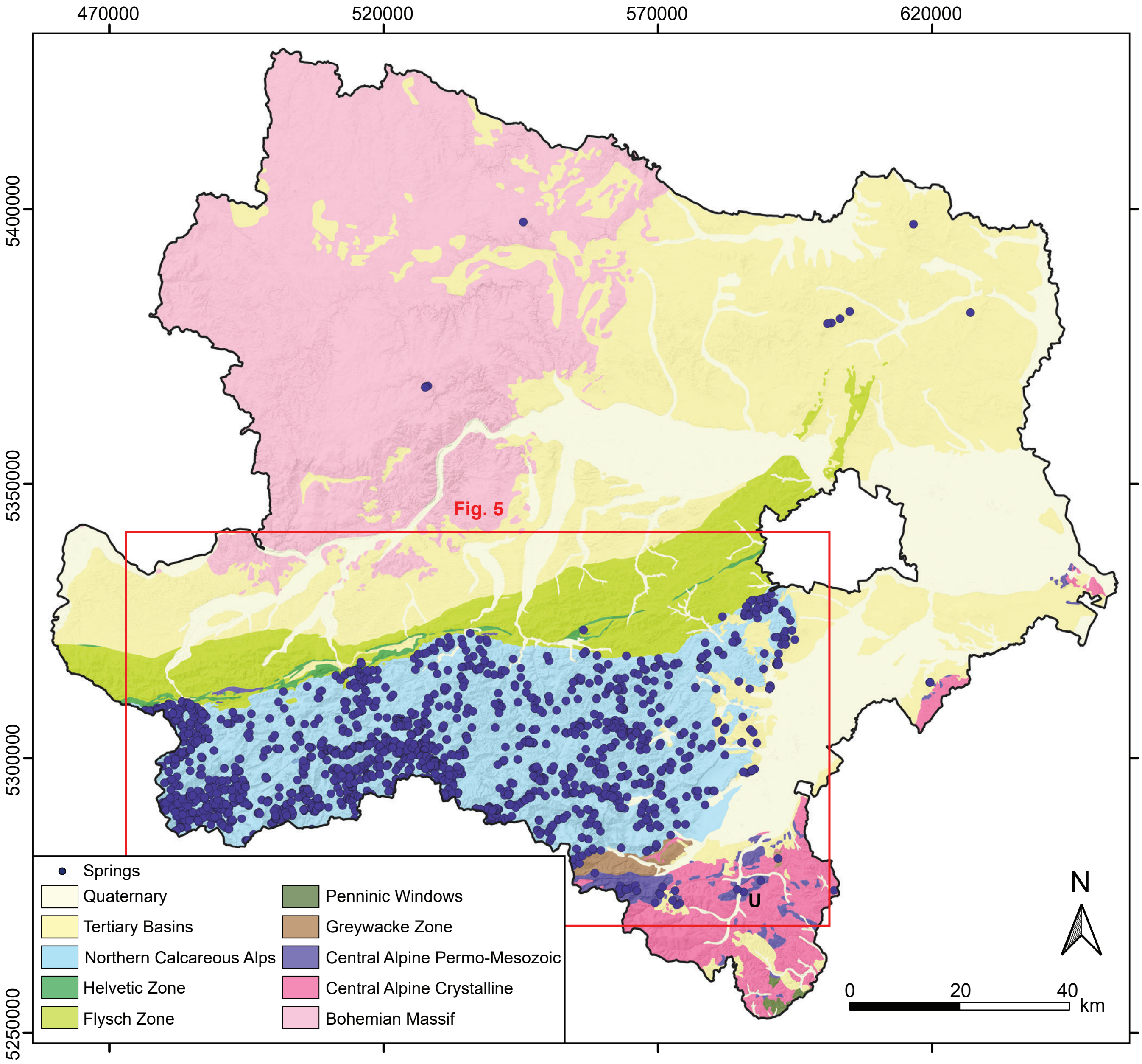

**Figure 3:** Spatial distribution of the karst springs included in the study (geological units from Weber, 1997; topographic data: courtesy Government of Lower Austria; coordinates: UTM 33N); U = Ursula Spring.

some areas were mapped with much more detail than others.

