The Hydrogeology of the Northern Calcareous Alps between the Rivers Enns and Ybbs

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Abstract

A knowledge base which combines hydrogeology, isotope hydrology, hydrochemistry, rock and soil chemistry, geology, speleology and tectonics has been created for the Northern Calcareous Alps, at the border between Upper and Lower Austria, forming the basis for future studies on groundwater protection, vulnerability assessment, catchment area delineation and groundwater management. Limestones and dolostones dominate the area, forming large-scale karst water reservoirs. Limestone aquifers create springs with highly dynamic discharges, typical of karst areas, while dolostone aquifers represent a transition between karst and fissured rock, with large storage volumes and good retention capacities. A third class of aquifers, also used for water supplies, consists of Quaternary coarse-grained valley fills, fed by groundwater flowing from surrounding hard rocks. Hydrofacies correlates directly with lithofacies; dolostone catchments yield water with equal Ca and Mg concentrations and low Na, K and Cl contents whereas groundwater from limestones has lower Mg concentrations and a wider range of Na, K and Cl values. High sulfate levels occur in areas with gypsum-bearing strata. Trace elements in groundwater exist in very low concentrations, occasionally elevated in sandstones and shales forming the impermeable base of karst reservoirs. Time-series measurements of discharge were used to classify springs according to their flow dynamics. For many springs, the hydrographs correspond to the type of groundwater flow expected from the geology (karst springs in limestone areas, fracture system drainage in dolostone areas). However, some springs cannot be explained so readily. Adding time variations of hydrochemical composition allows the effects of rainwater mixing and shifts of the catchment area during climate variations to be demonstrated and the internal dynamics of the groundwater systems to be properly assessed. A new integrative classification scheme, based on groundwater flow type, discharge variation, hydrochemical composition and mineralization origin, successfully classifies all the studied springs and may be applicable to other karst regions.

Für die nördlichen Kalkalpen im Grenzbereich von Ober- und Niederösterreich wurde eine Wissensbasis geschaffen, welche die Disziplinen Hydrogeologie, Isotopenhydrologie, Gesteins-, Boden- und Wasserchemie, Geologie, Höhlenforschung und Tektonik kombiniert und als Grundlage für nachfolgende Studien des Grundwasserschutzes, der Beurteilung der Grundwassergefährdung, der Abgrenzung von Einzugsgebieten und der nachhaltigen Grundwassernutzung dient. Das Gebiet wird von Kalksteinen und Dolomiten dominiert, die als großräumige Karstwasserspeicher fungieren. Während Aquifere aus Kalkstein Quellen mit für Karstgebiete typischen, sehr dynamischen Schüttungskurven hervorrufen, stellen Dolomite einen Übergang zwischen Karst- und Kluftwasserführung mit großen Speichervolumen und hohem Retentionsvermögen dar. Eine dritte Klasse von Aquiferen bilden grobkörnige Sedimente der quartären Talfüllungen, die von Grundwasser der umliegenden Festgesteine gespeist und zur Wasserversorgung genutzt werden. Hydrofazies korreliert deutlich mit Lithofazies. Einzugsgebiete, die hauptsächlich aus Dolomiten aufgebaut sind, weisen gleiche Ca- und Mg-Konzentrationen und geringe Na-, K- und Cl-Werte auf, während Grundwasser aus Kalksteinarealen geringere Mg-Gehalte und eine hohe Schwankungsbreite von Na-, K- und Cl-Werten zeigt. Hohe Sulfatgehalte treten in Gebieten mit Gips führenden Schichten auf. Spurenelemente kommen in sehr geringen Konzentrationen vor, die nur in Sandsteinen und Schiefern, die unter den Karststöcken Grundwasserstauer bilden, stellenweise erhöht sind. Schüttungsganglinien dienten zur Klassifizierung der Quellen hinsichtlich ihrer Abflussdynamik. Bei vielen Quellen entsprechen die Ganglinien der Dynamik, die von der Geologie zu erwarten wäre (Karstquellen in Kalksteinarealen, Kluftwasserabfluss in Dolo-mitgebieten). Manche Quellen sind jedoch nicht so leicht erklärbar. Erst zusammen mit Zeitreihen der hydrochemischen Analysener-gebnisse können der Einfluss von Zumischung von Niederschlagswässern oder die Verlagerung von Einzugsgebietsgrenzen während Veränderungen der Großwetterlage erkannt und quantifiziert werden. Ein neues, integratives Klassifizierungsschema, welches auf Aquifertypen, Abflussverhalten, Variabilität der hydrochemischen Zusammensetzung und Herkunft der Mineralisation beruht, wird für die Gruppierung sämtlicher Quellen im Arbeitsgebiet erfolgreich angewendet und kann möglicherweise auch in anderen Karstregionen verwendet werden.

