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Karst hydrogeology of the Untersberg massif and its interaction with the porous aquifer in the adjacent Salzburg Basin

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Abstract

The Untersberg is a heavily karstified massif at the Austrian-German border south of the City of Salzburg. Tracer tests conducted in the 1960s and 1970s showed that large parts of this massif are drained to the Fürstenbrunn spring, the main karst spring in the area. A deep karst flow system was previously postulated below this spring assuming that karst water infiltrates directly into the porous aquifer of the Salzburg Basin (Brandecker, 1974).

Here we present results from a hydrological study shedding new light onto the karst water flow system of the Untersberg and the adjacent porous aquifer. We analysed a series of springs at Untersberg as well as a number of wells in the basin. The mean altitude of the spring's catchments was assessed using a $\delta^{18}O$ altitude gradient of -0.14 ‰/ 100 m, calculated from precipitation data. A mean residence time of ca. 0.4 yr was obtained for water emerging at the Fürstenbrunn spring. In addition to the highly constant water temperature and electrical conductivity of this spring water, this rather long residence time underscores the unusual behaviour of the Fürstenbrunn spring compared to large karst springs in other karst regions of the Northern Calcareous Alps. Monitoring wells near the Berchtesgadener Ache show the same mean $\delta^{18}O$ values as the latter and also a very similar pattern throughout the year confirming the infiltration of this river into the porous aquifer. Further towards the basin, rainfall is the dominant source of recharge. Neither physical nor hydrochemical nor stable isotope data point towards karst water infiltration into the porous aquifer. In addition, the data of this study show that large fluctuations of the groundwater body in the basin also occur in winter when the discharge from the Untersberg karst system is very low.

Der Untersberg ist ein stark verkarsteter Gebirgsstock an der deutsch-österreichischen Grenze südlich der Stadt Salzburg. Markierungsversuche in den 1960er und 1970er Jahren zeigten, dass die Fürstenbrunner Quelle, die die bedeutendste Karstquelle des Untersberges ist, große Teile dieses Karstmassivs entwässert. Darüber hinaus wurde unterhalb dieser Quelle ein „tiefer Karst“ und somit eine Infiltration von Karstwasser in den Porenaquifer des Salzburger Beckens angenommen (Brandecker, 1974).

Mit dieser hydrologischen Studie wurde versucht anhand von Isotopenuntersuchungen der Quellen am Untersberg sowie von Grundwassermessstellen im angrenzenden Becken die Frage der Karstwasserwege neu zu beleuchten. Mit Hilfe der $\delta^{18}O$ Werte von Niederschlagsproben wurde ein isotopischer Höhengradient von -0,14 ‰/ 100 m berechnet, welcher die Grundlage für die Abschätzung der mittleren Einzugsgebietshöhen der Quellen darstellt. Für das Wasser der Fürstenbrunner Quelle wurde eine mittlere Verweilzeit von ca. 0,4 Jahren berechnet. Gemeinsam mit den sehr konstanten Temperatur- und Leitfähigkeitswerten zeigt dieser recht hohe Wert das ungewöhnliche Verhalten der Fürstenbrunner Quelle im Vergleich zu anderen großen Karstquellen der Nördlichen Kalkalpen.

In Grundwassermessstellen nahe der Berchtesgadener Ache wurden mittlere $\delta^{18}O$ Werte festgestellt, die denen der Ache gleichen. Auch die sehr ähnlichen Schwankungen der stabilen Isotope zeigen die Infiltration von Flusswasser in den Porenaquifer. Weiter in Richtung Salzburger Becken macht der Niederschlag den größten Teil der Grundwasserneubildung aus. Mit keiner der verwendeten Methoden konnten eindeutige Hinweise auf eine Infiltration von Karstwasser in den Porengrundwasserkörper nachgewiesen werden. Die Ergebnisse dieser Studie zeigen weiters, dass große Grundwasserspiegelschwankungen im Salzburger Becken auch im Winter auftreten, wenn der Abfluss aus dem Karstsystem des Untersberges sehr gering ist.

1. Introduction

Located southwest of the city of Salzburg at the Austrian-German border, the Untersberg massif is of fundamental importance for the supply of drinking water to the inhabitants of the city of Salzburg. Today around 77 % of the water supply originates from the porous aquifer in the area of Glanegg and St. Leonhard (Wassergenossenschaft Grödig, 2003).

Although the Untersberg was once assumed to be one of the best studied karst massifs in the province of Salzburg (Haseke-Knapczyk, 1989), some questions still remain. In particular, the relationship of this karst aquifer with the porous aquifer of the adjacent Salzburg Basin is only poorly understood. A “deep karst flow system” below the Fürstenbrunn

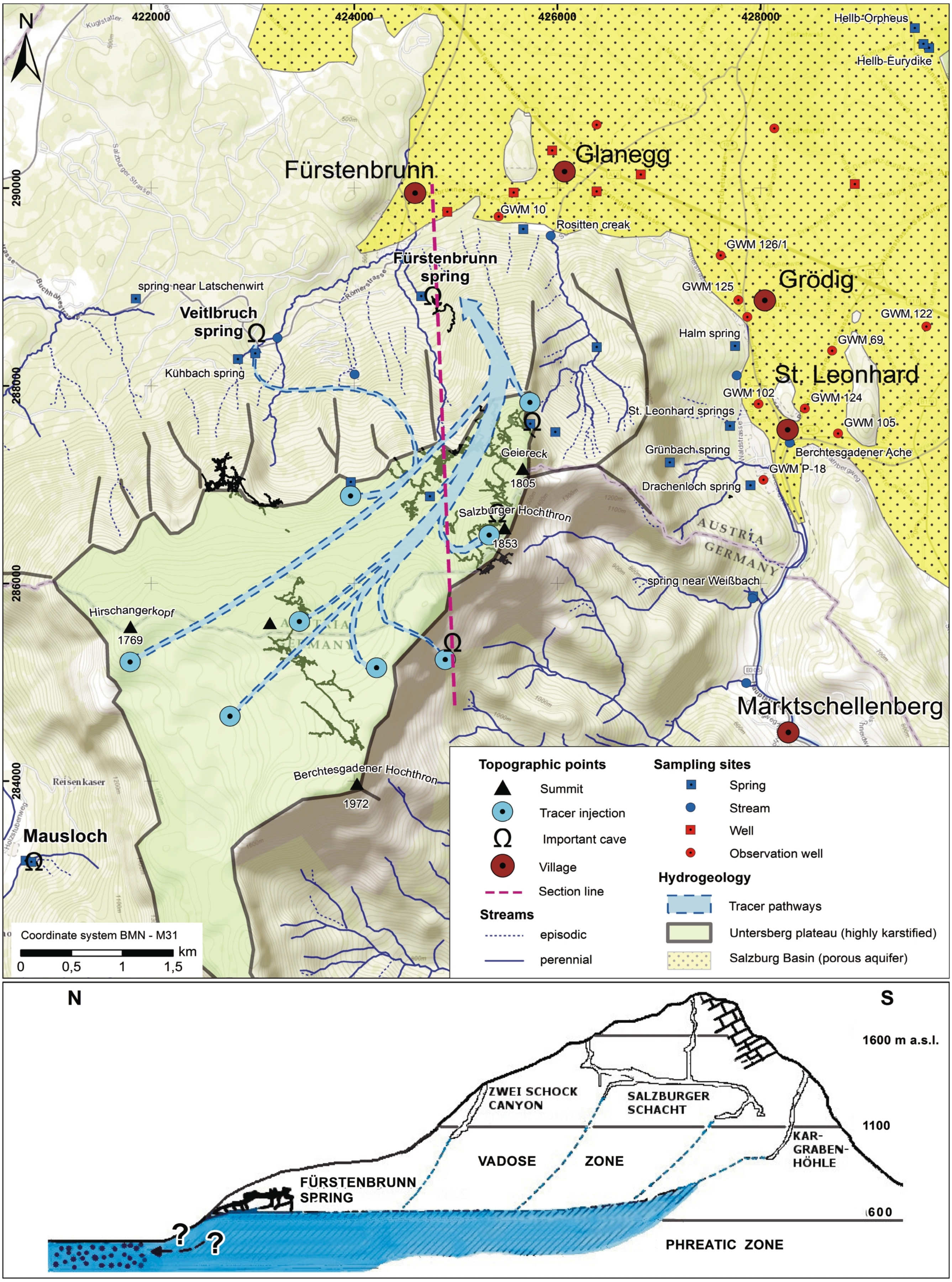

Figure 1: Topographic map showing all important sampling sites as well as the results of tracer tests conducted between 1967 and 1982 (upper) and simplified vertical cross-section of the Untersberg showing the assumed connection between karst water and porous aquifer (lower). Modified after Völkl (1983 in: Knapczyk, 1984).

spring was previously postulated (Fig. 1) assuming that karst water infiltrates directly into the porous aquifer (Brandecker, 1974). Evidence for such deep-reaching flow routes by-passing the Fürstenbrunn and other springs, however, has not been presented. Zötl (1974) suggested that the large extraction of up to 400 l/s from the porous aquifer near Glanegg is only possible because of the infiltration of undetected karst water. He assumed that the infiltration of karst water into the porous aquifer takes place along a N-striking fault. Both assumptions, however, lack evidence and have not been tested so far.