The histogram of spring discharges shows a near-log-normal distribution (Fig. 4a). This might be an artefact caused by an underrepresentation of small springs in the dataset. The distribution of EC values is right-skewed, which highlights the varying degree of evaporite dissolution with some values exceeding 2000 µS/cm (Fig. 4b). There is a distinct peak between 300 and 400 µS/cm with more than 40% of all springs falling within this interval. Only 11 of 1778 springs show EC values below 200 µS/cm.

Figure 5 shows an interpolated map of the EC values for the area of the NCA and the Semmering Mesozoic. The interpolation method used was inverse distance weighting (using the QGIS-algorithm 'IDW Interpolation'). It should be noted that the density of data points and thus the informative value of the map varies greatly from region to region. It is primarily intended to highlight regions with strongly elevated EC values. Values exceeding 700 - 1000 µS/cm, depending on elevation, occur almost exclusively in areas where gypsum is present. These are primarily linked to the gypsum bearing Haselgebirge and Werfener Schichten, which were major detachment horizons during nappe stacking in the NCA and lead to the predominance of outcrops of these units along the nappe boundaries (Neubauer et al., 2017). The map shows the base overthrusts of the major nappe systems (Bajuvaric, Tirolic, and Juvavic) of the NCA. It is evident that elevated EC values occur frequently at the base of the Tirolic (e.g. Ötscher area) and Juvavic (e.g. east of Schneeberg)