1. Introduction

At the border between Upper and Lower Austria, the Northern Calcareous Alps are dominated by Upper Triassic dolostones and limestones (Fig. 1), serving as large-scale karst water reservoirs. Even though only a few of these are currently used for drinking water, their importance for future provision and for existing water utilities should not be underestimated. However, apart from detailed studies at a local scale (hydrochemical monitoring of individual springs, tracer tests), very few regional studies have investigated the overall qualitative or quantitative groundwater potential of the reservoirs (Pavuza, 1983; Traindl, 1983; see review by Benischke et al., 2001). Their use as drinking water reserves coexists with other types of land-use, such as agriculture, forestry, local mineral extraction (especially dolostone) and tourism. For the purposes of groundwater protection, vulnerability assessment, catchment area delineation and future use for drinking water, there is a need for fundamental large-scale hydrogeological research.

Between 1992 and 2005, several major research projects investigated the hydrogeology of the area at a regional scale (Heinrich et al., 1995; Pfleiderer et al., 1999; Heinrich et al., 2000; Pfleiderer et al., 2005). The intention of this paper is to present some results from these projects. At the same time, the paper argues for a multidisciplinary approach to karst groundwater studies, in which data on hydrogeology, isotope hydrology, hydrochemistry, rock and soil chemistry, geology, speleology and tectonics are combined to characterize the hydrogeology of an area, describing aquifer properties and hydrofacies, and classifying springs and their catchment areas. By assimilating the information gained from various disciplines, this approach has proved highly effective. A systematic hydrogeological survey of the area, accompanied by mapping of hydrogeologically relevant tectonic elements, karst features and fracture systems, leads to an initial identification of aquifer types. Time-series measurements of spring discharge and conductivity and correlations with local precipitation patterns permit a preliminary description of aquifer dynamics. Monthly oxygen and hydrogen isotope data improve the characterization by indicating groundwater residence times and the locations of infiltration areas. Hydrochemical analyses of major ion and trace element contents in monthly groundwater samples further specify the effects of rainwater mixing and possible shifts of catchment areas during seasonal variations in weather conditions. Finally, correlation of hydrochemical data with the geochemical composition of soils and rocks occurring in the catchment area allows the origin of groundwater mineralization to be traced, natural background values to be quantified and the flux of dissolved solids through the system to be reconstructed. Only after all these processes have been well documented can one address the above mentioned topics of groundwater protection and management, catchment area delineation or vulnerability assessment.

2. Hydrogeology and tectonics

The study area (Fig. 1) is delimited by the river Enns in the west, the thrust fault between the Austroalpine (calcareous) and Penninic (flysch) units in the north, the Göstlingbach and Kleine Ybbs rivers in the east and the border with Styria in the south. Hydrogeological mapping of lithological units, tectonic structures and of discharge areas reveals three major groups of lithostratigraphic units within this part of the Northern Calcareous Alps (Fig. 1) - (a) limestones of the Middle and Upper Triassic and the Jurassic, (b) dolostones of the Middle and Upper Triassic and (c) sandstones and marls of either Lower or Upper Triassic and of Cretaceous age.

