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The Aquifer Characteristics of the Dolomite Formation a New Approach for Providing Drinking Water in the Northern Calcareous Alps Region in Germany and Austria

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Abstract In the Northern Calcareous Alps karst springs and wells in porous groundwater bodies are the common sources of drinking water. While karst springs deliver water with short residence times and extreme variabilities in discharge, porous groundwater bodies include high risks of pollution according to intensive agricultural and industrial activities in the catchment areas. As alternative in this densly populated region in Germany and Austria the widespread but rarely used dolomitic unit Hauptdolomit (HD) was investigated. The purpose was to find indications to identify springs and wells dominated by an HD-aquifer and to find significant differences in age distribution and flow rates between HD-aquifers and karstified groundwater bodies. The assumption was that springs in HD-aquifers do not deliver very young waters and so show significantly lower vulnerability to pollution and less variability in discharge because HD features the necessary retention capacity and very slow diffuse flow on micro fissure systems and also exhibits larger fractures for water sampling and conduit flow. The main results of the study were: (1) the structural setting on the surface is not significant for the internal hydro-geological properties, (2) the hydrochemical signature gives a good evidence to identify an HD-catchment area, (3) the hydrograph curves show significantly less variability which is the most important advantage over karst springs, (4) mean residence times of 2 years to two decades are conducted by an age distribution which ranges very young as well as more than

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50 years old components, (5) the amount of water available from the dolomite formation considerably exceeds the predicted requirements.

Keywords Northern Calcareous Alps · Dolomite-formation · Groundwater age · Hydrochemistry · Drinking water supply

1 Background

Carbonate catchment areas are one of the most important sources for drinking water supply in many parts of the world. For many large cities for example in North America (LaMoreaux and LaMoreaux 2007), in China (Dong et al. 2005), in Australia (Leaney and Herczeg 1995) or in the middle east (Al-Charideh 2010) carbonate rocks constitute the most interesting, sometimes the only applicable groundwater reservoir. Also in Europe for example in Spain (Andreo et al. 2008), in Swizzerland (Doerflinger et al. 1999) and in Germany (Kralik 2001) many regions are supplied from carbonate catchments. In Austria about 4.1 Million inhabitants (50% of the population) get their drinking water from areas with carbonate rocks (Plan et al. 2009). According to the regional geology of Austria these areas are in the surrounding and within the Northern Calcareous Alps, Dolomites and Karnic Alps.

The specific hydro-geologic characteristics of carbonate aquifers due to karstification lead to important disadvantages over non-karstic fractured groundwater bodies concerning their ability to provide a sufficient drinking water supply: (1) high vulnerability to pollution in consequence of human activities (Kacaroglu 1999), and (2) significant variabilities in discharge of springs due to seasonal effects and rapid response to precipitation (Hölting 2009).

To get the problem of vulnerability in karst environments under control some assessment methods have been established during the last two decades (Doerflinger et al. 1999; Plan et al. 2009). In addition well established hydro-geological methods have been applied to specific carbonate aquifers to get a solid basis for defining protections zones. Geological mapping, Tracer tests, hydro-chemical investigations and isotope hydrology are described in many test sites. Birk et al. (2004) described the identification of localized recharge and conduit flow by combined analysis of hydraulic and physico-chemical spring responses in southwest Germany. Linan Baena et al. (2009) used the parameters temperature and electric conductivity as tools to characterize flow patterns in carbonate aquifers in southern Spain. Fiorillo and Guadagno (2010) analyzed karst spring discharges in relation to drought periods and precipitation. In this study based on Atkinson (1977) two main types of karst aquifers were described: a conduit type characterized by fast flow and a diffused type, built up by a less developed karst network with slow flow properties. Geophysical methods, especially geoelectric measurements were used to characterize karst-aquifers in coastal areas for example in Greece (Koukadaki et al. 2007) or Denmark (Poulsen et al. 2010). Those methods mainly deal with the significant differences in electrical-resistivity between fresh-water, brackish water and saltwater intrusions or high mineralized groundwater in contaminated sites (Rucker et al. 2010).

In all these above cited studies the term “carbonate aquifer” is used more or less synonymous with “karstic aquifer” and often karst structures are explicitly described as “results of limestone and dolomite dissolution” (for example Stotler et al. 2010)

The significant differences in solubility and therefore in the degree of karstification of dolomite was not really considered yet.

Hydro-geological investigations in the Northern Calcareous Alps between the rivers Enns and Ybbs in Austria (Pfleiderer et al. 2006) showed the significant differences in the hydro-geological properties of karstified limestones and fractured dolostones. Few large springs (10 to >100 l/s) with high variabilities in discharge are observed in limestone regions while dolomite areas show a large number of springs each with low (<10 l/s) but more or less steady discharge.

Similar observations had been made by Fellehner (2004) and Kassebaum (2006). In their PhD-theses they investigated the aquifer characteristics of the dolomite unit Hauptdolomit (HD) in two Bavarian regions (Bad Reichenhall and Reit im Winkl) in order to provide sustainable and well protected drinking water supply for these Bavarian communities.

The PhD-theses delivered the main basics of the present study. The role of brittle structures inside the aquifer was investigated via drilling programs in both areas. The drilling cores of three wells in each study area showed that strongly micro fractured ranges alternated with rarely fractured massive HD-layers. By means of borehole investigations and pumping tests it was shown that the main and rapid leakage into the borehole while pumping is bound to greater fractures while the presence of micro fissures leads to an enduring and steady admission. The typical HD-aquifer was described by Kassebaum (2006) as a medium of double porosity. The larger fractures representing fracture porosity are responsible for discharge. The micro fractures determine the matrix permeability which is responsible for infiltration and retention capacity. In the context of these investigations the questions of the hydro-chemical properties and the mean residence times in HD aquifer have not been satisfiable answered yet.

In Austria there are very few waterworks abstracting from HD aquifers although Austrian communities in comparable geological settings are faced with the typical problems of karstified or porous aquifers. In the community of Waidhofen/Ybbs a significant component of water supply deliver drinking water to the city of Waidhofen. Comprehensive hydro-geological, hydro-chemical and isotope hydrological investigations were made by ARC Seibersdorf research GmbH. The unpublished report was kindly provided by the water works owner.

While the mentioned study areas provide a good data base for starting further investigations on a regional base they were assigned as the western (Reit im Winkl) and eastern (Waidhofen/Ybbs) borders of the larger study region.

2 Methods

2.1 Choosing Suitable Measuring Points

To find suitable waterworks, springs and wells the water registers of the provinces of Salzburg and Upper Austria were screened to find sources of public water supply within large scale HD-catchment areas. The main reason for generally searching only public waterworks was the expectation of comprehensive dataset concerning discharge measurements, hydro-chemical data and probably isotopic data. Within the region between Reit im Winkl and Waidhofen/Ybbs 8 areas with 12 groundwater withdrawals (springs and wells) were found suitable for use to characterize this special type of aquifer. In Fig. 1 (upper part) the geographical extent of the alpine karst region is shown. In these calcareous parts of the alps, the HD-formation is present in different vertical and lateral extent. In the lower part of Fig. 1 the E-W-trending line in the middle of the picture shows the southern border of the HD-Formation within the investigated area of the Northern Calcareous Alps.

In Reit im Winkl two wells (ER1 and ER4) and one spring (Rabengschöss) were studied, in Bad Reichenhall three wells (Brunnen Listsee, Brunnen Listwirt and Brunnen Listanger) are part of the investigations. In the other regions in each case one well or spring was studied.