The aim of this study was to better understand the possible interaction of karst and porous aquifers near the northern margin of the Untersberg and to contribute to the question of the presence of an alleged "deep karst" aquifer. In this project physical (discharge, temperature, electrical conductivity, EC) and isotopic methods were applied.

2. Geological and hydrogeological setting

Located southwest of the City of Salzburg the Untersberg forms a massif of about 70 km² whose summit reaches 1972 m a.s.l. The central part of the massif forms a triangular-shaped plateau of 11 km² located between 1500 and 1900 m a.s.l. The Untersberg consists mainly of Middle to Upper Triassic carbonate rocks (Ramsau Dolomite and Dachstein Limestone (Fig. 2) which show a general dip towards NW (Del-Negro, 1979). Block rotations at major faults, however, cause locally different dip azimuths. In the Fürstenbrunn spring cave, for example, a southward dip of the Dachstein Limestone can be observed (Knapczyk, 1984). In the northwestern part of the Untersberg the Upper Jurassic Plassen Limestone and some younger rocks are present.

Tectonically speaking, the Untersberg is a separate nappe (Berchtesgaden nappe), which lies on top of Upper and Lower Tirolic nappes. According to Missoni and Gawlick (2011), however, the Berchtesgaden nappe – previously regarded as part of the High Juvavic nappe system – was originally part of the Upper Tirolic nappe and only became slightly separated during the Eocene (Fig. 2).

Two important fault sets can be observed at the Untersberg: NW- to N-striking faults (e.g. the Brunntal fault, which was important for the development of the Fürstenbrunn spring) that are supposed to be of pre-Gosauic age, and NE- to E-striking faults which are connected to the alpine orogeny and formed during the Eocene (Tollmann, 1976).

Hydrogeologically, the Untersberg can be divided into two parts showing different drainage patterns. The eastern and southern part of the massif, dominated by Ramsau Dolomite and by Lower Triassic formations, is mainly characterized by

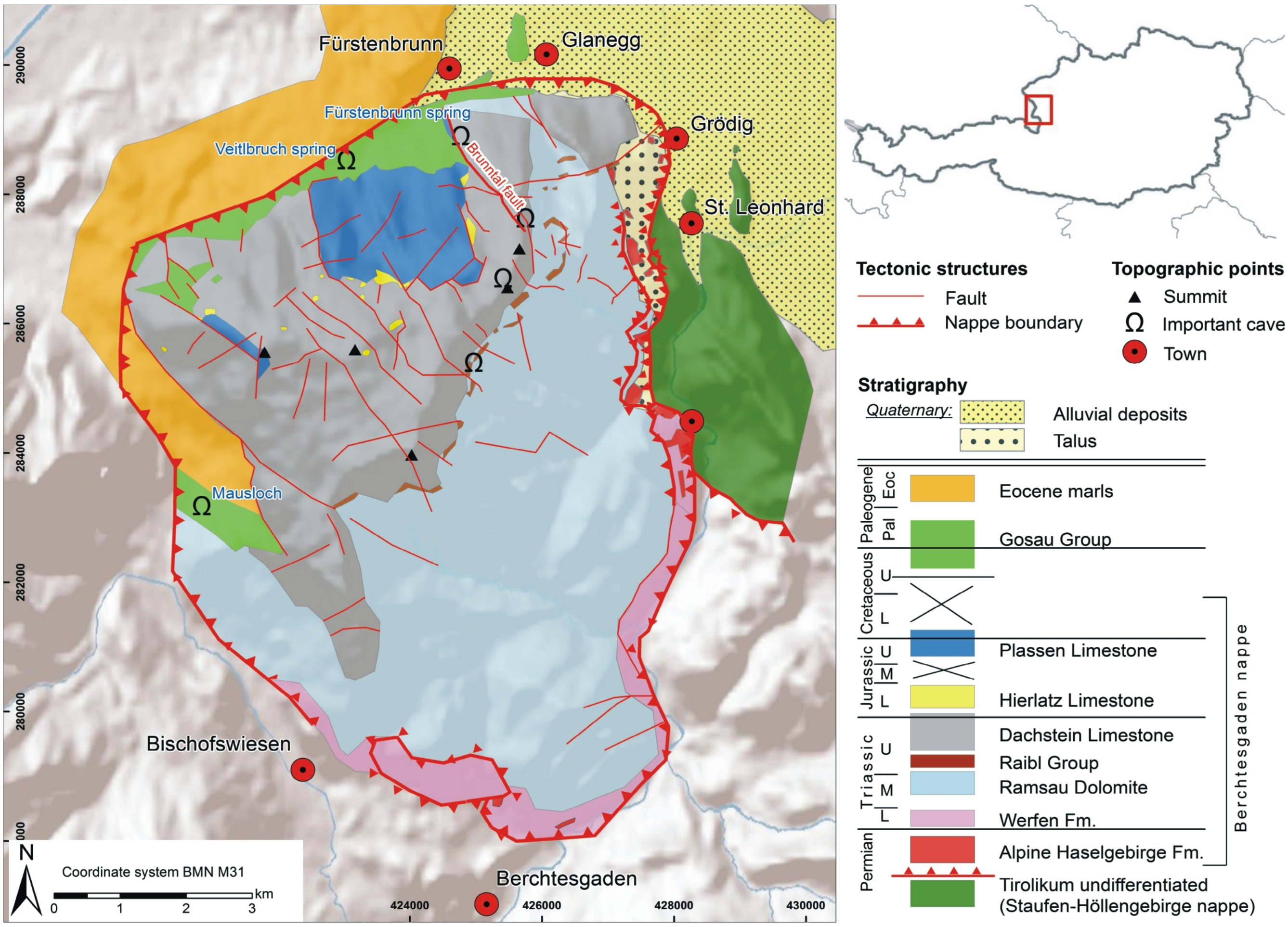

Figure 2: Simplified geological map of the Untersberg (based on Prey, 1969, and Loidl and Uhlir, 2012).

surface runoff. In contrast, the plateau and the northern parts of the Untersberg are heavily karstified and large parts of the massif are characterized by subsurface drainage via karst conduits. About 350 caves are known in this massif including the Gamslöcher-Kolowrat-System (with a length of 40 km) and the Riesending, currently Germany´s largest and deepest cave with 18.2 km length and over 1 km of vertical extension (Meyer, 2013).

Tracer tests showed that large parts of the Untersberg are drained to the Fürstenbrunn spring, the main karst spring of this massif located on a fault zone (Brunntal fault) near the northern tip of the massif at 595 m a.s.l. These dye-tracing tests showed that the catchment area of this spring reaches far to the South and West of the massif. The flow velocity is surprisingly low for a karst aquifer, i.e. on the order of 1 to 17.5 m/h (Knapczyk, 1984). Discharge varies between a minimum of 0.07 m^3/s and a maximum greater than 10 m^3/s (Knapczyk, 1984). New data show, that the discharge can even exceed 20 m^3/s during extreme events (Gruber, 2014). This high ratio between minimum and maximum discharge of the Fürstenbrunn spring (140-290, depending on the value used for the maximum discharge) is characteristic of mature karst springs. A karstwater table formed by interconnected conduits was postulated which has, at least partly, been proven by Gruber (2014). In contrast to the other main karst springs of the Untersberg (Veitlbruch spring and Mausloch), the presence of an extensive karst water body is thought to be the reason for the highly constant temperature of the Fürstenbrunn spring, which varies only slightly even following heavy rainfall events (Knapczyk, 1984).

The Salzburg basin is a glacially overdeepened basin filled by lacustrine sediments, delta complexes and fluvial sediments following the last glaciation (Preusser et al., 2010; Donadel et al., 2014). The fine-grained lacustrine sediments ("Salzburger Seeton") constitute an aquiclude, whereas the fluvial sands and sandy gravels above form an aquifer. This aquifer has a thickness on the order of a few meters to few tens of meters and is regarded as more or less coherent and unconfined throughout the basin.