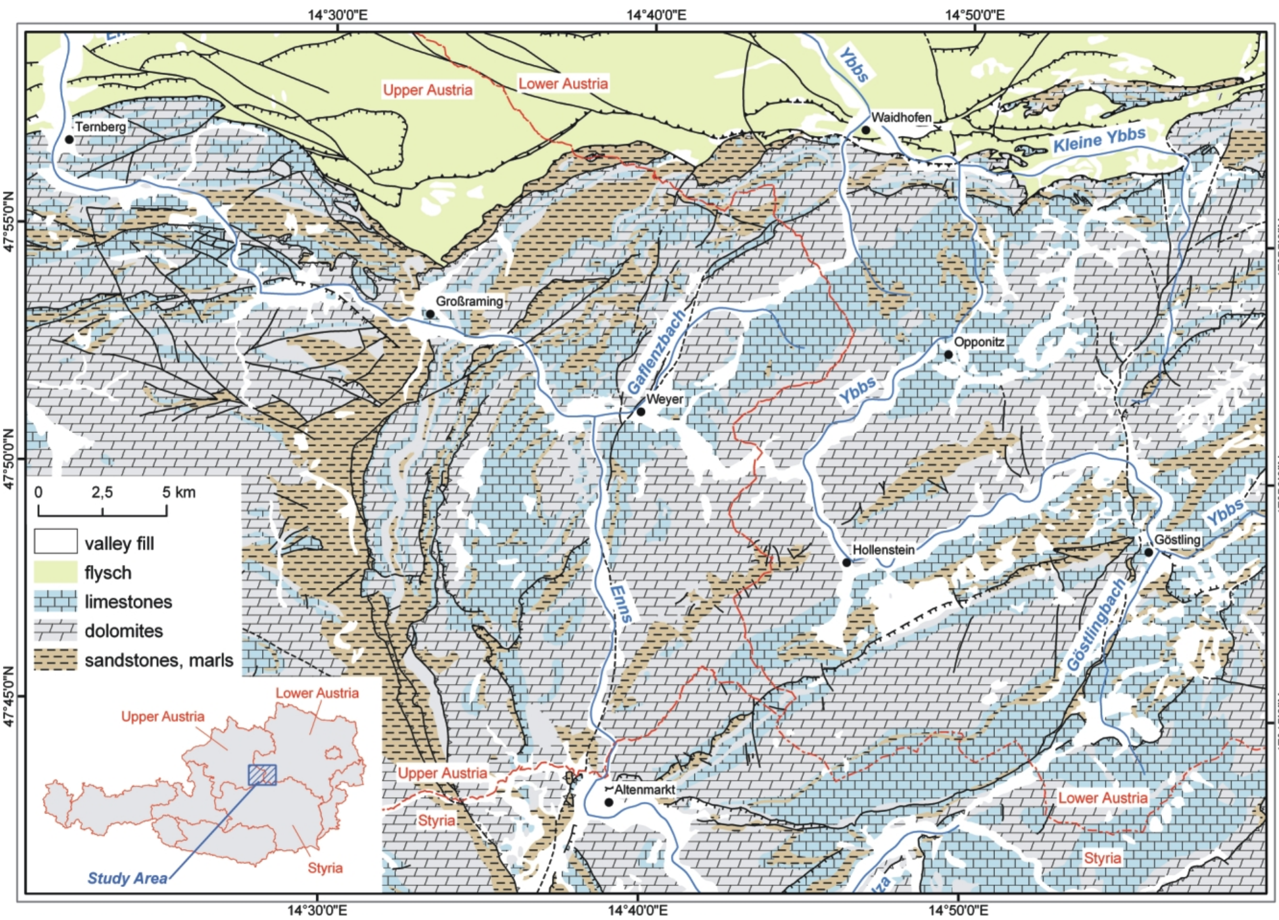

Figure 1: Geological overview of the study area, simplified after Schnabel (2002).