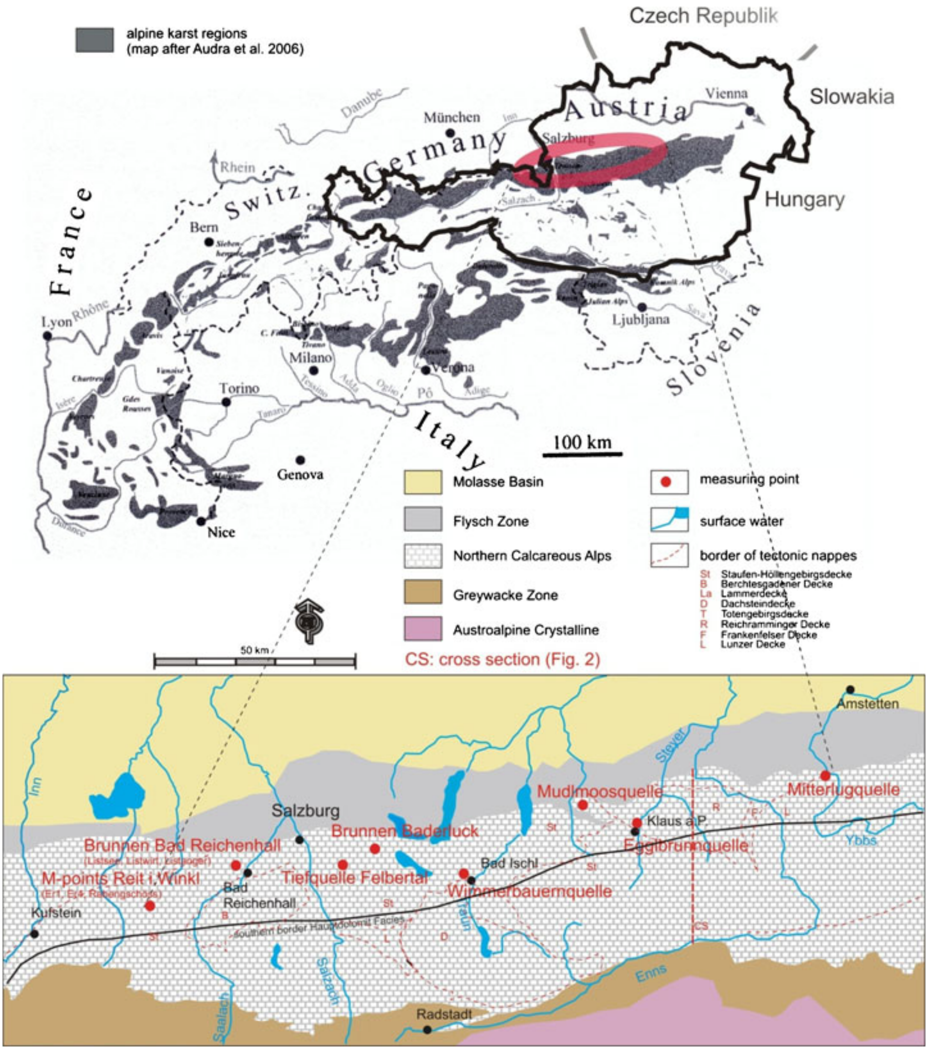


Fig. 1 Overview of the study area (simplified after Beck-Managetta and Matura 1980, Geol. Karte von Österreich 1:1,500,000) supplemented after Tollmann 1976)

In Fig. 2 a cross section in the eastern part of the larger study area shows the general structural situation and thickness of dolomite units up to 2000 m within the investigated area.

2.2 Hydro-Geological Mapping

Initially the topographical catchment areas of the chosen springs and wells were mapped geologically in order to verify the basic requirement to deal with HD-dominated catchment areas. In addition to the geological framework hydro-geological objects like seepages, swallow holes, further springs and signs of karstification were of special interest in each catchment area. Field parameters like electric conductivity, water temperature and the amounts of discharge were measured in samples from springs and surface waters.

Structural data were collected to explore the network of fissures in the catchment areas because they are supposed to be responsible for infiltration, flow velocity in the aquifer and variability in discharge.

2.3 Hydro-Chemistry

The analysis of the hydro-chemical composition of the groundwater in the investigated areas was generally based on the assumption that precipitation, on its way between infiltration and discharge alters depending on the geological setting of the aquifer. So there must be a characteristic composition for water from a pure HD-aquifer and the hydro-chemical setting must be different due to chemical impacts of other formations.

Physico-chemical parameters like temperature and electric conductivity were measured in the field for getting a first advice about the flow patterns in the aquifer (Linan Baena et al. 2009). In addition hydro-chemical analysis focused on the main ions Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Sulphate

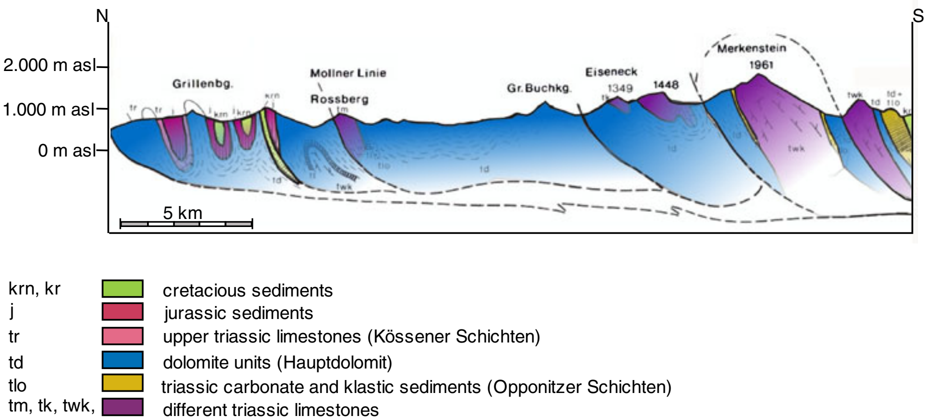


Fig. 2 N–S cross-section in the eastern part of the study area (simplified after Plöchinger 1980)

($SO4^{2-}$), Chloride (Cl^-) and Hydrocarbonate (HCO^{3-}) because those are the most important parameters to be considered in the formations of the Northern Calcareous Alps.

One important topic was the Ca/Mg-ratio which should be 1 in a pure HD-catchment area (Merkel 1983; Fellehner 2004). The dominance of Ca^{2+} (Ca/Mg-ratio >1) indicates appearance of limestones in the catchment area.

Other ions should not play a major role in the composition of HD dominated water. Appreciable concentrations of Na^+ and Cl^- for example are indicators of the presence of halite. $SO4^{2-}$ would be a sign for gypsum within the aquifer. These parameters could be regarded as indicators for an influence of "Haselgebirge" (formation of lower Triassic shale, gypsum and salt) or "Raibler Schichten" (upper Triassic sequence consisting of clastic sediments, carbonates and evaporites) in the catchment area which are supposed to confine the convenient properties of the HD-dominated aquifer concerning its suitability as drinking water supply.

Because most of the chosen waterworks are controlled by communities, some hydro-chemical data were available for the investigations. For some test points it was necessary to produce our own data by means of sampling and laboratory analysis.

The data were processed by using the software Aquachem 4.0 by Waterloo Hydrologic Inc. to show the concentration in charts and to work it out statistically. Hydro-chemical modeling using the software PhreeqC (Parkhurst and Appelo 1999) had the aim of checking the plausibility of the analyzed concentrations and to calculate saturation indices. The evaluation of the saturation indices for dolomite and calcite in combination with the Ca/Mg-ratio was used to distinguish between HD-water, limestone-dominated water and water influenced by low mineralized run off of precipitation.

2.4 Isotope Hydrology

Isotope methods were used to determine the mean elevation of the catchment areas and to get a first idea of the mean residence time and the age distribution of the investigated springs.

In combination with hydro-geological and geological data the effect of fractionation with altitude of the stable isotope ^{18}O was used to determine the mean elevation of the infiltration areas. The variability of the $^{16}O/^{18}O$-ratio over the hydrological year gives a first overview of the mean residence times because seasonal deviations in precipitation are evident in groundwater with relatively short mean residence times while a longer residence time (some years) attenuates any seasonal effects (Moser and Rauert 1980; Schneider et al. 2003).

To determine mean residence times in detail the radioactive isotope tritium (half life 12.32 years $\pm$8 days) (Clark and Fritz 1999) was used. For two study areas (Bad Reichenhall and Waidhofen) time series of about 20 and 4 years respectively were available, in other areas only data sampled in the years 2005 and 2006 were used for dating. Because of the extreme man-made increase in tritium concentration in the atmosphere in the 1960's (Clark and Fritz 1999) detailed knowledge of the input concentration is of importance for calculating the age distribution. Therefore weighted long-term measurements of tritium in precipitation were used as input function. Data of appropriate measuring points of the Austrian network of isotopes in precipitation (ANIP) published in Humer (1995), Kralik et al. (1998, 2005) were used for creating input functions for each test area.