3. Methods

3.1 Field and laboratory analyses

24 springs and 20 wells were selected for this study and

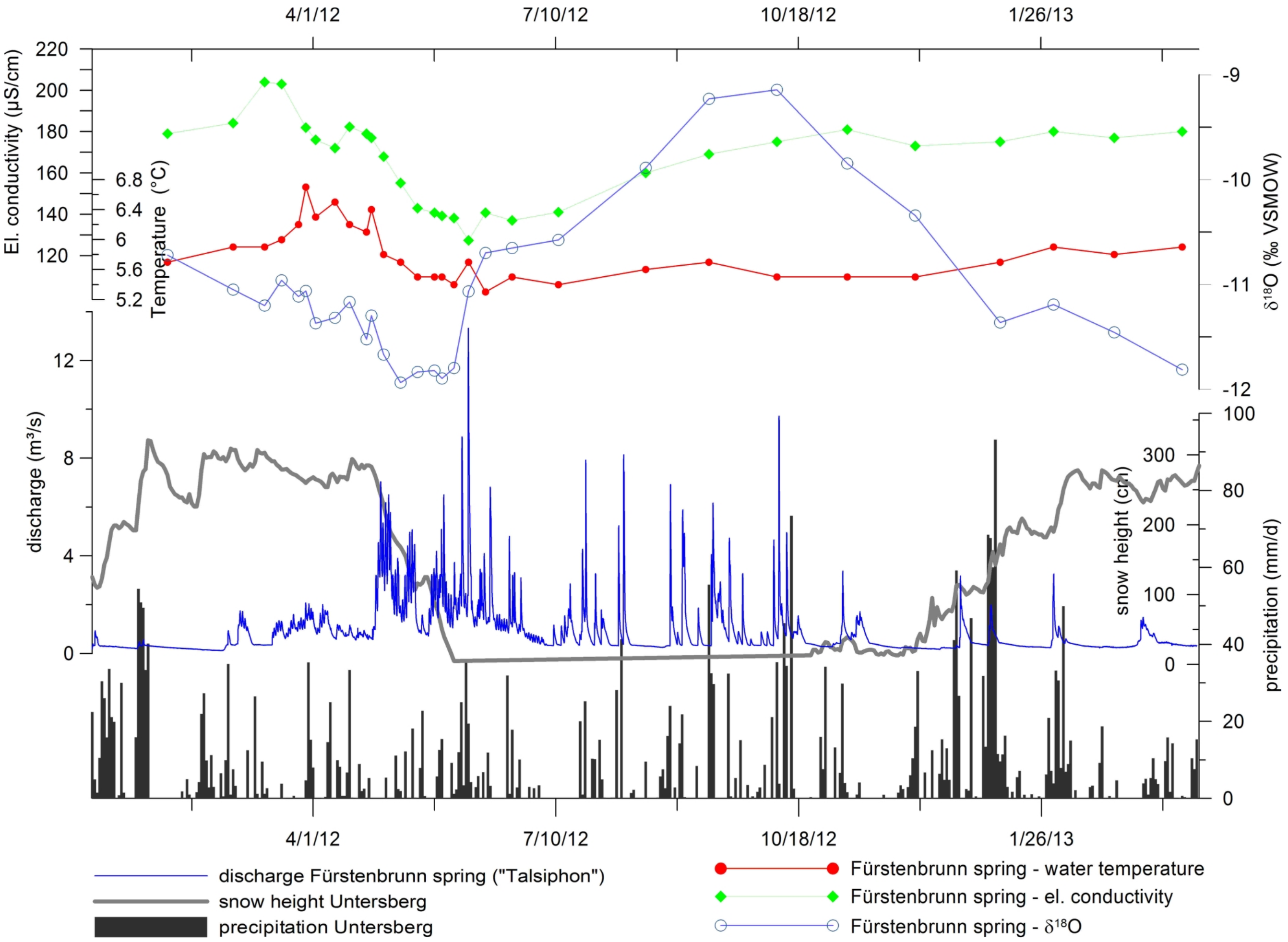

Figure 3: Comparison of electrical conductivity, temperature and $\delta^{18}O$ values (from top to bottom) of the Fürstenbrunn spring. In the lower part of the figure, the discharge of the spring (calculated using water pressure data (Gruber, 2014), snow height and precipitation at the Untersberg – station Geiereck (both from the Central Institute for Meteorology and Geodynamics, 2013) are shown.

sampled monthly for the analysis of $\delta^{18}O$ and $\delta^{2}H$ between April 2012 and March 2013 and two times for the analysis of the ionic composition. Chemical analysis was conducted by the Center Wasser (Salzburg AG). At the Fürstenbrunn spring samples were also taken for the analysis of ^{3}H. Wells were pumped until temperature and EC reached stable values and were then sampled. Discharge, elevation of the water table, water temperature and EC (referenced to 25 °C) were measured on site. Discharge was measured with a bucket and a stop watch or using the salt dissolution method. Seven rain gauges were installed for measuring the amount of precipitation and for obtaining isotope samples.

The O isotopic composition was determined at the University of Innsbruck by equilibration with carbon dioxide using an on-line, continuous-flow system (Gasbench II) linked to a Finnigan Delta^{plus}XL mass spectrometer. Calibration of the mass spectrometer was accomplished using VSMOW, GISP, and SLAP standards. The long-term 1-sigma analytical precision of the $\delta^{18}O$ values is 0.08‰.

The hydrogen isotopic composition of water samples was analysed using a Picarro L1115-i Isotopic Liquid Water and Water Vapor Analyzer (laser spectroscopic analyzer) at the Austrian Institute of Technology (AIT) in Tulln. All results are reported as the relative abundance ($\delta^{2}H$ and $\delta^{18}O$, respectively) of the isotopes ^{2}H and ^{18}O with respect to VSMOW. The precision of the measurements is better than ±1.0 ‰ for $\delta^{2}H$ and ±0.1 ‰ for $\delta^{18}O$.

The ^{3}H measurements from water samples were electrolytically enriched and analysed using low-level liquid scintillation counting (LLSC, precision ±5 %) at the laboratory in Seibersdorf.

3.2 Isotope data analysis

Radiogenic (^{3}H) and stable isotopes (^{18}O, ^{2}H) are suitable for studying the origin of water. Because ^{18}O, ^{2}H, ^{3}H are part of the water molecule, they can be used for tracing the hydrological cycle. Stable Isotopes in precipitation are influenced by several fractionation processes, the magnitude of which in temperate climates depends mainly on temperature and altitude. These result in typical isotope values and seasonal patterns for different catchment areas and allow the discrimination of water samples and therefore provide the basis for assessing the mean altitude of the catchment using the following equation:

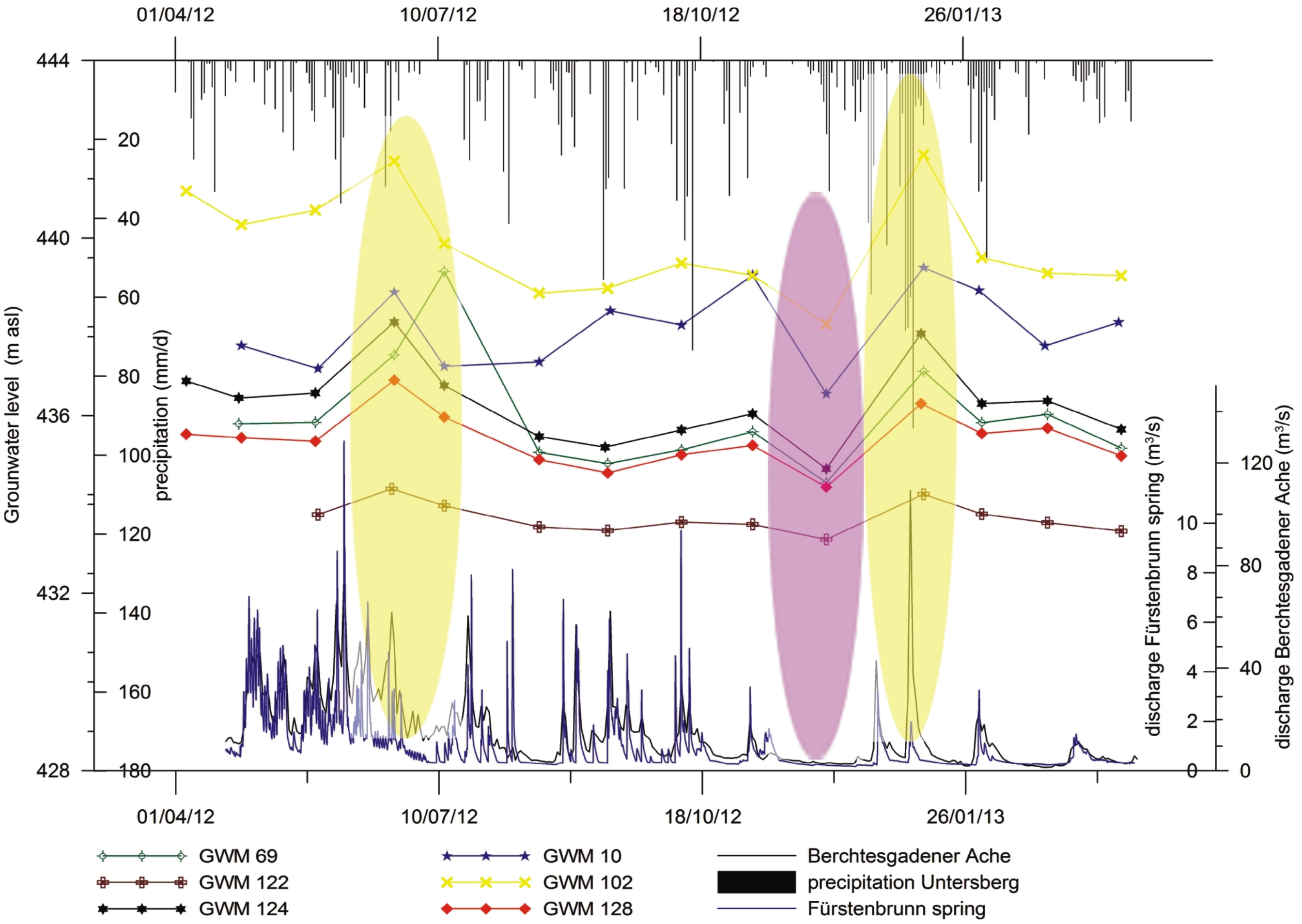

Figure 4: Diagram showing the relationship between the groundwater level in five wells of the Salzburg Basin and the discharge of the Berchtesgadener Ache at the gauge in St. Leonhard, discharge of the Fürstenbrunn spring and precipitation at the Untersberg. Note that periods of high discharge (yellow ellipses) coincide with higher groundwater levels in the porous aquifer and that the interval of minimum discharge coincides with a dry period (purple ellipse).