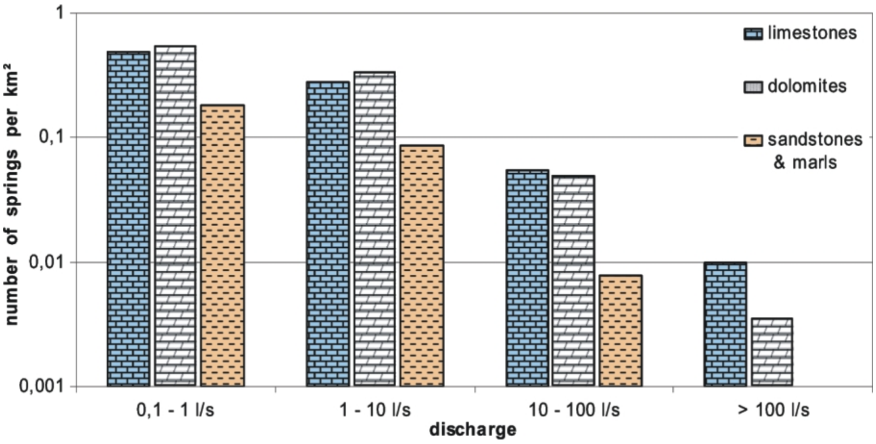

Figure 2: Number of springs per km² for the three major lithological groups, classified according to discharge during dry periods. Springs with high discharge occur more often in limestone areas, whereas small springs are slightly more frequent within dolostone areas.

Middle Triassic (Muschelkalk) and Jurassic limestones exhibit distinct karst features (Nagl, 1970; Plan, 2003), with groundwater flowing through caves, pipes and enlarged fractures. Flow rates at springs reach high values (up to several m^3/s) and typically show a large variability. Upper Triassic limestones (Opponitz Formation) are generally less karstified but contain gypsum-bearing strata, in which the combined dissolution of carbonate and sulfate leads to large voids, and springs again display karst spring characteristics. Discharge areas often coincide with tectonic fault zones or lineaments which constitute preferred flow paths within the aquifers. Surface runoff in limestone areas is minimal due to high infiltration rates.

In dolostone units, such as the Hauptdolomit and Wetterstein Formation, small-scale tectonic fracturing results in a large number of springs, each with a low, steady discharge (Q < 10 l/s). Aquifers possess good retention and filter capacity (Pfleiderer et al., 2002) and caves or pipes can be observed only occasionally, in areas where tectonic folding has increased the opening of fractures and dissolution becomes enhanced (Decker et al., 1998). Morphologically, dolomitic areas are characterized by narrow, V-shaped valleys in which the location of springs corresponds to, and varies with, the height of the water table. Such valleys often contain enough coarse debris to enable torrents and even rivers to disappear during dry periods, only to reemerge further down-valley.

Sandstones, shales and marls of Lower Triassic (Werfen Formation), Upper Triassic (Lunz Formation) or Cretaceous age yield little groundwater and act as relative aquitards (Pavuza and Traindl, 1984). In areas where these lithologies appear at the surface, groundwater recharge is minimal and surface runoff reaches a high percentage of total runoff. Numerous springs with very low, yet perennial, flow rates (Q < 0.5 l/s), very low mineralization (< 200 µS/cm electrical conductivity) and low pH values (~ 6) are typical for these areas.

Approximately 900 springs recorded during mapping as having a discharge of more than 0.1 l/s in dry periods were analyzed with respect to their frequency and their correlation with the lithology of the catchment area. For the three major lithological groups, the number of springs per km² is shown in Fig. 2. While springs with low discharge during dry periods (Q < 10 l/s) occur slightly more frequently within dolostone areas, large springs are more frequent in karstified limestone regions. Springs with catchment areas made of sandstone or marl are less numerous, especially those with high discharge.

Other field parameters recorded during mapping include electrical conductivity, pH and water temperature. These parameters have been used to identify spring water originating from sand-stone areas, as values of both conductivity and pH are distinctly smaller than for groundwater from carbonate lithologies. Since aquifers in sandstones are mostly shallow, they can also be recognized by high water temperatures (up to 13°C) in summer months. However, these field parameters are not suitable for distinguishing between limestone and dolostone dominance within a catchment area, as the distributions of values measured from the two lithologies overlap significantly (Pfleiderer et al., 2002). Only hydrochemical analyses of groundwater samples can help to make this distinction.