To improve the result of isotope investigations micro pollutants like CFC and SF_6 were used. The world wide concentration of these micro pollutants in precipitation has increased since the 1950's. The development is known by international long-term measurements (Oster 2002) which have been used as input function.

Tritium based residence times and the adjustments via micro pollutants were calculated by using the program MULTIS by Richter and Szymczak (1992).

3 Results

3.1 Geological Setting, Tectonics and Aquifer Dynamics

The test points are located within the tirolean units on the northern edge of the Northern Calcareous Alps embedded in the stratigraphical units of triassic sequences. The more western areas between Reit im Winkl and Mudlmoosquelle (Fig. 1) are parts of the Stauffen-Höllengebirgs nappe. The eastern study areas are in the range of Reichramminger nappe and Frankenfelser-Lunzer nappe. Although the proximate environment of each studied spring is made up of HD, the situation in the catchment areas differ and may be affected by limestone-dominated overlying units.

As hydro-geological properties and the dynamic behavior of an HD-aquifer strongly depend on the brittle structures, structural data and the characteristic of fractures were documented in the field. Hydro-geological features like the occurrence and the spatial arrangement of further springs, surface run offs, indicators of karstification and seepages were sampled to characterize the aquifer. The main results of the field survey are listed in Table 1.

In only two of the catchment areas (Wimmerbauernquelle, Mitterlugquelle) no other units but HD were found. The discharge of Tiefquelle Felbertal may be affected by moraine sediments. In the catchment areas of Brunnen Baderluck, Mudlmoosquelle and Egglbrunnquelle different limestone units were found in the remote parts of the catchment areas.

The field survey in some of the test sites in the range of Stauffen-Höllengebirgs nappe showed springs leaking from steeply dipping macro fractures striking more or less in E-W or in N-S-direction. The more eastern situated springs are results of NW-SE (Egglbrunn) and N-S (Mitterlug)-striking fractures, whereas the main joint set in the catchment area of Mitterlugquelle is NW-SE and NE-SW-directed.

Besides these bigger scale fractures, small-scale brittle structures play an important role in the dynamic behavior of the aquifer and lead to the characterization as double porosity medium (Kassebaum 2006). The approach of a double porosity model has been developed over the last five decades to describe flow and transport phenomena in fractured groundwater bodies (Moutsopoulos and Tsihrintzis 2009).

As characteristic omnidirectional micro fractures in the HD-unit are regarded as responsible for infiltration and for retention capacity, these small scale structures

Table 1 Basic data of field survey in some of the study areas

Study area	Geological formations besides HD	Direction of main joint sets	Direction of the spring relevant fracture	Presence of micro fissures	Spring situation in the catchment area	Distinctions
Tiefquelle Felbertal	Moraine		Steep ENE striking fracture, open width decimeter	Seperate mircofractured areas, HD for the most part massy	Widespread diffuse discharge, only few small springs	Scale deposits in the range of diffuse discharge
Brunnen Baderluck	Limestones (Dachsteinkalk, Oberalmer Schichten) moraine		Unknown	Seperate mircofractured areas, HD for the most part massy	Very rare diffuse run off, no further springs in the whole mapped area	Black bituminous layers, distinctive banking
Wimmerbauernquelle	No extreneous units		Steep N-striking joint sets	Very few sperate microfractured areas, HD for the most part massy	No further springs, little creeks E and W of the spring border the catchment area	Relatively low conductivities and high temperatures, very steady discharge
Mudlmoosquelle	Limestones (Plattenkalk) talus material		NNE-striking fracture under debris	No microfractured areas	Many small springs, obviously near surface water	
Egglbrunnquelle	Limestones (Riffkalke)		WNW-striking fractures	Widespread strongly microfractured parts in the cachtment area, massy HD in the proximity of the spring	Two other small springs lateral to eggelbrunn, no further springs	
Mitterlugquelle	No extreneous units		N-striking morphological structure, direction not found in exposures	Microfissures widespread in the cathment area, HD-detritus	No further springs but some diffuse run offs	Spring not bound to the main joint set in the catchment area

While measuring points within Stauffen-Höllengebirgs nappe are based on N or E-striking fractures, the more eastern situated catchment areas are dominated by NW- or NE-striking structures. In every study area micro fissures are not developed laminary, further springs, surface run offs etc. are rare in each area were of special interest. In Table 1 it is shown that the presence of micro fissure structures on the surface strongly differs in the study areas. Widespread micro fractured surfaces were only detected in the catchment areas of Egglbrunn and Mitterlug. Contrary to the expectations no widespread micro fracturing was found the on the surface of the other catchment areas.

The results of the field survey are consistent with the findings of the borehole investigations in Bavaria (Fellehner 2004; Kassebaum 2006) with strongly micro fractured ranges alternating with only slightly fractured or massive HD-layers.

It is noticeable that very few springs or surface run offs were found and significant karst formations are almost completely missing in all studied sites. Karstification was found only in the overlying limestone units in some of the studied catchments.

To evaluate the influence of the mapped geological surface features on the aquifer dynamics it must be seen in conjunction with the discharge dynamics of the studied springs. Although the frequency of measurements and the observed time ranges differ strongly, the measured discharge variations can be used to characterize each aquifer. The measured values are shown in Fig. 3.

While there is a very steady discharge in Wimmerbauernquelle, a moderate seasonal variation is observed in the springs of Tiefquelle Felbertal and Mitterlugquelle. Extreme variations are detected in Egglbrunnquelle and Mudlmoosquelle. Comparing the two available hydrograph curves over 1 year of Egglbrunnquelle and Mitterlugquelle the differences are obvious. While Egglbrunnquelle shows a very rapid reaction to precipitation, a very fast decrease in dry periods and only a little influence of seasonal variations Mitterlugquelle shows a strong and sustained increase in discharge at the time of snowmelt in springtime, moderate reactions to precipitation but significant seasonal dependent variations. The ratio of highest and

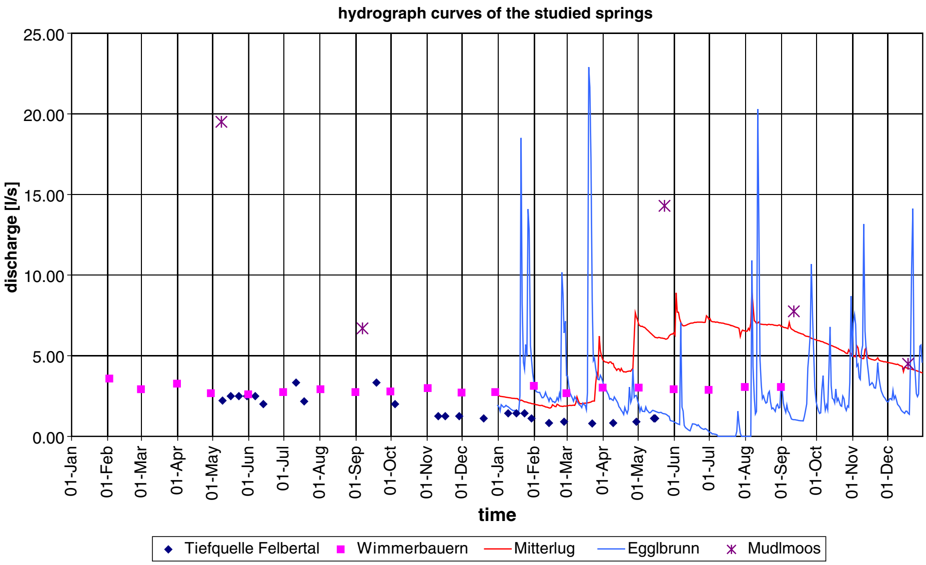


Fig. 3 Discharge variations of the studied springs. Relatively steady discharge in Wimmerbauernquelle, Tiefquelle Felbertal and Mitterlugquelle is of significant difference to the strong variations in discharge in Mudlmoosquelle and Egglbrunnquelle

lowest discharge at Egglbrunnquelle is in the range of 10:1 compared to a ratio of 4:1 at Mitterlugquelle. Regarding the results of the field survey and the observed discharge ratios of the different springs two facts are obvious. (1) The presence of micro fractures as a result of tectonic stress and weathering on the surface obviously does not affect the discharge variations and the aquifer dynamics because the absence of those structures on the surface does not reflect the internal structural character of the groundwater body. (2) The presence of karstified limestone in the catchment area significantly influences the hydrograph curve of a spring within a HD-dominated catchment area. While springs in catchment areas without any contact to limestone units show a steady discharge the test points influenced by limestone units in the adjusted catchment area show the typical flow behaviour of karst springs with strong variabilities in the flow rates. This observation may be explained as a result of karstification by mixing corrosion (Appelo and Postma 2005) when limestone influenced and pure dolomite waters are mixed within the HD-aquifer.