$$\text{Mean altitude of catchment} = \frac{(Pr\text{-}Q)}{G} + EP$$

whereby

Pr Mean value ($\delta^{18}O$) of precipitation at sampling station
Q Mean value ($\delta^{18}O$) of sampled spring water
G Isotopic altitude gradient ($\delta^{18}O$) per m of elevation
EP Elevation of precipitation gauge

The temporal variation of the stable isotope values can be used for estimating the mean residence time (MRT) of the groundwater. The seasonal variation of isotopes in precipitation can be described by a sinus curve, which is the input function for the hydrogeological system. The outflow at the spring is the output function and can be described by a sinus curve as well. With increasing MRT of the groundwater, the amplitude of the output function is progressively damped compared to the input function. With lumped parameter models (Maloszewski and Zuber, 1996) it is possible to calculate the MRT. Three models are commonly used, piston-flow-model (PFM), the dispersion model (DM) and the exponential model (EM) (see McGuire and McDonnell (2006), Mehlhorn (1998) and Stichler and Herrmann (1983) for further details). For a general assessment of the MRT the EM was applied in this study, which assumes that the decrease in permeability with depth can be modelled by an exponential distribution of the flow velocity. The EM matches the good-mixing model which was introduced for lakes and reservoirs under the assumption that the tracer is well mixed within the reservoir (Mehlhorn, 1998).

For calculating the MRT, the damping of the amplitude between input and output $f = \frac{B_n}{A_n}$ is used and the MRT is calculated as follow:

$$T = w^{-1}(f^{-2}-1)^{0.5}$$

whereby

T Mean residence time (years)
w Frequency (w = 2π/365 days)
$f = \frac{B_n}{A_n}$ where A_n and B_n are the amplitudes of the isotopic input and output functions, respectively.

We used both the input amplitude from the ANIP station Salzburg (ANIP, 2013) for the period 2011 – 2012 and our own precipitation data. For the second approach, we used the mean $\delta^{18}O$ value of snow from the Salzburger Hochthron sampled in spring 2012 (-12.5‰) and the highest $\delta^{18}O$ value of the precipitation sampled at Salzburger Hochthron (-6.5‰) as minimum and maximum values, respectively, to calculate the isotopic input amplitude. Water samples from the Gamslöcher-Kolowrat cave system taken in winter 2012 show $\delta^{18}O$ values very similar to snow sampled in spring, which supports the conclusion that these $\delta^{18}O$ values accurately describe the isotopic input of the system during winter. The output amplitude was calculated using one year of monthly $\delta^{18}O$ values for each spring.

Apart from stable isotopes the MRT can also be calculated using tritium data, which was done only for the Fürstenbrunn spring using a combined EM and PFM, as well as a simple PFM.

Mixing calculations were also performed to assess the proportion of infiltrating stream water in the porous aquifer. We applied a simple binary mixing model:

$$\delta_{A+B} = x\delta_A + (1-x)\delta_B$$

whereby

δ_{A+B} resulting mixture
δ_A & δ_B endmembers
x portion of endmember δA.

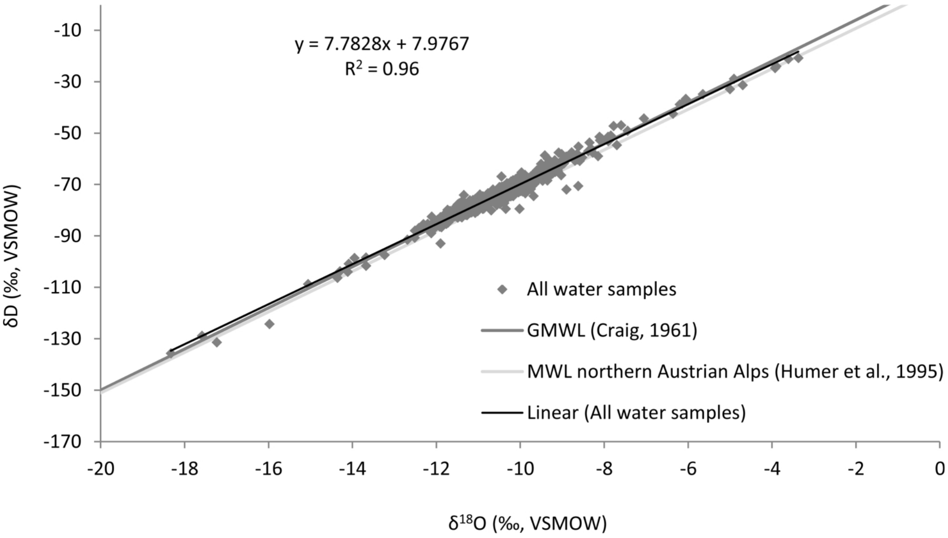

Figure 5: Water isotopes of the Untersberg massif and the adjacent Salzburg Basin in comparison with the global and regional meteoric water lines.

Rearranging the equation, the portion x of δ_A in the mixture can be calculated as follows:

$$x = \frac{\delta_{A+B} - \delta_B}{\delta_A - \delta_B}$$

4 Results

4.1 Physical parameters

4.1.1 Spatial and temporal variation of temperature

The mean temperature of the springs is between 5.5 and

9.0 °C. The springs can be dived in two groups. One group shows mean temperatures between 8 and 9 °C. These springs are situated close to the valley floor and have rather small catchments. The second group (karst springs and springs on the plateau) show a mean temperature below 7 °C.

The spring temperature varies seasonally following the air temperature, except for the Fürstenbrunn spring, which shows a different seasonal pattern (Fig. 3). In contrast to all other springs, the temperature of the Fürstenbrunn spring is highest in late winter (6.7 °C) and decreases during spring until a minimum of 5.3 °C is reached at the end of snow melt in June. Afterwards the temperature rises slowly again.

The groundwater in the porous aquifer shows temperatures between 8 and 11 °C and the mean is close to the mean annual air temperature of 9.9 °C measured in Salzburg. A seasonal pattern is present in all wells. A spatial analysis taking into account additional data from Schmitzberger (2013) reveals anomalously low groundwater temperatures close to the Berchtesgadener Ache and near of the Rositten creek.

4.1.2 Spatial and temporal variation of electrical conductivity

The mean EC of the investigated springs varies between 83 and 436 µS/cm (Fig. 3). The Fürstenbrunn spring shows the lowest values of all springs. The karst springs show lower values compared to the springs on the eastern side of the massif. Snow melt and major precipitation events cause a decline of the EC in all springs. The amplitude of the seasonal fluctuations differs, however, from spring to spring. The Fürstenbrunn spring shows only a muted response to precipitation events and reaches the highest EC (and temperature) values in March followed by a decrease during snowmelt. Afterwards, EC rises slowly in parallel with the water temperature and reaches its maximum in late winter of the next year (Fig. 3). All other karst springs reach their EC maximum in summer.

The EC of the porous aquifer varies between 240 and 750 µS/cm. The Hellbrunn springs, located farthest away from the Untersberg, show the highest values. None of the wells in the basin show EC values in the range of the Fürstenbrunn spring. The annual variation in EC are very different without a clear pattern, except that the wells further towards the basin tend to show smaller variations (less than 50 µS/cm) than wells located near the foot of the massif. Some wells, especially those near the Berchtesgadener Ache, show intraannual va-riations of more than 200 µS/cm. The maximum is reached in fall by most of the wells. Taking additional data from Schmitzberger (2013) into account, EC increases from the Berchtesgadener Ache to the NE and from the Rositten creek