3. Hydrochemistry and geochemistry

To describe the groundwater mineralization and to increase the level of detail from the three lithological types to the full spectrum of lithofacies occurring in the study area, 344 groundwater samples were collected during dry weather conditions and analyzed for Ca, Mg, Na, K, SO_4, HCO_3, Cl, F and NO_3 ion concentrations. Fig. 3 shows the different water types named after ions present in concentrations > 20% meq/l (milliequivalent per litre). By far the most frequent water type is Ca-Mg-HCO_3 which is associated with dolostone areas. Analyzing the cumulative distribution function of Ca/Mg ratios allows further differentiation between dolomitic water types. A distinct group of spring water samples with Ca/Mg < 1.2 occurs in catchment areas made purely of the Hauptdolomit Formation, while Ca/Mg ratios of 1.2 - 5 occur where limestone forms an increasing part of the catchment area. The Ca-HCO_3 groundwater type is typical for, and statistically most frequent in Jurassic limestones (e.g. Kössen Formation), but also for marls of Upper Triassic (Lunz Formation) or Cretaceous age.

In addition to Ca and Mg, SO_4 represents a major ion well suited to further distinguish between hydrofacies. It originates from either gypsum-bearing strata within the Opponitz Formation or from evaporites of the Permo-Scythian rocks (Haselgebirge). While groundwater traveling through evaporites is of the Ca-SO_4 water type, the gypsum-bearing Opponitz Formation limestones and dolostones lead to mixed water types, such as Ca-HCO_3-SO_4 and Ca-Mg-HCO_3-SO_4. These sulfate water types are all far less abundant than dolostone or limestone waters (Fig. 3). In the field, an elevated sulfate content can be deduced from high electrical conductivities (> 500 µS/ cm for Ca-Mg-HCO_3-SO_4; > 1,000 µS/ cm for Ca-HCO_3-SO_4 and Ca-SO_4).

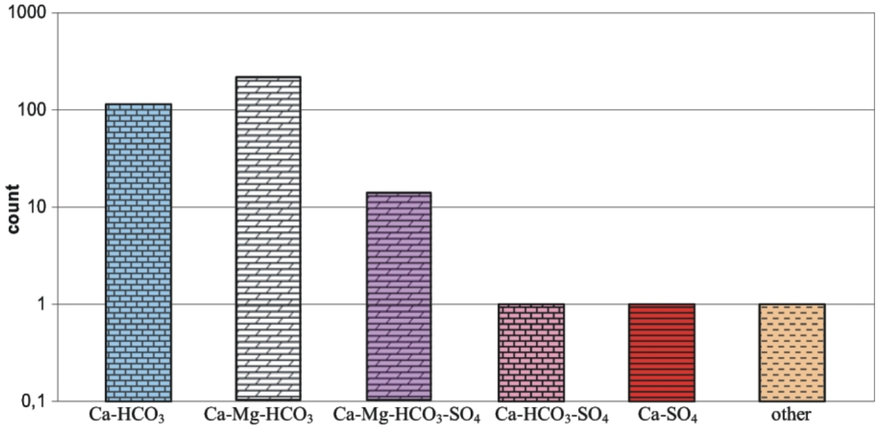

Figure 3: Frequency distribution of water types: Ca-HCO_3 occurs in catchment areas made of limestone, Ca-Mg-HCO_3 in dolostone areas, Ca-SO_4 in evaporites. Ca-Mg-HCO_3-SO_4 and Ca-HCO_3-SO_4 represent dolostone or limestone waters mixed with evaporite water. For the water type "other", concentrations are so low that no ion can lend its name for being a major component. This type is typical of groundwater from sandstones and shales.

Fig. 4 presents a Schoeller diagram of median values of major ion concentrations. The six water types differ most significantly in their Ca, Mg, HCO_3 and SO_4 concentrations. These ions are therefore well suited for inferring the lithological makeup of the catchment area. Within each water type they show little variability. On the other hand, Na, K and Cl concentrations show less characteristic differences between water types and the spread between individual samples of one water type is much larger. These ions are therefore less informative. However, extreme values of Na, Cl and NO_3 content are important indicators of the influence of agricultural activity on groundwater chemistry.

Similar results are obtained if major ion concentrations are considered as a closed data set and analyzed using compositional data analysis (Aitchison, 2003). This also singles out Ca, Mg and SO_4 as the most important components for sample classification, resulting in the same, statistically distinct groups of water types.