3.2 Hydro-Chemical Classification

Temperature and electrical conductivity of the springs and wells were measured regularly over a period of 1 year in order to determine the influence of short-term infiltration and discharge which leads to seasonal variations in temperature and to dilution shown by a decrease in conductivity while increasing discharge. As lower temperatures are a sign for higher altitudes (Linan Baena et al. 2009), the mean temperature gives an overview of the mean elevation of the catchment area.

Temperatures of all observed test points vary between 6 and 10°C except Wimmerbauernquelle which shows very constant temperatures of about 11.5°C.

Concerning the electric conductivity there are four groups of springs shown in Fig. 4a). One group consists of the measuring points in Reit im Winkl, Egglbrunnquelle and Brunnen Listsee. This group shows conductivities between 300 and 350 μS/cm. A second group consisting of Brunnen Listanger, Brunnen Listwirt and Brunnen Baderluck exhibits conductivities in the range of 400 to 450 μS/cm. The third group built of Mitterlugquelle and Tiefquelle Felbertal is characterized by strong variations in conductivity in the range of 300 to 450 μS/cm (Mitterlugquelle) and 350 to 500 μS/cm (Tiefquelle Felbertal). While conductivity increases with temperature in Mitterlugquelle it is obviously independent of temperature in Tiefquelle Felbertal.

The fourth group consists only of samples from Wimmerbauernquelle and shows the lowest conductivities between 250 and 300 μS/cm.

To identify a dolomitic aquifer by means of hydro-chemical data first of all the Ca/Mg-ratio should be significantly different from limestone aquifer dominated waters (Fellehner 2004). Because of the lower concentration of Mg in limestones and the smaller dissolution rate of Mg-calcite (Appelo and Postma 2005) the Ca-cations should dominate limestone influenced waters whereas the Ca/Mg-ratio of dolomite waters should be in the range of 1. In Fig. 4b) this ratio is shown for the observed springs and wells. In all samples the Ca/Mg-ratio ranges between 1 and 2 but two groups can be distinguished. One group consisting of the wells and the spring in Reit im Winkl and the springs Mitterlug and Wimmerbauernquelle shows ratios which are close to 1 (±0.2). The other group shows ratios in the range of 1.5 to 2 and represents groundwater influenced by both dolomitic and limestone units.

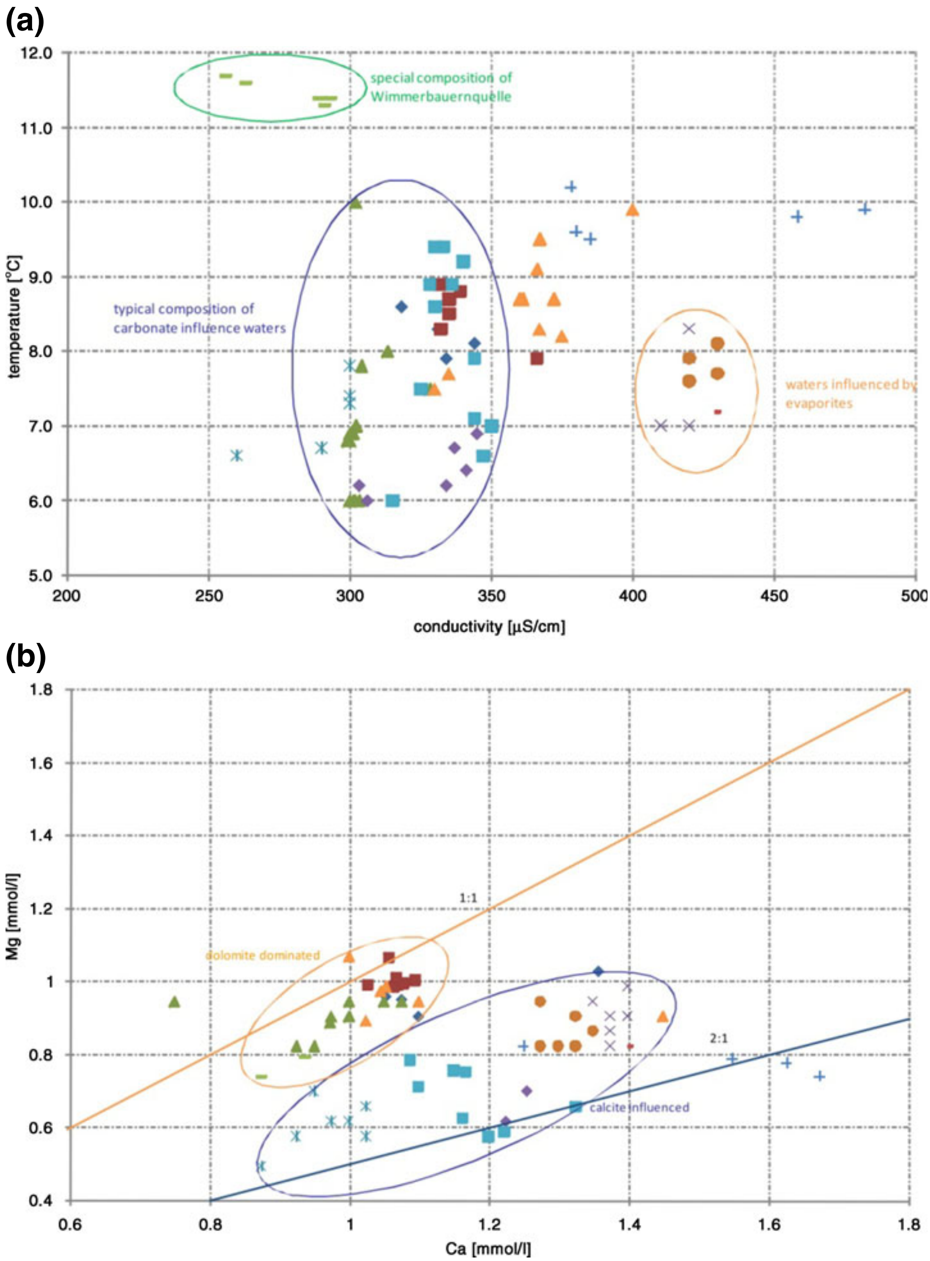


Fig. 4 Field parameters and hydrochemical composition of the investigated test points. Typical conductivity values of 300 to 350 µS/cm identify carbonate waters without any influence of other units, Ca–Mg ratio near to 1 is a characteristic sign for a dolomitic aquifer

Figure 4c) shows the correlation of $SO4^{2-}$ concentration with Ca/Mg-ratio. The group of sulphate influenced springs is identical to the group of higher conductivities shown in Fig. 4a).