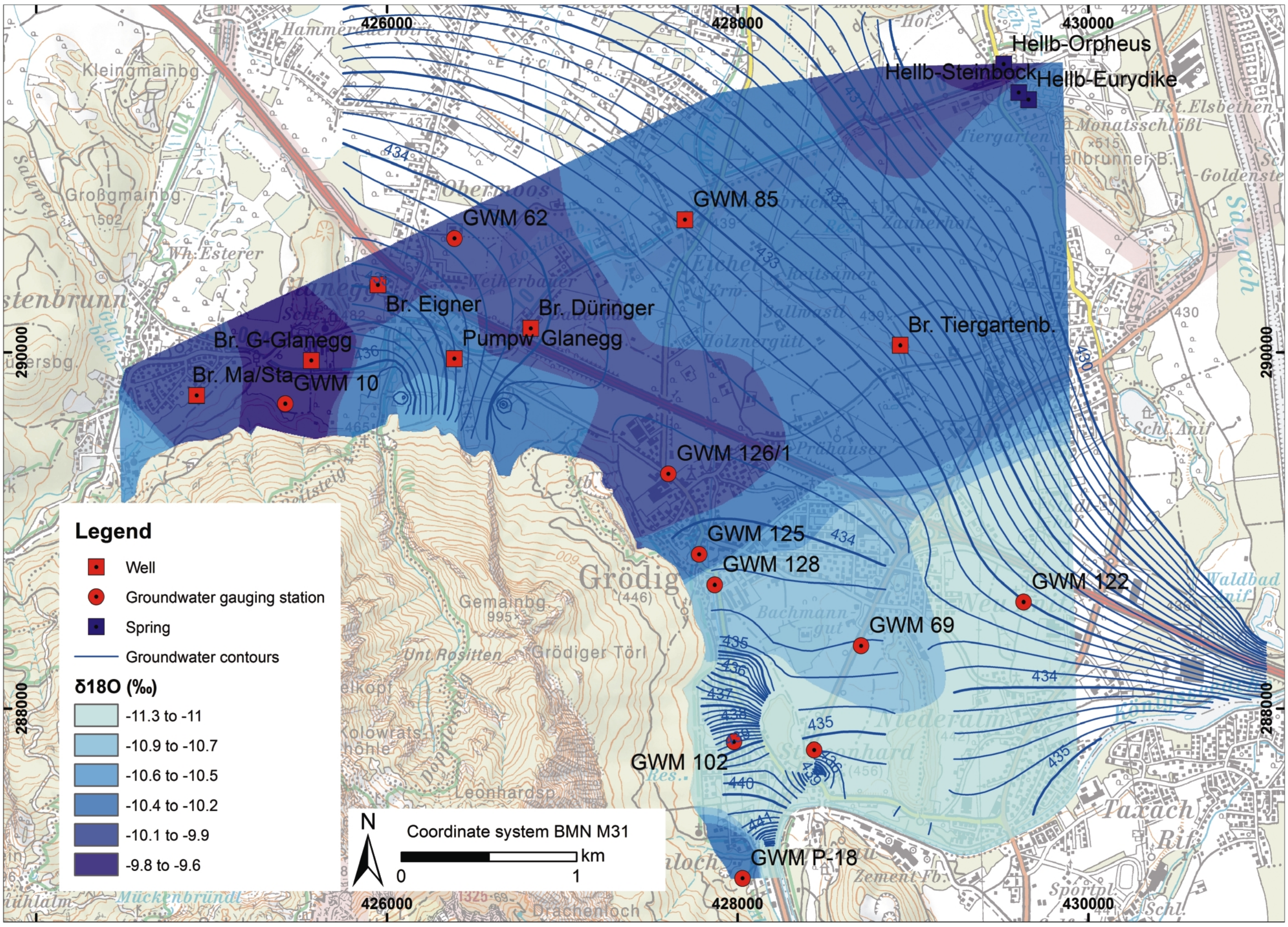

Figure 6: Contour map of the δ^{18}O composition of groundwater in the western part of the Salzburg Basin adjacent to the Untersberg massif.

to the N and NE. Low EC values coincide with low water temperatures. Monitoring wells close to the Berchtesgadener Ache exhibit values similar to those of this stream.

4.1.3 Discharge and groundwater level

The large karst springs, especially the Fürstenbrunn spring, show large discharge fluctuations and also a fast reaction to rainfall events. During the measuring period the Fürstenbrunn spring's discharge varied between 54 l/s and more than 9 m^3/s. Discharge is typically highest during the snowmelt period in spring and early summer. Springs in the eastern part of the massif show only a minor maximum during snowmelt and a downward trend during summer and fall. Logger data from the Fürstenbrunn spring (Talsiphon) show a detailed picture of the discharge of the Fürstenbrunn spring (Fig. 3) (Gruber, 2014).

The groundwater level fluctuates between 1 and 6.7 m with the highest amplitude close to the Untersberg and the lowest in wells out in the basin. Most wells show two maxima (Fig. 4) which coincide with the discharge maxima of the Berchtesgadener Ache and are caused mainly by snowmelt and precipitation (Fig. 4).

Comparing the groundwater maximum of January 2013 with precipitation and discharge data reveals that the rise of the groundwater table by about 4 m occurs at a time when the discharge of the the Fürstenbrunn spring is low (Fig. 4). This supports the hypothesis that groundwater recharge into the porous aquifer occurs only by infiltration of surface waters and/or precipitation. Infiltration via a deep karst flow system, however, is not supported by the data.

4.2 Hydrochemistry

Springs emerging from the Dachstein Limestone generally show a Ca-carbonate composition (Mg < 20 eq.-%). Springs emerging from the Ramsau Dolomite belong to the dolomite-carbonate type (Mg > 40 eq.-%). Groundwater in the basin is generally higher mineralized than spring water, but its chemical composition is intermediate between the two types of springs (20 – 40 eq.-% Mg).

Springs in the eastern part of the massif, the Berchtesgadener Ache and also the porous aquifer, show slightly higher sulphate concentrations (10 to 20 mg/l) than the large karst springs and other springs in the northern part of the massif. While the Na and Cl concentrations of the large karst springs are very low (below 1 and 2 mg/l, respectively), the porous aquifer contains up to 16 mg/l Na and 38 mg/l Cl.

4.3 Stable Isotopes

4.3.1 Spatial and temporal variation of stable isotopes

All water samples analysed in this project plot on or near the global meteoric water line (Craig, 1961; Fig. 5). The mean $\delta^{18}O$ values of the springs are very similar and lie around -10.5 ‰ with only few springs showing slightly more negative values. The mean $\delta^{18}O$ values of the porous aquifer close to the Untersberg are very similar as those of the springs what does not allow discriminating possible infiltration sources to the porous basin aquifer using water isotopes. Further towards the basin the mean $\delta^{18}O$ values tend to increase (Fig. 6). Fluctuations of the $\delta^{18}O$ values are higher at the karst springs than in the porous aquifer (Fig. 7).

The mean deuterium excess (d), globally defined as $d = \delta^2H - 8\delta^{18}O$ (Dansgaard, 1964) and adapted for Austria as $d = \delta^2H - 7.88\ \delta^{18}O$ (Humer et al., 1995), of spring and river water ranges from 9 to 13 ‰ and the value increases with altitude. The uncertainty of the deuterium excess is ±1.3 ‰ (combined uncertainties of δ^2H and $\delta^{18}O$ measurements). As a result, the Fürstenbrunn spring with its high catchment area also shows a high d value.

Most of the springs show annual $\delta^{18}O$ variations on the order of 1.5 to 3 ‰. In general, the lowest values occur in spring during snowmelt, followed by an increase during summer. Also the Fürstenbrunn spring shows decreasing $\delta^{18}O$ values

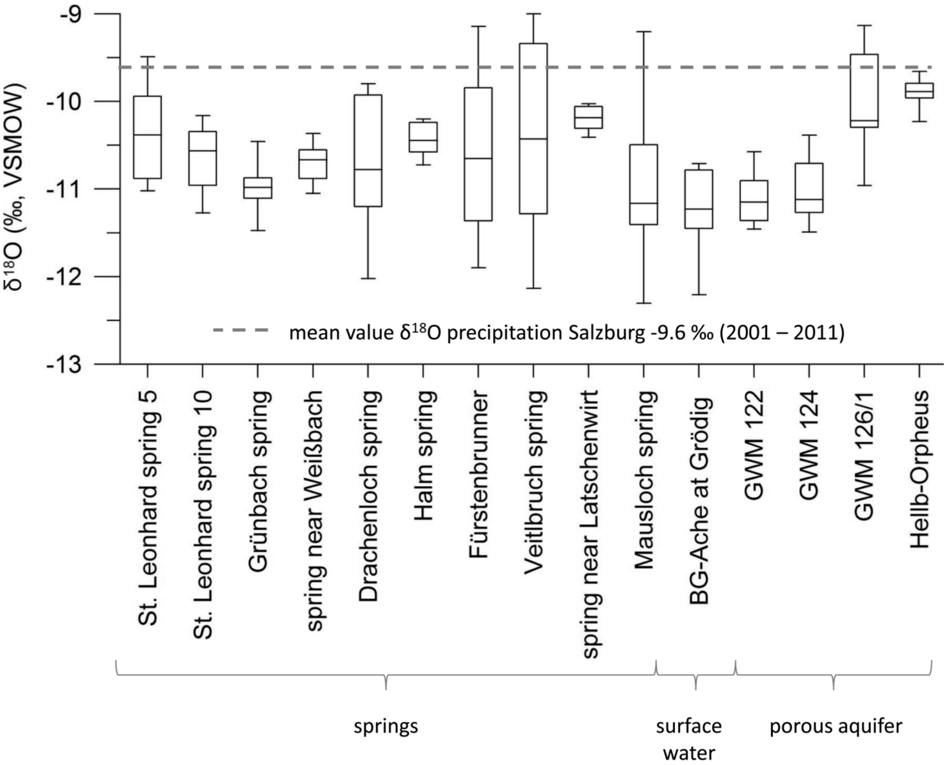

Figure 7: Box and whisker plot showing the $\delta^{18}O$ composition of selected springs and wells in the study area in comparison to the mean of precipitation in Salzburg.

more or less simultaneously with rising proportions of isotopically lighter snowmelt water in spring and early summer. After the minimum at the end of the snowmelt period the $\delta^{18}O$ values increase abruptly (Fig. 8). A few springs in the study area (e.g. Halmquelle) lack a seasonal isotope pattern.