Quaternary coarse-grained valley fills form another class of aquifer, intensively used for water supply (Lipa et al., 1996). Natural springs in these soft sediments are mostly located close to valley flanks. Water samples clearly show the hydrochemical fingerprint of the neighboring hard-rock lithologies, which indicates that valley fills are at least partially fed by groundwater flowing from surrounding hard rocks. As Quaternary sediments were not the focus of this study, no samples were taken from groundwater wells situated near rivers. Hydrological and hydrochemical characteristics of groundwater from Quaternary aquifers and their interaction with karst aquifers form the subject of ongoing investigations.

The direct correlation documented between the dominant lithology in the catchment area and the major ions in the spring water is also seen in the trace element concentrations. In the study area, 132 whole-rock geochemical analyses reveal low trace element contents (sum of Co, Cr, Cu, Ni, Pb, Zn and V < 100 ppm) in carbonates and elevated values (> 250 ppm) in terrigenous sediments such as clays in the Permo-Scythian rocks, sandstones and shales of the Lunz Formation and Cretaceous marls (Losenstein, Tannheim and Schrambach Formations) (Pirkl, 1998; Pirkl et al., 2003). Occasional intercalations of marls within Upper Triassic limestones and dolostones show equally high trace element concentrations. This distribution is mirrored by 850 hydrochemical analyses of groundwater samples taken monthly at 47 springs. In carbonate areas, trace elements (Cd, Cr, Cu, Pb, Zn, Al, Fe, Mn, Li) occur in very low concentrations in spring water (total sum < 30 ppb) whereas in catchments dominated by sandstones and shales, Al and Fe contents alone often exceed 200 ppb, the indicator level set by the EU council directive 98/83/EC on the water quality for human consumption.

The spatial and temporal distributions of the data demonstrate clearly that generally these levels do not represent contamination due to human activity but reflect natural background levels (Pfleiderer et al., 2004). Most of the trace elements are also concentrated in soils overlying the sandstones and shales, and are mobilized during periods of intense precipitation or after the snow melt, and washed into the groundwater. However, some trace elements originate from non-natural sources; Pb and Cd concentrations are insignificant in lithologies within the study area, and hence the elevated levels (> 10 ppb Pb and > 5 ppb Cd) found in some dolostone aquifers must be the result of con-

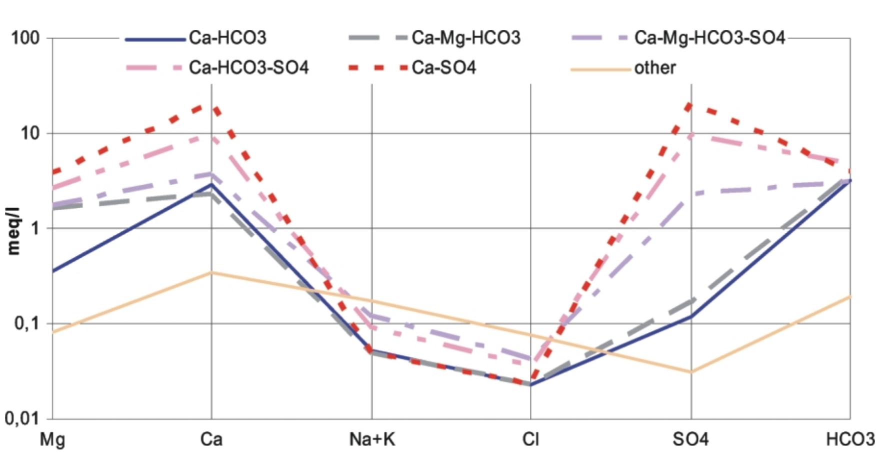

Figure 4: Schoeller diagram of median values of major ion concentrations for the six water types of Fig. 3.

tamination from airborne sources (immission). Spatial patterns and time-series analyses of the data support this conclusion.