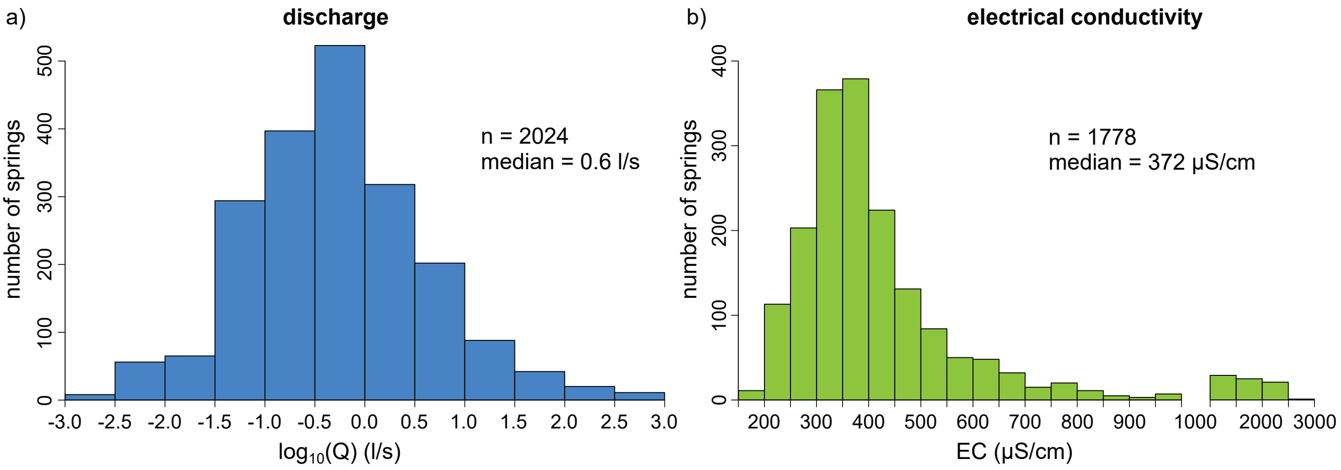

**Figure 4:** Frequency distribution of (a) spring discharge and (b) EC.

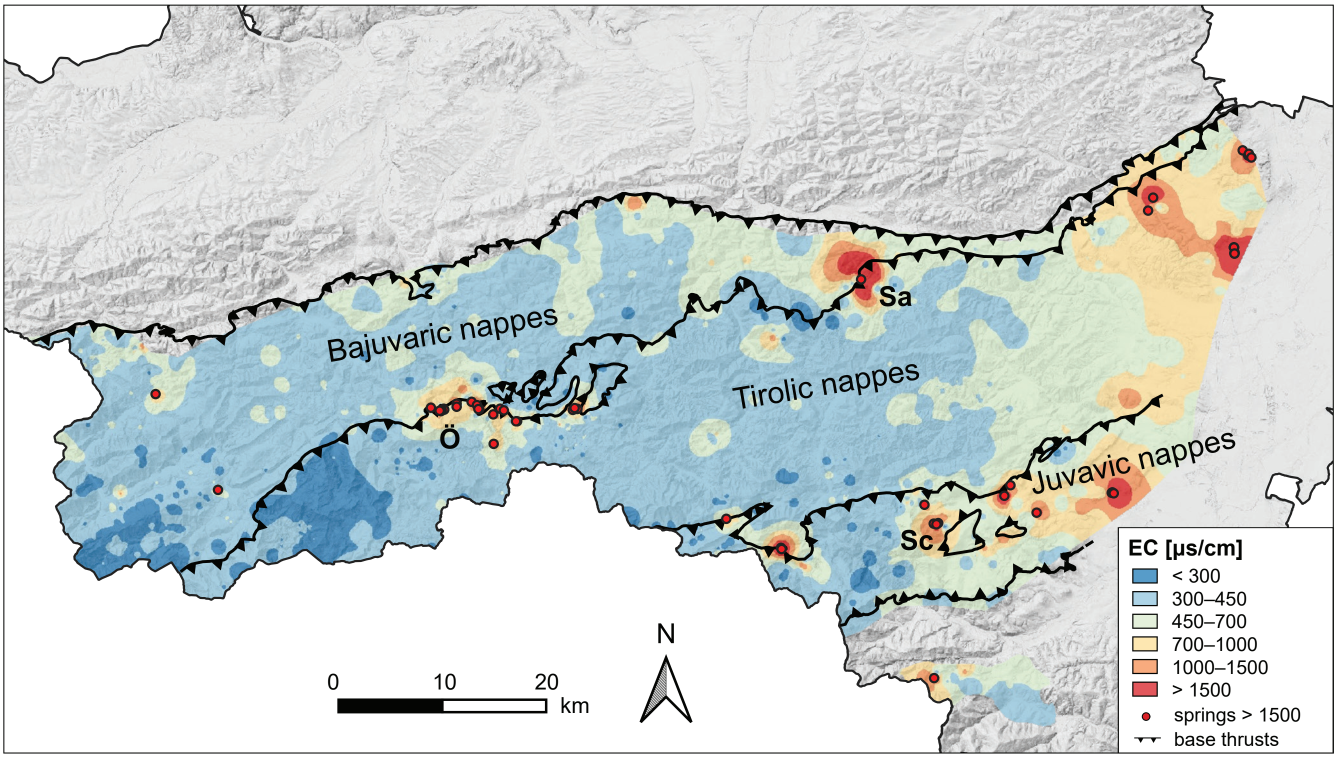

**Figure 5:** Interpolated map of EC for southern part of Lower Austria and locations of springs with EC > 1500 *µS*/cm; interpolation method: QGIS algorithm "IDW-Interpolation" using a distance coefficient of 3; nappe system boundaries from Weber (1997); topographic data: courtesy Government of Lower Austria; Ö = *Ötscher*, Sa = Salzerbad, Sc = Schneeberg. Position within Lower Austria: see Figure 3.

nappe systems due to the widespread presence of the Haselgebirge or Werferner Schichten. Isolated gypsum occurrences in the rauhwacken of the Opponitz Formation and the 'Gipskeuper' of the Semmering Mesozoic also result in some highly mineralised springs.

## 5.2 Hydrochemistry

The hydrochemical data show that $Ca^{2+}$ and $Mg^{2+}$ are the main cations in the vast majority of springs, while the anionic composition is dominated by $HCO_3^-$ and $SO_4^{2-}$. $Na^+$ and $Cl^-$ only reach significant concentrations in a small number of springs (see Supplemental Material). Figure 6 shows that the springs can be subdivided into three groups reflecting different aquifer lithologies. Spring water dominated by the dissolution of dolomite is characterised by a low molar Ca/Mg-ratio between one and around three. Limestone springs display higher Ca-concentrations and slightly lower amounts of total dissolved solids (TDS), which is reflected in lower EC-values. Dissolution of evaporites can result in elevated TDS-values exceeding 2 g/l, with $SO_4^{2-}$ as the main anion. However,