The ^{3}H values of the Fürstenbrunn spring decrease in parallel with the ^{3}H values of the precipitation in Salzburg (Fig. 9). The latter decrease is the result of the decay of this radioisotope since the end of the thermonuclear tests (1953 – 1962; Fig. 10).

5 Discussion

The temperature of the spring water is negatively correlated with the elevation of the catchment and hence the air temperature. Also the groundwater temperature in the porous aquifer is mainly controlled by the air temperature, as the mean groundwater temperature in most wells is close to the mean air temperature at Salzburg (9.9 °C, station Salzburg Airport, 1981 – 2010, Central Institute for Meteorology and Geodynamics, 2013) and the temperature maximum is observed in late summer or early autumn.

The EC reflects the geology of the catchment area and the residence time of the water in the aquifer. The large karst springs therefore show lower EC values than springs in the eastern part of the massif and the EC in the porous aquifer is far higher than that of the springs.

The key period for karst water recharge is the snowmelt on the plateau, leading to high discharge and low EC due to the dilution by meltwater. The largest spring in the Untersberg region, the Fürstenbrunn spring, is exceptional in this context. Its temperature and EC co-vary but do not follow short-term fluctuations in discharge (Fig. 3). This leads to the concept that the Fürstenbrunn spring drains a much larger aquifer volume compared to all other karst springs on this massif and its water is therefore well mixed before emerging at the spring. Hence, precipitations events do not significantly affect the physico-chemical (temperature, EC) properties of this aquifer, but are propagated throughout this extensive aquifer as hydraulic pulses and manifest themselves as discharge peaks at the spring. A recent study using water pressure data logger inside the massif indeed showed that phreatic parts of the Fürstenbrunn spring cave and the Gamslöcher-Kolowrat cave system act like communicating pipes over a horizontal distance of at least 2 km (Gruber, 2014).

The isotope data show that springs with rather constant EC values lack a clear annual isotopic pattern pointing toward high mean residence times. In contrast, springs with large fluctuations of temperature and EC also show a larger variability in the stable isotope values, hinting towards infiltration/mixing by surface waters and shorter mean residence time. $\delta^{18}O$ data of the Fürstenbrunn spring show a similar intra-annual amplitude compared to other springs (e.g. Mausloch and Veitlbruchquelle), but its overall variability is more damped (Fig. 8).

The ^{3}H data illustrate that since 1973 no major changes occurred in the karst system feeding the Fürstenbrunn spring (Fig. 9).

The hydrochemistry of the sampled springs and wells reflects the geology of the catchment. Springs on the eastern part of the massif belong to the dolomite-carbonate water type, whereas the large karst springs contain very little Mg. Interestingly, the Fürstenbrunn spring also shows very low Mg concentration, although the karstwater table is situated near the boundary between the Dachstein Limestone and the underlying Ramsau Dolomite. This suggests the epikarst as the main zone where dissolution takes place.

The stable isotope data of the spring waters plot very close to the global meteoric water line (Fig. 5) indicating that they are purely meteoric in origin and have not been significantly affected by evaporation.

The deuterium excess (d) increases with altitude in the study area, probably due to less sub-cloud evaporation on the plateau and increased evaporation down in the Salzburg Basin because of higher air temperature and longer falling time of the water drops (Fig. 11). Froehlich et al. (2008) showed, that sub-cloud evaporation is the reason for the lower deuterium excess of valleys stations in Austria where evaporation reaches 7 %. Mountain stations show a higher deuterium excess and the sub-cloud evaporation is less than 1 % of the precipitation.

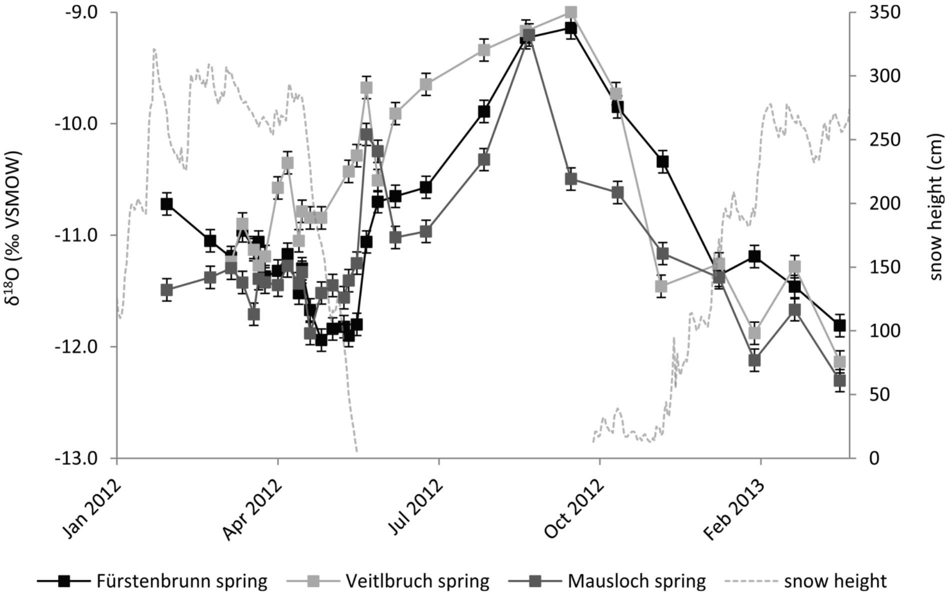

Figure 8: Seasonal change in the $\delta^{18}O$ composition of three major springs in comparison to the snow height measured at the upper station of the Untersberg cableway.

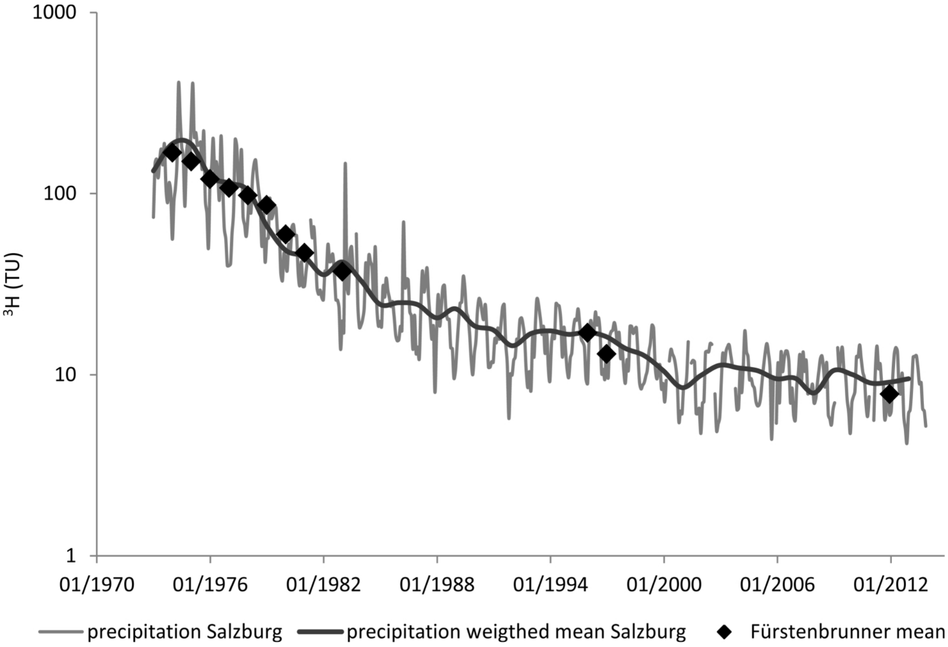

Figure 9: Decline in ^{3}H concentration (1 TU = 0.118 Bq/kg) at the Fürstenbrunn spring (G. Völkl, pers. comm.) and in the precipitation in Salzburg since 1973 (S. Wyhlidal, unpubl. data).

The isotopic composition of precipitation changes with altitude as a function of temperature and rainout leading to a depletion of the precipitation in heavy isotopes at higher altitudes (Clark & Fritz, 1997). This is known as the isotopic altitude effect and has been widely used to assess the mean altitude of a catchment (Etcheverry & Vennemann, 2009).

In this study, the altitude effect was computed using data from custom-built rain gauges. The isotopic composition of precipitation in the Untersberg area shows an altitude gradient of -0.14 ‰/100 m (Fig. 12), which is close to the mean gradient of -0.16 ‰/100 m for Austria (Humer et al., 1995).

The mean elevation of a springs' catchment can be assessed by plotting the mean δ^{18}O value of individual springs against their elevation (Fig. 12). In the case of the Fürstenbrunn spring and the Mausloch spring, the δ^{18}O values were weighted according to the discharge at the time of sampling because of the highly variable discharge of these large karst springs. According to these calculations a mean altitude of 1670 m was obtained for the catchment of the Fürstenbrunn spring.