4. Aquifer dynamics and classification

Time-series measurements of discharge shed more light on the flow dynamic properties of aquifers. Springs in limestone areas generally display karst spring characteristics, with a quick response to daily rain events and a large variability between maximum and minimum flow rates. On the other hand, springs in dolostone areas show less variable hydrographs, due to the slow and steady drainage of small fractures. However, some springs in dolomitic regions can exhibit properties of karstified catchment areas. Fig. 5 demonstrates hydrographs of springs from two dolostone aquifers. Although only 3.5 km apart and both having catchment areas of approximately 6 km², one aquifer shows clear signs of karstification while the other displays a dense pattern of regular microfractures. Preliminary interpretation of ^{3}H isotope data indicate that groundwater transit times in the karstified aquifer reach 6 - 7 years for the base flow through fissures and joints (Rank and Papesch, 2005). Hydrograph analysis shows a second flow component, consisting of rapid runoff (within several hours) of vadose water flowing through wide drainage channels. Transit times for the fractured dolostone aquifer amount to 12 - 15 years, with no superimposed component.

Fig. 5 clearly indicates that monthly monitoring intervals are insufficient to study flow dynamic properties of dolomitic karst aquifers. For example, the heavy rain which fell on August 11, 2002, and which caused widespread flooding over much of eastern Austria, is not seen in the measurements, as the signal had already passed through the system by August 21, 2002, the next monthly measurement time.

In addition to hydrographs and isotope analyses, time-series measurements of electrical conductivity help to differentiate the various flow components within aquifers. However, only time variations of major ion and trace element concentrations provide the necessary data to quantify rainwater mixing and to detect shifts of catchment areas during seasonal variations in weather conditions. For some of the springs in the study area, the hydrochemical makeup varies with the climatic season, especially if the catchment consists of heterogeneous lithologies. Therefore, we propose a classification scheme based in equal measure on the type of aquifer (porous, fractured, karst or epikarst), on the dynamic behavior of groundwater flow (variability with high frequency, low frequency or constant) and on the origin of hydrochemical composition (autogenic or allogenic). Table 1 illustrates schematically how springs and aquifers are grouped according to this combined classification, using examples from the typical lithologies studied. In practice, all the springs in the area could be classified, although naturally transitions exist between categories. As these lithologies occur throughout the Northern Calcareous Alps, the classification scheme may be useful for other areas with comparable geological and tectonic settings.

5. Conclusions

Upper Triassic dolostones and limestones represent large-scale karst water reservoirs in the Northern Calcareous Alps. So far, very few regional studies have carried out fundamental research on the overall qualitative or quantitative groundwater potential of these reservoirs. Systematic hydrogeological mapping of lithological units, tectonic structures and of discharge areas reveals three major hydrogeological groups within the lithostratigraphic units of the Northern Calcareous Alps - (a) limestones of Middle and Upper Triassic and of Jurassic age, (b) dolostones of Middle and Upper Triassic age and (c) sandstones and marls of either Lower or Upper Triassic and of Cretaceous age. Limestone aquifers mostly exhibit typical karst characteristics, including groundwater flow through caves, pipes and enlarged fractures. Flow rates at springs reach high values (up to several m³/s) and typically show strong variability. Discharge areas often coincide with tectonic fault zones or lineaments which constitute preferred flow paths within the aquifers. In dolostone areas, small-scale tectonic fracturing results in a high number of springs with low, steady discharges (Q < 10 l/s). Aquifers possess good retention and filter capacity. Large conduits can be observed occasionally where tectonic folding supports the opening of fractures and dissolution becomes enhanced. Sandstones, shales and marls of the Lower or Upper Triassic or of the Cretaceous yield little groundwater and act as relative aquitards. As an additional class of aquifers, Quaternary aquifers and their interaction with karst aquifers remain the subject of future investigations.

Hydrochemical and whole-rock geochemical analyses demonstrate a direct correlation between the composition of the main lithology in the