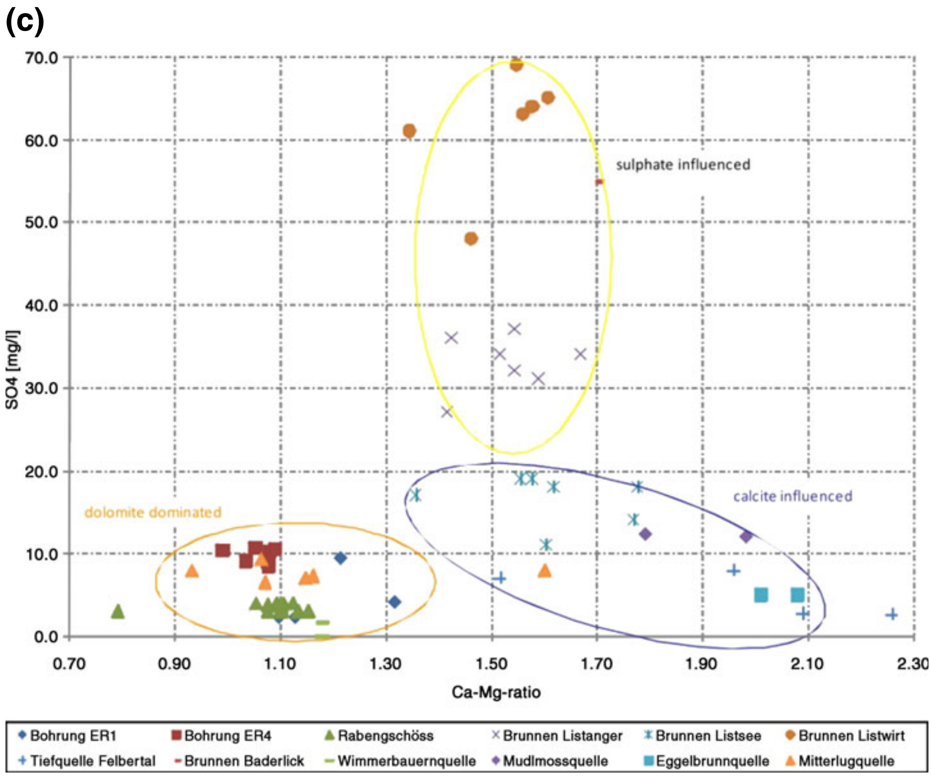


Fig. 4 (continued)

The interpretation of physico-chemical data shows that groundwater in calcareous or dolomitic aquifers have mean electric conductivities in the range of 300 to 350 µS/cm. A higher total mineralization is caused in the participation of other components like gypsum or halite for instance and indicates evaporitic units in the catchment area. Lower conductivities measured in Wimmerbauernquelle must be seen in combination with the observed significantly higher water temperatures. As carbonate dissolution is an inverse function of water temperature (Plummer and Busenberg 1982) the absence of other components but carbonates combinated with the observed higher temperatures must lead to a lower total mineralization. The possible reasons for the very constant and relatively high water temperatures measured in Wimmerbauernquelle will be discussed in Section 4.2.

Hydro-chemical modeling using the software PhreeqC was done in order to check the plausibility of the analyses and to calculate saturation indices of the essential phases. The calculations showed that in all samples the phases of gypsum, anhydrite and halite are definitely unsaturated. In consideration of the high solubility of these phases the findings prove that there are no important deposits of evaporites in the investigated aquifers although small amounts of evaporitic influence were detected in some of the springs. Only the carbonate phases of calcite and dolomite are eminent for the hydro-chemical composition.

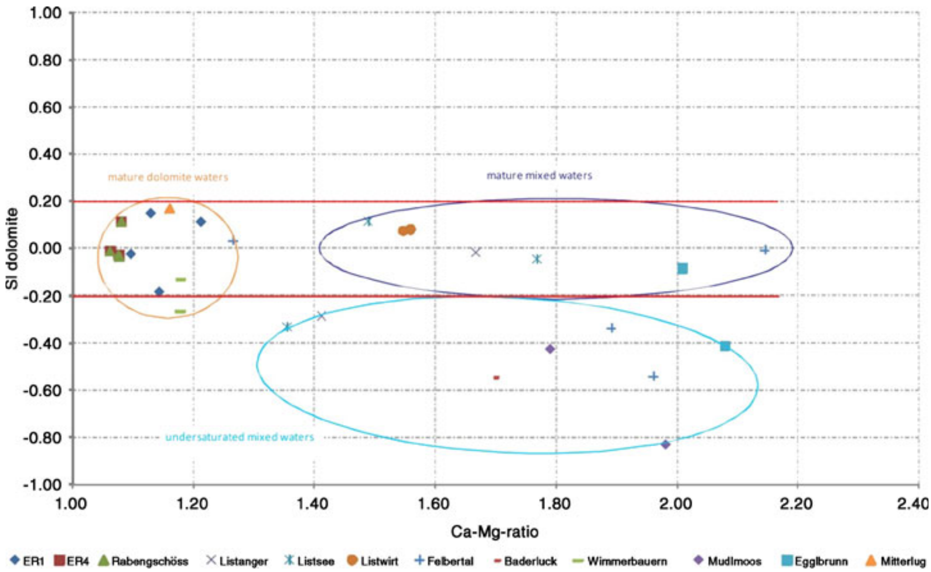


Fig. 5 Ca–Mg ratio versus SI Dolomite. Three groups of water types can be defined considering Ca/Mg rati4o and saturation indices of dolomite. Mature dolomite water shows a Ca/Mg ratio <1.2 and is saturated in the dolomite phase. The influence of limestone in the range of the aquifer leads to a widespread group of mature mixed water or unsaturated water

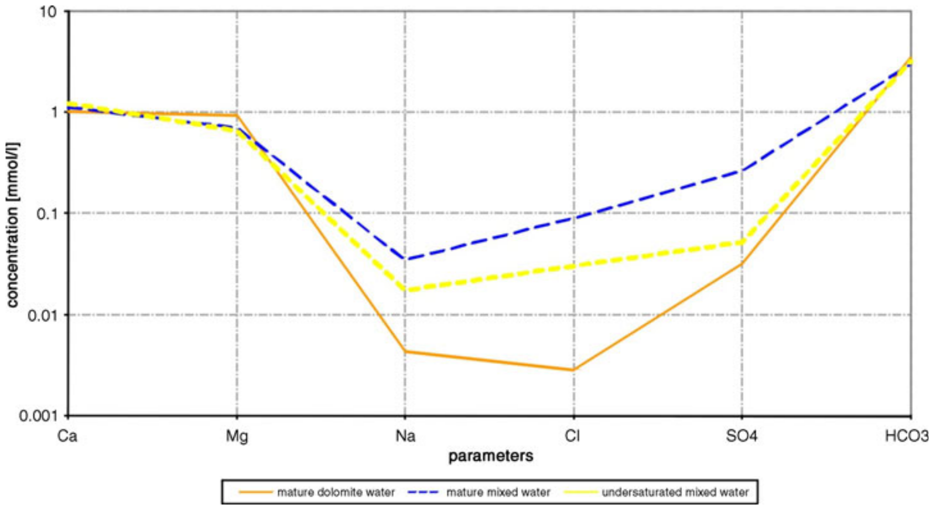


Fig. 6 Schoeller plot for characterizing the hydrochemical composition of the measuring points (median values). The three groups of water developed in consideration of saturation indices show a characteristic hydro-chemical composition considering the main parameters Ca, Mg, Na, Cl, SO_4 and HCO_3

Considering the saturation indices most of the samples are in equilibrium with calcite. The samples showing a Ca/Mg-ratio close to 1 are also saturated or only slightly subsaturated in dolomite, whereas some of the samples showing a Ca/Mg-ratio close to 2 are clearly subsaturated in dolomite.

Concerning the relation between Ca/Mg-ratio and the saturation index of dolomite, shown in Fig. 5, three groups of water types can be defined: (1) dolomite water type in equilibrium with dolomite, (2) mixed water type, saturated in dolomite and (3) mixed water type, subsaturated in dolomite.

The schoeller plot in Fig. 6 shows the characteristic composition concerning the most important parameters of the observed springs and wells by means of median values and approves the above described grouping.

The median values of the three water types show differences in the Ca/Mg-ratio as well as in the concentrations of extraneous parameters like Na^+, Cl^- and ${SO_4}^{2-}$.