Applying the equation introduced in chapter 3.2 (exponential model) the calculated mean residence time of the Fürstenbrunn spring is on the order of 0.4 yr. Applying a piston-flow-model to the tritium data (suitable for hydrogeological settings with high average linear velocity, low dispersion and short flow paths from the catchment to the spring) on the amount-weighted annual precipitation mean values the best-fit algorithm yields a MRT of 0.9 years for the Fürstenbrunn spring mean values (Fig. 10) with a maximum deviation of 23.8% (relative squared error) in 1976. Detailed analysis of precipitation data shows extraordinary low precipitation amounts for several months between September 1975 and May 1976 which is reflected in the ^{3}H values of the Fürstenbrunn spring especially in the first half of 1976. Taking only the second half of ^{3}H values from 1976 into account, the best-fit calculates a MRT of 0.4 years which is closer to the calculated MRT using the δ^{18}O data. To assess the influence of a certain catchment contributing to the Fürstenbrunn flow system a combined EM and PFM approach was applied. Because of the short MRT the curve of the combined model does not significantly differ from the piston-flow calculations.

This lag of ca. 0.4 years is clearly seen in the offset of the isotope maxima between precipitation (July) and spring water (November). On the other hand, the isotope minimum of the Fürstenbrunn spring occurs during May and June, i.e. there

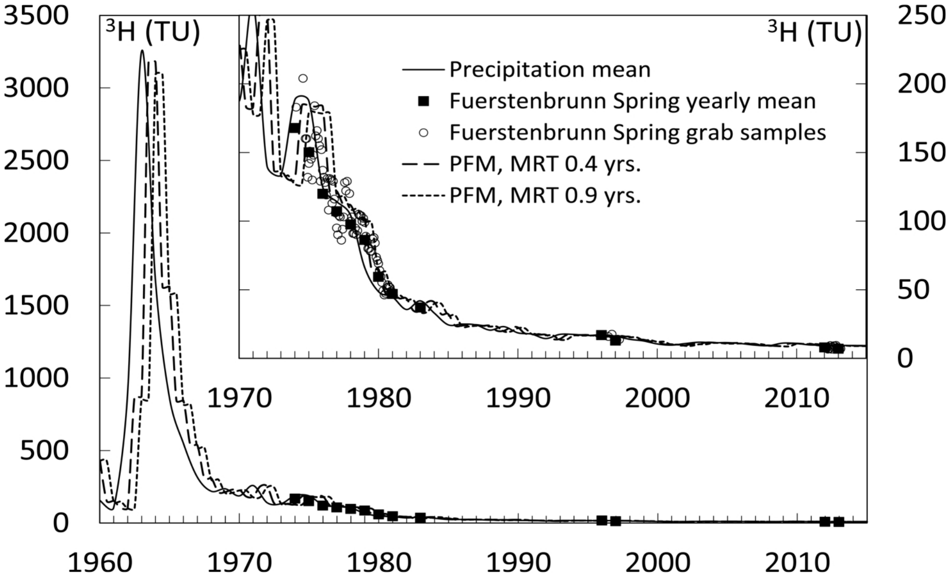

Figure 10: Comparison of measured and modelled ^{3}H contents of Fürstenbrunn spring (US Geological Survey: http://ca.water.usgs.gov/user_projects/TracerLPM/). Precipitation ^{3}H data are from Ottawa (1953-1960), Vienna Hohe Warte (1961-1972) and Salzburg (1973-2013) from the Austrian Network of Isotopes in Precipitation (ANIP, 2013).

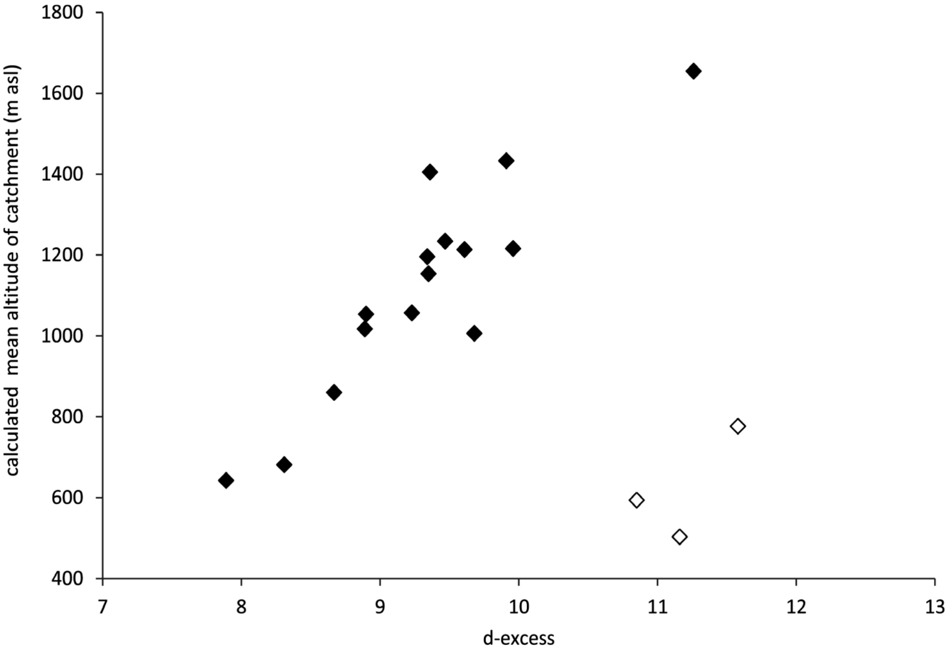

Figure 11: The mean deuterium excess of the springs increases with increasing altitude. The deuterium excess was calculated using the equation d = δ^2H - 7.88 δ^{18}O (Humer et al., 1995). The open symbols are springs showing only a short time series.

is no significant offset to the forcing (snow melt period) at this time of the year and this timing is consistent with isotope minima observed in other karst springs on Untersberg. These observations strongly suggest that the Fürstenbrunn spring water likely presents a two-component system: a large baseflow component with a mean residence time on the order of several months and a quickflow component entering the aquifer during the snowmelt period with a much shorter residence time. Compared to many other karst springs in the Northern Calcareous Alps, where flow velocities are on the order of hours to few days (Knapczyk, 1984; Scheidleder et al., 2001), the Fürstenbrunn spring shows a rather damped signal underscoring the large aquifer volume drained by this single spring.

Mixing calculations were also performed to assess the portion of infiltrating stream water in the porous aquifer. The mean δ^{18}O values of the Berchtesgadener Ache and of precipitation at Wals fall close to a mixing line (Fig. 13). Using the equation introduced in chapter 3.1, the portions of rain water and water of the Berchtesgadener Ache infiltrating into the porous aquifer were calculated under the assumption that these are the only sources of recharge in the area. Precipitation accounts for only 13 % of the recharge in the area near well GWM 124 (and the Berchtesgadener Ache accounts for 87 %), whereas further north at the Hellbrunn springs precipitation constitutes for at least 80 % of the groundwater recharge.

In summary, the isotope data confirm the flow paths of the numerical model of the porous aquifer in the Salzburg Basin (Höfer et al, 2007). Observation wells near the Berchtesgadener Ache and the river itself have almost the same δ^{18}O values and show a very similar pattern throughout the year. These groundwater observation wells show also fluctuations of the water table and of EC in response to changes in the discharge of the Berchtesgadener Ache. This highlights the important role of the Berchtesgadener Ache for recharging the aquifer in the area of St. Leonhard (Fig. 14). Moreover, this shows also that the groundwater flow follows most likely the former flow direction of the Berchtesgadener Ache, which was changed by several rockslide events (Donadel et al., 2014).

Further towards the basin, precipitation is the main source of recharge. The isotopic composition of the springs at Hellbrunn is therefore very similar to the isotopic composition of the precipitation over the Salzburg Basin.

Secondly, water from the Untersberg (Rosittenbach, Fürstenbrunn spring) infiltrates - partly

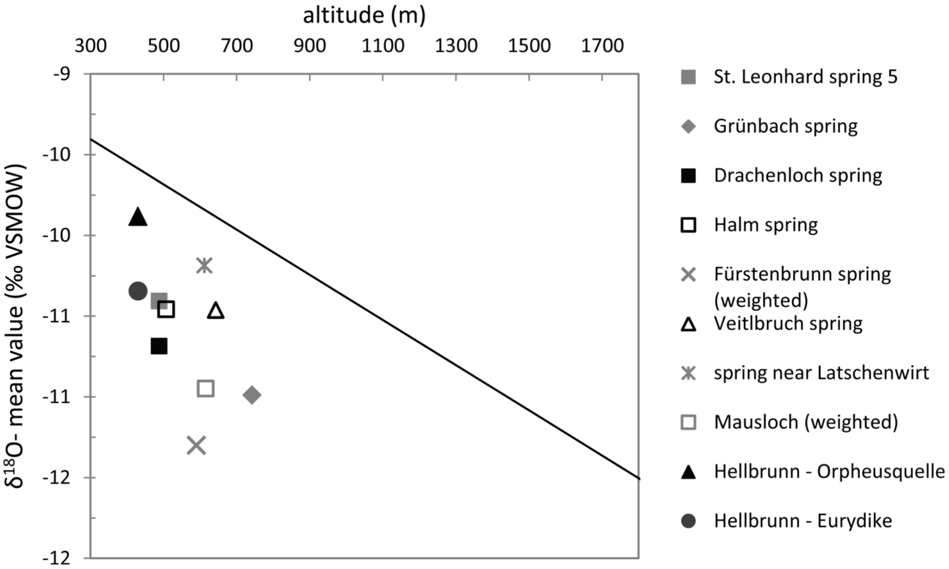

Figure 12: Annual mean δ^{18}O values versus the discharge altitude of the springs. The black line indicates the local altitude gradient of -0.14‰/100 m. For the Fürstenbrunn and Mausloch springs δ^{18}O values were weighted according to the springs' discharge at the time of sampling.

artificially - into the porous aquifer. A distinction between these waters from the Untersberg is not possible because of their similar δ^{18}O values. Consequently, the hypothesis of additional infiltration via a deep karst aquifer cannot be tested using stable isotope data, because this source would have an isotopic composition indistinguishable from that of the Fürstenbrunn spring.