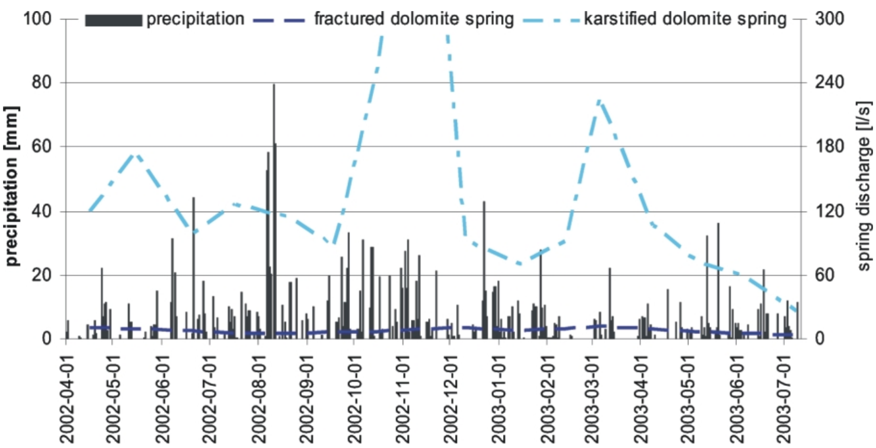

Figure 5: Daily precipitation and monthly spring discharge measurements of two springs, one in a fractured, the other in a karstified dolostone aquifer. While the catchment areas of the two springs are of the same size, discharge is drastically different both in size and variability. The fractured aquifer provides low and steady base flow, the karst aquifer responds quickly to daily events of precipitation.

aquifer type / origin of mineralization	**karst aquifers** strong component of conduit flow	**fractured aquifers** flow mostly through fissures	**epikarst or shallow fracture aquifers**	**porous aquifers**
	high frequency variability of flow rate, strong influence of rain events	fairly constant flow rate, strongly reduced influence of climate or short-term rain events	low frequency variability of flow rate, influence of climate seasons	moderate variability of flow rate, buffered influence of climate and short-term rain events
allogenic groundwater	limestone areas or karstified dolostone areas with at least intermittent input from other lithologies	dolostone aquifers with regular, small-scale fracturing; recharge from other lithologies	sandstone areas, marls	coarse-grained valley fill fed by groundwater from neighboring hard rock aquifers
autogenic groundwater	limestone areas or karstified dolostone areas with constant hydrochemical composition corresponding to the (homogeneous) lithology of the catchment area	dolostone aquifers with regular, small-scale fracturing; recharge, transit and discharge area made of dolostone	limestone beds in between marls	scree or slope debris; mass movements; deeply weathered or tectonically fragmented rock masses

Table 1: Classification of springs and aquifers according to aquifer type, flow dynamics and origin of mineralization.

catchment area and the major ions and trace element concentrations in the spring water. Six water types occur in the study area, with Ca, Mg, SO_4 and HCO_3 being the key major ions defining the hydrofacies. Trace element concentrations are naturally elevated in terrigeneous sediments such as sandstones, shales and marls, as well as in groundwater passing through, and in soils overlying, these rock types. Lead and cadmium, however, result from contamination through immission. A complete discussion of hydrochemical data applying statistical methods of compositional data analysis is being prepared by the authors.

Time-series measurements of discharge and ^{3}H isotope data reveal multiple flow components in karstified aquifers with transit times of 6 - 7 years for base flow through fissures and joints, superimposed by rapid runoff (within several hours) of vadose water flowing through wide drainage channels. These characteristics occur both in limestone areas and, less frequently, in karstified dolostone regions. In dolostone areas without karstification, springs show less variable hydrographs due to the slow and steady drainage of small fractures. Transit times for such aquifers are 12 - 15 years, with no superimposed flow components. Interpretation of the isotope data is so far only preliminary, although in-depth analysis of ^{3}H as well as of δ^{18}O data is expected to provide further insights into groundwater residence times and the elevation of infiltration areas.

By combining information on the aquifer type (porous, fractured, karst or epikarst), on the dynamic behavior of groundwater flow (variability with high frequency, low frequency or constant) and on the origin of mineralization (autogenic or allogenic), we propose an integrated classification scheme to group all types of springs and aquifers occurring in the study area. As the same lithostratigraphic units exist throughout the Northern Calcareous Alps, this combined classification may be useful for other areas with comparable geological and tectonic setting.

The study followed a multidisciplinary approach, by combining data on hydrogeology, isotope hydrology, hydrochemistry, rock and soil chemistry, geology, speleology and tectonics. The data have been integrated to characterize the hydrogeology of the area, to describe aquifer properties and hydrofacies, and to classify springs and their catchment areas. This approach proved very effective at assimilating information gained from various disciplines and led to the creation of a knowledge base which will form the fundamental basis for subsequent studies regarding groundwater protection, vulnerability assessment, catchment area delineation and groundwater management.

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