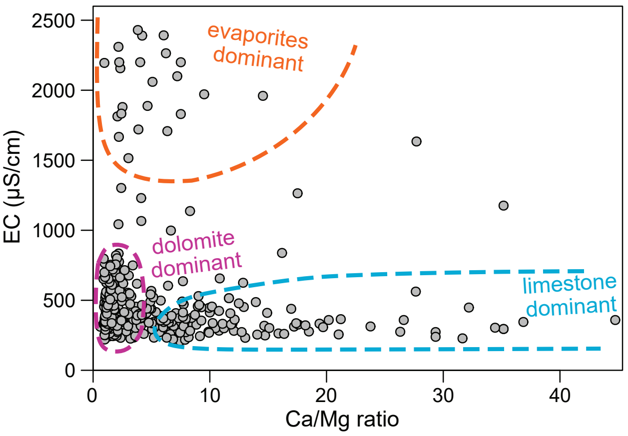

**Figure 6:** Scatterplot of molar $Ca^{2+}/Mg^{2+}$ ratio versus EC. Outliers with Ca/Mg ratios >45 and EC >2500 µS/cm (e.g. Salzerbad) are excluded.

mixtures between these three water types are also common. While dolomite and limestone karst areas cover large parts of Lower Austria, evaporite karst is much rarer and mainly limited to occurrences of gypsum and anhydrite in Haselgebirge, Werfener Schichten, and Opponitz Rauhwacke rocks of the NCA.

Chemical analyses of $Na^+$ and $Cl^-$ show that concentrations rarely exceed 30 mg/l. One notable exception is the brine spring of Salzerbad with a TDS-value around 21 g/l (Elster et al., 2018), which can largely be attributed to rock salt dissolution. The thermal springs along the margins of the Vienna Basin show elevated concentrations of $Na^+$, $Cl^-$ and $SO_4^{2-}$ of up to 175, 280 and 960 mg/l, respectively (Elster et al., 2016). Temporarily elevated concentrations of $Na^+$ and $Cl^-$ have occasionally been observed in areas without natural salt deposits, presumably due to the application of road salt (e.g., spring NK737, see Supplemental Material).

## 5.3 Relation of elevation and temperature

Figure 7 illustrates the relation between estimated MCE and spring water temperatures. For reference, the air temperature gradient for Austria determined from the long-term mean annual temperatures (1991 - 2020) of 170 measurement stations is shown (ZAMG, 2022):

$$T = -0.0047 \cdot Z + 11.97 \qquad (2)$$

The spring temperature data, although mainly consisting of single measurements, clearly show a correlation with the mean annual temperature at the MCE. Most spring temperatures follow a linear trend with respect to MCE, which corresponds well to the air temperature gradient. The temperature of smaller springs is more easily influenced by the air temperature in the immediate surroundings, resulting in a larger variance of measured temperatures. As measurements during the summer months are overrepresented in the dataset, positive deviations from the linear trend are more common than negative ones, presumably largely representing measurements influenced by air temperature. Only a small number of springs can be classified as thermal or thermally influenced springs. The clear linear trend observed in the data indicates that the method used to estimate the MCE yields good results. Therefore, it can be stated that a high proportion of the temperatures of karst springs with a discharge of 1 l/s or more reflect the catchment elevation well. Temperatures of smaller springs are a less reliable source of information on the catchment.