The different approaches to classify the investigated aquifers on the base of their hydro-chemical settings are shown in Table 2. It shows that a pure dolomitic aquifer delivers groundwater of Ca–Mg–HCO_3-water type, free of sulphate (or other extraneous parameters) and in equilibrium with dolomite.

3.3 Isotope Hydrology

Concentrations of the stable Isotope ^{18}O were measured quarterly over 2 years to estimate the mean residence times and the fraction of young components (less than 3 years old water) in the discharge via regarding seasonal variations. The sampling was done during dry periods to avoid the influence of rapid run off of precipitation like it was observed for example in Egglbrunnquelle (Fig. 3).

Figure 7 shows the $\delta^{18}O$-values measured in the years 2005 and 2006. Only the test points Tiefquelle Felbertal and Brunnen Baderluck show significant variations. Obviously these two measurement points deliver a significant amount of very young water even in the base flow.

To determine the mean residence time in detail tritium concentrations were measured in the period of 2005 and 2006. Some long-term measurements were available for the test points in Bad Reichenhall (Brunnen Listsee, Listanger and Listwirt) and for Mitterlugquelle. In combination with CFC and SF_6-data measured in Mitterlugquelle, Egglbrunnquelle and Brunnen Baderluck, the mean residence times were calculated by using the software MULTIS (Richter and Szymczak 1992). Regarding the hydro-geological situation and the hydro-chemical classification the best fit between output function and measured values was calculated for each test point.

Generally the exponential model (EM) (Moser and Rauert 1980; Hebert 1999) represents the situation in a dolomitic aquifer described as double porosity medium consisting of large fractures combined with micro fracturing (Kassebaum 2006) which allows a perfect mixing in every part of the groundwater body. Karstification in limestone dominated units as well as the observed lack of micro fractures in the dolomite-dominated sections lead to a partial conduit flow and a mixed discharge model with a more or less formative participation of piston flow components (PM). Therefore it was necessary to determine the discharge model for each measurement point based on the results of field survey and of the hydro-chemical characterization. In Table 3 the appropriate discharge models combined with the hydro-chemical characterizations are listed.

Table 2 Classification of springs and wells by different approaches

Measuring point	Water type (>20%)	Ca–Mg-ratio (≤1,2)	Classification by sulphate concentration	Classification by hydrochemical modeling
			Sulphate > 10 mg/l	
Reit i. Winkl, ER1	$Ca–Mg–HCO_3$	Dolomitewater	Free of sulphate	Mature dolomite water
Reit i. Winkl, ER4	$Ca–Mg–HCO_3$	Dolomitewater	Free of sulphate	Mature dolomite water
Reit i. Winkl, Rabengschöss	$Ca–Mg–HCO_3$	Dolomitewater	Free of sulphate	Mature dolomite water
Bad Reichenhall, Listanger	$Ca–Mg–HCO_3$	Mixed water	Sulphate	Mature mixed water
Bad Reichenhall, Listsee	$Ca–Mg–HCO_3$	Mixed water	Sulphate	Mature mixed water
Bad Reichenhall, Listwirt	$Ca–Mg–HCO_3–SO_4$	Mixed water	Sulphate	Mature mixed water
Tiefquelle Felbertal	$Ca–Mg–HCO_3$	Mixed water	Free of sulphate	Undersaturated mixed water
Brunnen Baderluck	$Ca–Mg–HCO_3–SO_4$	Mixed water	Sulphate	Undersaturated mixed water
Wimmerbauernquelle	$Ca–Mg–HCO_3$	Dolomitewater	Free of sulphate	Mature dolomite water
Mudlmoosquelle	$Ca–Mg–HCO_3$	Mixed water	Sulphate	Undersaturated mixed water
Egglbrunnquelle	$Ca–Mg–HCO_3$	Mixed water	Free of sulphate	Undersaturated mixed water
Mitterlugquelle	$Ca–Mg–HCO_3$	Dolomitewater	Free of sulphate	Mature dolomite water

The measuring points in Reit im Winkl, Wimmerbauernquelle and Mitterlugquelle are identified as dolomitic waters while every other points show a significant influence of limestones. Brunnen Listwirt Bad Reichenhall and Brunnen Baderluck exhibit the influence of evaporites

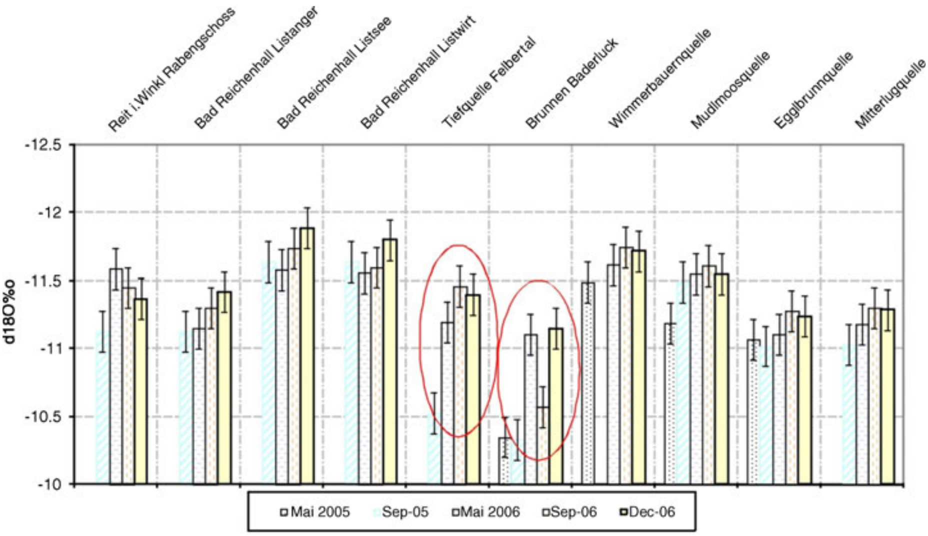


Fig. 7 δ^{18}O variations in the years 2005 and 2006. Only the values of Tiefquelle Felbertal and Brunnen Baderluck exhibit significant variations over the observation time which must be interpreted as influence of very young water components. All other values are nearly steady considering the measurement error

For some of the test points the dating via tritium was verified by measuring the concentrations of CFC (Mitterlugquelle) or SF_6 (Tiefbrunnen Baderluck and Egglbrunnquelle). By means of the example Mitterlugquelle the approach is shown in Fig. 8.

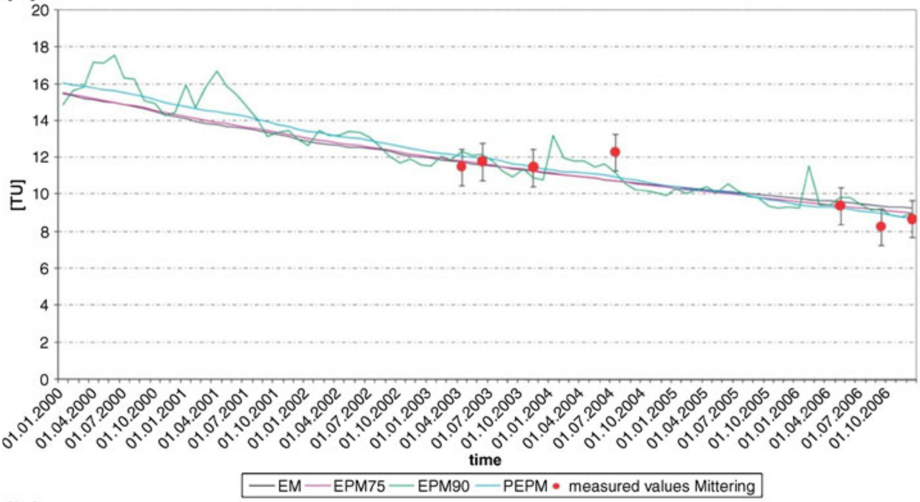
Figure 8a shows the results of the calculated output functions using different flow models and the measured values of Mitterlugquelle. The example shows that for recent samples (only 7 samples taken in the time period 2005 to 2006 were available for this test site) different flow models lead to very similar output functions because of the relatively low variations of Tritium input over time but the different input functions also lead to very different mean residence times (Fig. 8b). So it is not possible to determine the most appropriate flow model only in choosing the best fitting output function. Considering the hydro-geological situation also does not lead to a clear advantage for one of the regarded flow models. For this reason it is useful to implement a second tracer to find the flow model which leads to the best accordance for both micro pollutant and isotopic tracers. As the table in Fig. 8b shows the exponential model leads to the best result for Mitterlugquelle. In the current case the tracer CFC11 was used. The combination of Tritium data and CFC11 data is additionally shown in the harp-diagram after Bauer et al. (2002) or Schneider et al. (2003), shown in Fig. 8c. In Fig. 8c the inverse calculated residence times for CFC11 and ^{3}H-concentrations considering an exponential flow model were plotted in a scatter diagram. The combination results in a so called harp diagram which is based on input functions for both parameters. In the same scatter diagram the measured CFC11 and ^{3}H-concentrations of the samples of Mitterlugquelle were plotted to determine the mean residence time and contingent of recent water (younger than 50 years (after thermonuclear bomb testing). In the example nearly 100% of the