The data of this study show, however, that large fluctuations of the groundwater body do also occur in winter when the discharge of the karst system is very low (Fig. 4). This leads to the conclusion that precipitation in the Salzburg Basin is more important for recharging the porous aquifer than was previously assumed. Furthermore, neither temperature nor EC show evidence of infiltration of cold and low-mineralized waters into this aquifer (except for the known and described infiltration points).

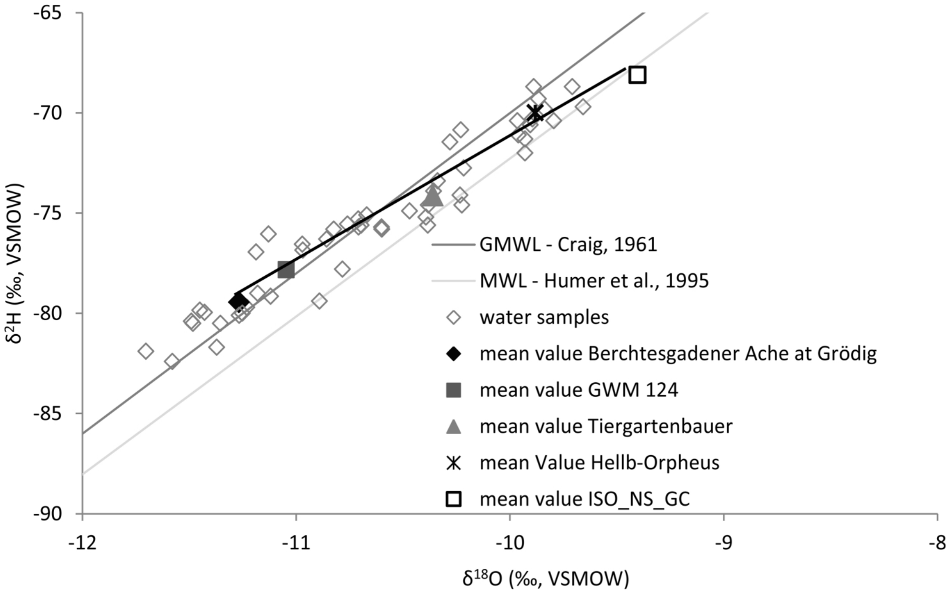

Figure 13: δ^{18}O versus δ^{2}H plot emphasizing wells in the Salzburg Basin along a transect from St. Leonhard towards north. The filled/bold symbols (wells) show δ values which fall on a mixing line between the isotopic composition of the Berchtesgadener Ache at Grödig and the precipitation sampled in Wals near Salzburg.

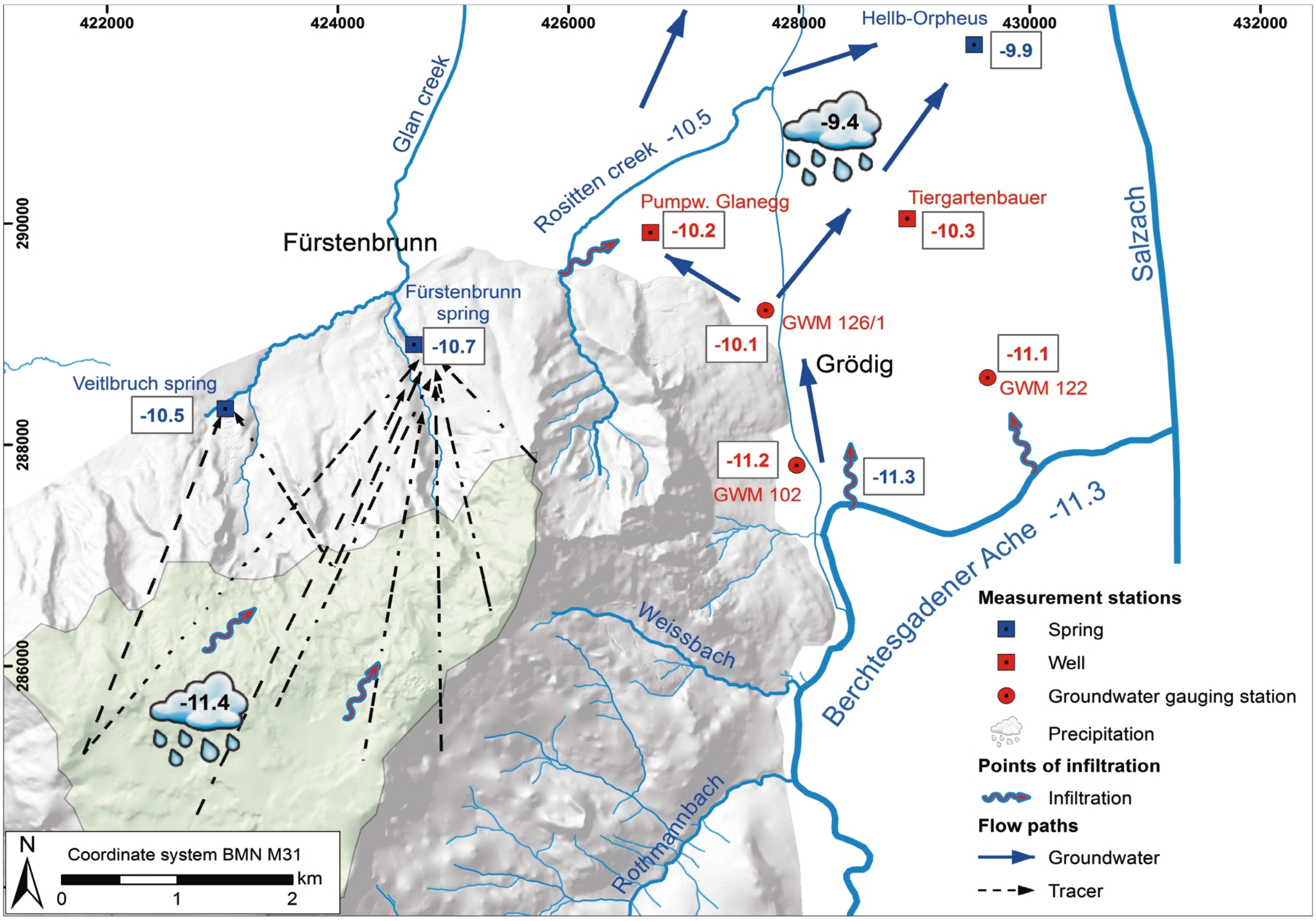

Figure 14: Simplified hydrogeological model of the dominant flow routes in the northern part of the Untersberg (based on tracer tests) and the adjacent Salzburg Basin as indicated by their O isotopic composition (values in per mil).

6 Conclusions

The mean temperature of the springs at Untersberg correlates roughly with the mean air temperature in the catchment. A clear relationship between groundwater temperature and air temperature can also be seen in the Salzburg Basin, as many wells show a temperature similar to the mean annual air temperature of 9.9 °C in Salzburg. The EC of the springs (83 – 436 µS/cm) is generally lower in comparison to the porous aquifer (240 – 750 µS/cm). There is a clear trend of increasing EC towards the basin and with rising distance from known infiltration points. The latter ones are the Rositten creek, Fürstenbrunn spring and Berchtesgadener Ache. The mean $\delta^{18}O$ value of the springs is around -10.5 ‰ and shows slightly more negative values and hence suggests a higher mean elevation of their catchment. An isotopic altitude gradient of -0.14 ‰/100 m was calculated using our precipitation data.

In the Salzburg Basin $\delta^{18}O$ isotope values are slightly higher (-10.0 to -9.5 ‰) and tend to increase further towards the basin center. This is mainly due to the infiltration of the Berchtesgadener Ache into the porous aquifer at St. Leonhard leading to lower $\delta^{18}O$ values in nearby wells. Also the EC of wells near the Berchtesgadener Ache is very similar to the EC of the river itself and fluctuations of the groundwater table correlate with changes in river discharge. Large changes of the groundwater table of up to 4 m in the Area of Glanegg and Grödig do also occur in winter. As the discharge of the karst system is very low at that time, water infiltrating via a "deep karst" cannot be the reason for these fluctuations of the groundwater level.

This study also shows that none of the parameters (temperature, EC, stable isotopes) allows to unequivocally differentiate between karst water (Fürstenbrunn sping, Rositten creek and possible other infiltration sources) and groundwater at Glanegg, as the latter one is recharged (partly artificially) by karst water of the Fürstenbrunn spring and the Rositten creek.

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