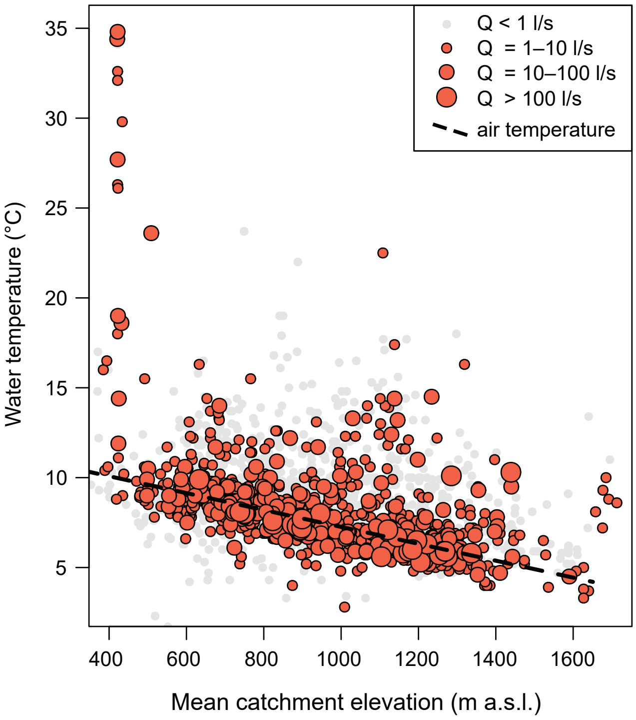

**Figure 7:** Scatterplot of MCE and spring water temperature. The dashed line represents the temperature gradient of annual mean air temperature in Austria (see text).

## 5.4 Relation of elevation and EC

Figure 8a shows the EC of the springs plotted against the estimated MCE. It is noticeable that the vast majority of data points are concentrated in a relatively narrow band. Points with higher EC are springs influenced by evaporite dissolution. The double-logarithmic plot shows a linear decrease in EC towards higher catchment elevation, which means that this relation is reasonably well described by a power-law. This trend can be explained by a decrease in carbonate dissolution, as shown by the corresponding plot of $HCO_3^-$ concentrations in Figure 8b. An outlier in the data set is Ursula Spring in the Bucklige Welt region, which has a markedly low EC relative to the elevation of its catchment. This anomaly can be explained by the springs' allogenic recharge from two streams with poorly soluble, non-karstifiable catchments and a very short residence time (Völkl, 1987; Schmalfuss et al., 2021).

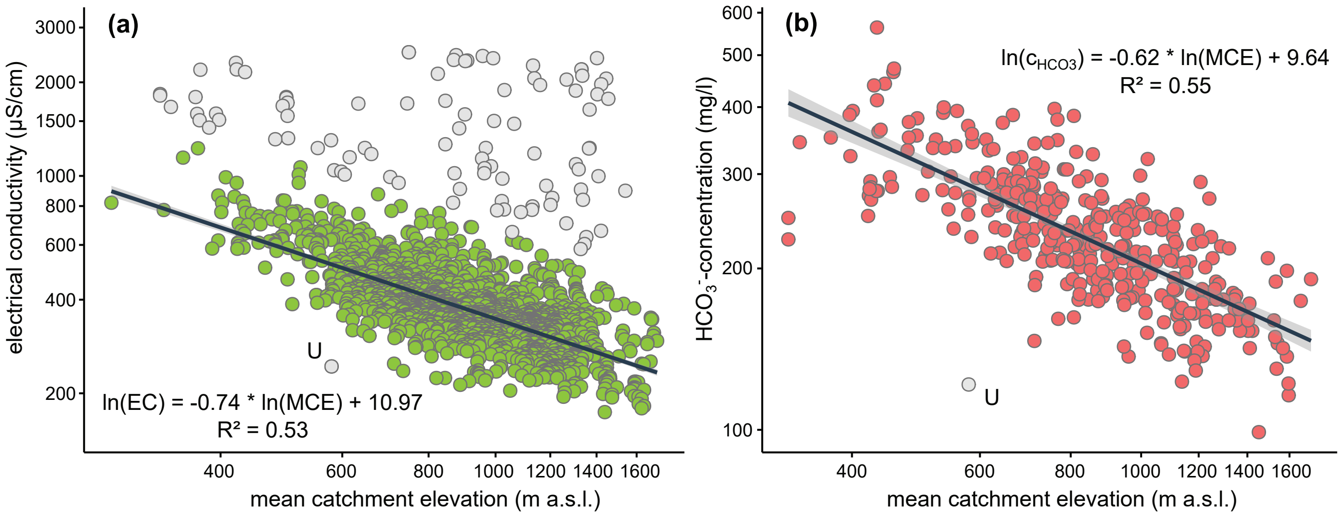

**Figure 8:** Mean catchment elevation (MCE) versus (a) electrical conductivity and (b) HCO3- concentration. Grey points are outliers. The grey shaded area indicates the 95% confidence interval. U = Ursula Spring.