Table 3 Basic results of groundwater dating considering geological and hydrochemical results of the study

Measuring point	Geological units	Classification by hydrochemical modelling	Best fitting discharge model	Calculated mean residence time (Years)	Components younger than 1 year (%)	Components older than 50 years (%)
Reit i.Winkl Rabengschöss	Hauptdolomit	Mature dolomite water	EM	10.5	9.1	0.9
Bad Reichenhall, Listanger	Hauptdolomit + Wettersteinkalk	Mature mixed water	EPM (75%)	EM 11, PM 15.5	6.5	5
Bad Reichenhall, Listsee	Hauptdolomit + Wettersteinkalk	Mature mixed water	EPM (50%)	EM 24, PM 17.5	2	6.2
Bad Reichenhall, Listwirt	Hauptdolomit + Wettersteinkalk	Mature mixed water	EPM (75%)	EM 27, PM 16	5.4	11.8
Tiefquelle Felbertal	Hauptdolomit	Undersaturated mixed water	EM	9	11.5	0.4
Brunnen Baderluck	Hauptdolomit	Undersaturated mixed water	EM	7.5–10	13.5	0.1
Wimmerbauernquelle	Hauptdolomit	Mature dolomite water	EPM (30%)	EM 30, PM >100	1	75.7
Mudlmoosquelle	Hauptdolomit, Dachsteinkalk, Plattenkalk	Undersaturated mixed water	EPM (90%)	EM 8.5, PM 6	10	0.1
Egglbrunnquelle	Hauptdolomit, Kössener Schichten	Undersaturated mixed water	EM	9–10	10	0.4
Mitterlugquelle	Hauptdolomit	Mature dolomite water	EM	10–14.5	9.5	5.7

EM exponential modell, *PM* pistonflow modell, *EPM* (75%) combined modell 75% exponential component

(a)



(b)

Mean residence times after different calculation approaches [years]

tracer	Tritium		CFC11	
flow model	EM	PM	EM	PM
EM	10		14.5	
EPM75	16.5	65	5	29.5
EPM90	10	23	13.5	22
PEPM	14 (65%)	14	12 (99%)	12

EM exponential modell EMP75 exponential pistonflow modell (75% EM-portion)

EMP90 exponential pistonflow modell (90%EM-portion)

PEPM exponential pistonflow model (50% EM-Portion) combinated with a fixed pistonflow portion

(c)

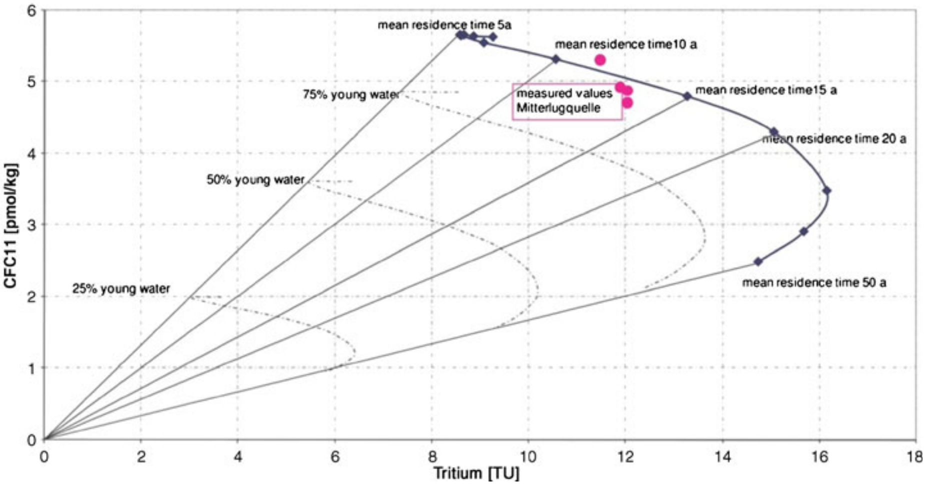


Fig. 8

◀ **Fig. 8** Groundwater dating by means of tritium and CFC data measured in Mitterlugquelle. **a** Shows the very few differences between the applied output functions. It is not possible to identify the current function only by comparing with the measured values. For finding the best fitting output function a second tracer (CFC11) was used. As shown in **b** the best accordance is found in using the exponential flow model. The combination of tritium and CFC11 is shown in **c**, diagram according to Bauer et al. (2002) and Schneider et al. (2003)

water has a mean residence time of about 13 years. Obviously there is only a very small or no contingent of water older than 50 years (precipitation before bomb testing era).

Table 3 shows the results of groundwater dating for the tested springs and wells.

There are partly significant differences between the calculated mean residence times of EM and PM components. The reason for those differences is founded in the completely different flow mechanisms. While the exponential flow occurs in a diffuse micro fractured system the piston flow takes place in macro fractured or even karstified conduit systems which could be occasionally independent of the micro fractured flow patterns.

The highest amount of young water (>10% younger than 1 year) and the lowest amount of old waters (<1% older than 50 years) are found in those springs delivering subsaturated water (type 3 concerning the hydro-chemical signature). There is no significant difference in age distribution between dolomite (type 1) and mixed water (type 2). Both mature water types show amounts of very young water (1 to 10% younger than 1 year) and of very old water (1 to 12% older than 50 years) except Wimmerbauernquelle which exhibits more than 75% old waters.

3.4 Regional Estimation of Supply and Demand

Based on a national study about present and future water supply and demand in the alpine regions of Austria presented in Joanneum Research (2001) the potential water supply abstracted from HD formation in the study area was estimated and evaluated with regard to the known consumption (based on data of 2001) and the estimated future consumption in the year 2031 (30 years after the study-period). The data are shown in Table 4.

The mean annual precipitation is about 1.700 mm per year with approximately 40% mean annual groundwater recharge (671 mm per year). To evaluate the quantitative suitability economic and ecologic aspect must be taken into account.

The values determined for each alpine region by Joanneum Research (2001) were used to calculate mean values for our larger study area and for the HD-dominated regions in the Northern Calcareous Alps which are assumed to be approximately 2.000 km^2.

The results of these calculations in Table 4 show an absolute annual amount of available water supply in HD-formations of about 216 $*10^6$ m^3 while the current consumption in the study area constitutes 68 $*10^6$ m^3. Future demand is predicted to be 93 $*10^6$ m^3 in the year 2031. These approximate calculations show that the potential water supply from HD exceeds the predicted future demand of drinking water for more than 100%.