| lithostratigraphic unit | mean EC (µS/cm) | mean Q (l/s) | mean T (°C) | mean MCE (m a.s.l.) | mean relative EC deviation from the model (%) | number of springs |
|---|---|---|---|---|---|---|
| **all springs** | 459 | 8.7 | 8.7 | 953 | 18.4 | 2056 |
| **dolomite** | 375 | 8.1 | 8.5 | 935 | 0.2 | 1000 |
| **limestone** | 345 | 14.5 | 7.8 | 1067 | -2.5 | 574 |
| Hauptdolomit | 391 | 9.5 | 8.7 | 926 | -0.3 | 745 |
| Wettersteindolomit | 375 | 3.9 | 7.8 | 959 | 1.9 | 255 |
| Gutensteiner Kalk | 359 | 12.0 | 8.2 | 997 | 0.2 | 232 |
| Opponitzer Schichten | 471 | 3.4 | 9.3 | 754 | 4.9 | 146 |
| Dachsteinkalk | 292 | 25.0 | 7.0 | 1287 | -4.2 | 117 |
| Werfener Schichten | 879 | 3.1 | 9.2 | 953 | 137 | 80 |
| Wettersteinkalk | 327 | 23.8 | 7.3 | 1076 | -3.2 | 78 |
| Haselgebirge | 2062 | 1.8 | 10.8 | 1016 | 417 | 72 |

**Table 2:** Summary of mean values of spring parameters for the most common lithostratigraphic units (more than 50 springs per unit) and all springs classified as limestone or dolomite. The mean relative EC deviation was calculated with respect to the regression model shown in Figure 8.

## 5.5 Relation of EC and lithology

Table 2 summarises the mean values for EC, discharge, temperature and elevation grouped by the most common lithostratigraphic units. With 745 springs, Hauptdolomit is by far the most frequent unit, followed by Wettersteindolomit and Gutensteiner Kalk. Regarding the mean EC values, Haselgebirge and Werfener Schichten stand out with 2062 and 879 µS/cm, respectively (Fig. 8a). As gypsum-influenced spring waters were excluded from the calculation of the model parameters, the mean relative EC deviation from the model for all springs (including gypsum springs) is 18%. For the units largely unaffected by evaporite dissolution, the influence of MCE on EC values is reflected in the mean values. To correct for this elevation effect, the mean relative deviation from the regression line shown in Figure 8a was calculated for each lithostratigraphic unit.

Wettersteinkalk and Dachsteinkalk show negative EC deviations of -3.2 and -4.2%, respectively, and also show by far the highest mean discharges. The slightly positive EC deviation of the Gutensteiner Kalk (+0.2%) might be explained by its stratigraphic position, often overlying Werfener Schichten or Haselgebirge. The comparison between the two major dolomite units, Hauptdolomit and Wettersteindolomit, shows that spring waters in the former are on average less mineralised (-0.3% to +1.9%), while the discharge is significantly higher (9.5 to 3.5 l/s). This reflects the stronger karstification tendency of the Hauptdolomit (Fink, 1999). The comparison of the units grouped into limestone and dolomite shows a relative difference in EC of 2.7%. For the median EC of the dataset (372 µS/cm), this corresponds to a difference of 10 µS/cm.

## 6. Discussion

Our data show that dolomite springs have a slightly higher EC than limestone springs (by 2.7%), when the measurements are corrected for elevation effects, which is done by the MCE approach. Without this, the difference is more pronounced, as limestone is generally more abundant than dolomite at higher elevations in our study area (Tab. 2). Although dolomite dissolves more slowly than calcite (De Waele & Gutiérrez, 2022, p. 583), it is more soluble than calcite at low temperatures (Palmer, 2007). As dolomite aquifers are typically more densely fractured and major conduits with high flow velocities are less frequent than in limestone karst aquifers, residence times of the water are higher in dolomite. This again illustrates the complex interplay of the factors controlling the observed parameters.

Concerning the relation of elevation and spring water temperature, Pavuza & Traindl (1984) investigated the pre-Alpine karst at the border of Lower and Upper Austria and yielded

$$T = -0.0051 \cdot MCE + 11.23 \qquad (3)$$

which has been used since successfully in other karst areas of the NCA even at higher elevations for the estimation of MCEs combined with the use of the elevation dependent $HCO_3^-$ content (e.g. Fink et al., 2005). In our study, a linear regression was not performed due to the skewed dataset and a good visual fit with the air temperature regression. However, the observed recent warming trend of air temperatures complicates any interpretation of the temporally inhomogeneous dataset or comparison with older studies.

Regarding the relation between elevation and EC, similar studies have been carried out by Pavuza (1994) using drip water samples from caves in different karst areas of Austria where the estimation of the catchment area is more accurate. A comparison shows that the results from the karst springs of Lower Austria yield a higher MCE. This may be due to the strict exclusion of waters with low to medium sulphate contents in the earlier study, as well as to the different geological and geographical setting, and thus soil cover, in the central and western part of the NCA included in the drip water study.

Our study suggests that electrical conductivity, properly done with frequent re-calibration, is a quick and easy approach to estimate the mean catchment elevation if sulphate-bearing rocks in the catchment can be ruled out. While it may not be as precise as $\delta^{18}O$ measurements, it is much cheaper and mean annual values can be easily derived with a data logger. However, as climate is undoubtedly a major factor in controlling rock dissolution processes, the relationship derived from our data can only serve as a useful estimate in regions with climatic conditions similar to the Eastern Alps.

Mastrocicco et al. (2019) made similar observations on data from mostly karst springs in Campania (southern Italy), interpreting it as an effect of shorter residence times at higher elevations. A more detailed explanation of this relationship is given by Kralik et al. (2007), who attribute it to an increase in precipitation and a decrease in the thickness of the soil cover. The result is a dilution effect and reduced $CO_2$ dissolution in the infiltrating water, reducing its dissolution power. This scheme has been described by Pavuza (1994, p. 43) with some examples, including results from dripping waters in caves, where the catchment area can in most cases be more precisely defined than for springs. Ford (1971) plotted the hardness of Rocky Mountain waters against $pCO_2$ and interpreted the tree line as an important threshold for soil $CO_2$. However, this is not evident in our data, although it should be noted that relatively few springs had their catchments exclusively above the tree line.

With respect to lithology and EC or dissolved content, Pavuza & Traindl (1983) studied different types of limestones and dolomites from several karst areas in the NCA and found TDS values of 318 mg/l for limestones and 321 mg/l for dolomites. Assuming a linear relationship between TDS and EC (e.g. De Waele & Gutiérrez, 2022, p. 85), their results are similar to ours. Laboratory tests with both rock types showed differences in solution kinetics, which may also affect the potential for cave development.

An obvious limitation of this study is that it relies on single measurements rather than time series. However, we believe that the large number of observations used here compensates for this. Another restriction is that the often very complex lithological setting of spring catchments has been greatly simplified and represented by a single rock type only. Furthermore, this type of statistical approach requires comprehensive datasets, which are not available at this level of detail for many parts of the world. On the other hand, our results may help to interpret data in other study areas.

## 7. Conclusions

Karst springs in Lower Austria are most common in the NCA, where limestones and dolomites are the dominant lithologies. Evaporites of the Haselgebirge and Werfen Formation are regionally significant karst rocks, which is demonstrated by the spatial distribution of EC values of the karst springs showing spikes along the base thrusts of the major nappe systems in the NCA. The statistical analysis of 2056 springs shows that dolomite springs are on average more highly mineralised than limestone springs, which can be explained by longer average residence times. Springs in the Wettersteindolomit show slightly higher average EC values than those in the Hauptdolomit, probably reflecting the higher tendency towards karstification and therefore shorter residence times of the latter.

It was found that the spring water temperatures show an altitude gradient, which corresponds well to the regional air temperature gradient. Low-discharge springs were excluded, as their temperatures show large variations due to the strong influence of air temperature. Our data show that the EC of the spring water is negatively correlated with the MCE. This is likely caused by reduced carbonate dissolution in high elevation catchments due to thinner soil cover and less biological activity combined with a dilution effect from increased precipitation. This relation shows that EC measurements of karst spring water can be used to get a rough estimate of the MCE, both in limestones and dolomites, if the catchment lithology is well known and significant evaporite dissolution can be ruled out.

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