Table 4 Hydrological and water supply data of the studied region, data published in Joanneum Research (2001)

Range (based on historical and topographical criteria)	Surface area [km^2] without porous aquifers	Mean annual precipitation [mm/a]	Mean groundwater recharge [mm/a]/ [% of prec.]	Economically usable contingent of recharge [mm/a]/ [% of prec.]	Ecologically usable contingent of recharge [mm/a]/ [% of prec.]	Absolute amount of ecologically usable water supply per year [Mio. m^3]	Current consumption [Mio m^3/a] (2001)	Estimated consumption [Mio. m^3/a] (2031)
Waidringer Alpen	422.18	1,686	688/40.8	328/19.45	88.6/5.25	37.4	1.9	2.5
Salzburger Kalkalpen	571.11	1,815	674/37.1	282/15.54	81.9/4.51	46.8	23.7	35.1
Chiemgauer Alpen	132.18	1,752	686/39.2	446/25.46	151.5/8.65	20.0	1.3	1.7
Tennengebirge	273.76	1,723	693/40.2	406/23.56	72.8/4.23	19.9	4.1	5.3
Salzburger Mittelgebirge	534.04	1,696	659/38.9	325/19.16	102.2/6.03	54.6	12.3	16.6
westl. Trauntaler Alpen	497.29	1,832	688/37.6	434/23.69	186.6/10.18	92.8	6	7.7
östl. Trauntaler Alpen	349.03	1,753	676/38.6	262/14.95	68.1/3.89	24.1	11.1	14
Windsichgarstener, Reichramminger Hintergebirge	440.53	1,494	649/43.4	365/24.43	149.6/10.01	65.9	1.4	1.8
Ybbstaler Voralpen	922.6	1,427	623/43.7	381/26.7	72.4/5.07	66.8	6.2	8
Calcareous Alps between Reit im Winkl and Waidhofen/Ybbs	4,142.72	1,686	671/39.8	358/21.44	108.2/6.42	448.2	68	92.7
Estimated area composed of HD-formation	2,000	1,686	671/39.8	358/21.44	108.2/6.42	216.4	68	92.7

Data for the HD-dominated regions were calculated by the authors on base of the cited national study

4 Conclusions

4.1 Special Characteristics and Advantages of HD-Aquifers

Considering the assumption of Fellehner (2004) and Kassebaum (2006) that steady and efficient discharge out of a well protected aquifer depends on a double porosity system with great fractures responsible for conduit flow and discharge combined with a system of micro fractures which affords infiltration and impacts the retention capacity the question of generally valid rules considering the structural situation were of special interest.

Hydro-geological mapping in each test sites showed that the expected typical micro fractured weathering structures are not developed consistently over the HD-dominated catchment areas. Borehole investigations in Reit im Winkl and Bad Reichenhall showed strongly fractured domains alternating with massive HD-ranges. So it can be assumed that the surface consistency of the catchment area registered via geological mapping is no reliable indicator for a suitable aquifer in the above described sense.

Of more importance for a sufficient ability of an aquifer as drinking water supply is the absence of limestone units in the orographic catchment areas. It was observed that those springs and wells dominated by an HD-aquifer but also characterized by karstified limestone units in the distant ranges of the catchment areas show significant variations in discharge depending on precipitation whereas the catchments with no other formations but HD lead to springs with only moderate seasonal variations in the hydrograph curves, in water temperature and electric conductivity. Obviously karstified limestone units overlying the HD-formation impact the tendency for internal karstification of the HD-aquifer. In those cases the HD environment behaves like a karstic aquifer and looses the advantages of a typical double porosity medium. It is assumed that the punctual crossover of groundwater from a karstified limestone aquifer into a fractured HD-aquifer is responsible for this fact because of physical weathering due to infiltration via some favored fractures and expansion of preexisting fractures. The second important mechanism is the so called mixing corrosion (Appelo and Postma 2005). Water influenced by overlying limestone units is mixed with water infiltrated directly into the HD-aquifer via micro fissures. As result of mixing these different carbonate influenced waters the solution becomes subsaturated and karstification starts. As result conduit flow dominates the system affiliated with the above discussed disadvantages of a karstified aquifer.

The comparison of the hydro-chemical composition of the samples generally supports the above statement as the classification by hydro-chemical modeling leads to the three groups; mature dolomite waters, mature mixed waters and subsaturated mixed waters. Mature dolomite waters free of extraneous parameters like sulphate or chloride only appear in aquifers without any influence of limestone or evaporite units in the catchment area. Conductivity obviously is not a significant parameter to identify HD-dominated waters because limestone influenced waters and pure dolomite waters show no differences in conductivity. Characteristic conductivity values of carbonate waters without any influence of extraneous units are in the range of 300 to 350 μS/cm. Higher conductivity gives an evidence for the influence of evaporitic units within the aquifer like they were found in the test points in Bad

Reichenhall and Brunnen Baderluck. The possible reason for the significantly lower conductivities measured in Wimmerbauernquelle is discussed in Section 4.2.

Groundwater dating had the aim to find out significant differences in age distribution between pure dolomite waters and limestone influenced aquifers. The assumption that pure dolomite aquifers show significantly higher mean residence times without any contingents of very young waters was associated with the advantage of smaller protection areas and less restrictions concerning the land use within these areas. Therefore the base flow of both aquifer types was investigated by means of stable isotopes as well as tritium. To check the results the micro pollutants CFC and SF_6 were supplementary used in some of the test sites. It was shown that there is no significant difference in age distribution between pure dolomite water and mature mixed water. While the mean residence times differ between 10 and about 30 years the contingent of young components (<1 year) varies between 2 and 9.5% and the contingent of old components (>50 years) are in the range of 0.9 to 6.2% independent of the classification of the catchment area. This leads to the conclusion that there is no general advantage of HD-aquifer considering the necessity of defining protection areas covering the whole topographical catchment like it is common for karst springs.

A significant difference in age distribution is seen in comparison with the unsaturated mixed waters sampled in the measuring points Tiefquelle Felbertal and Brunnen Baderluck. They have portions of young water in the amount of 11.5% and 13.5% respectively and almost no older components. The strong influence of short-term water leads to accordingly higher vulnerability to pollution.

Wimmerbauernquelle with the smallest amount of young water (1%) and 75% portion of water older than 50 years is the other very interesting exception to the above summarized results. The special situation of this measuring point is discussed in Section 4.2.

In summary the main advantage of using pure HD-aquifers rather than karst springs for drinking water supply is the steady discharge which is minimally influenced by precipitation or seasonal effects. Apart from the ensured minimum discharge in dry periods the technical requirements in using these types of springs are significantly lower in comparison to karst springs. There is no advantage relating to the need for protection areas and restrictions for the land owners because the portion of very young water does not differ between dolomite and calcite influenced water types.

Some characteristic properties can help to define a pure dolomitic aquifer with its important advantage for suitability as drinking water supply. (1) The enhanced catchment area should be free of limestone units because their influence leads to karstification inside the HD-aquifer. For this aspect hydro-geological mapping is essential to characterize the catchment area. (2) The hydro-chemical composition should be proved. The total amount of dissolved solids expressed in electric conductivity varies in the range of 300 to 350 μS/cm in carbonate aquifers. The hydro-chemical analysis of the main ions Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^- and Na^+ are important to identify pure dolomite water. Concentrations of sulphate, sodium and chloride should be insignificant. The Ca/Mg-ratio should be close to 1 (±0.2) and the solution should be saturated in calcite and dolomite.

If these assumptions are achieved a spring will show the typical dolomitic property of steady discharge in relation to karstified limestone aquifers.

The results of this regional study may be applicable to other carbonate dominated regions with distinctive and dilimitable dolomitic units delivering drinking water from springs with a more or less steady discharge. Vulnerability studies and intensive hydro-geological investigations are as essential as they are in karstified regions to protect those types of springs.

4.2 Special Situation of Wimmerbauernquelle

Finally the special situation of the measuring point Wimmerbauernquelle in Bad Ischl should be discussed concerning further investigations. As shown in the sections on hydrochemistry and isotope hydrology the waters sampled in Wimmerbauernquelle show different properties in the amount of total dissolved solids, water temperature and isotopic composition. There are no other formations in this catchment area; the electric conductivity is in a range of 250 to 300 μS/cm and therefore lower than the postulated normal range, the mean water temperature varies between 11 and 12°C and is significantly higher than all other measured temperatures, hydro-chemical modeling shows a subsaturation for the phases calcite and dolomite and groundwater dating indicates a portion of more than 75% of very old water (tritium values of about 4TU and SF6 value of 0.4 pmol).

Circulation in a carbonate aquifer for more than 50 years should lead to saturation for the phases of calcite and dolomite so a possible reason for the described situation is that Wimmerbauernquelle delivers water out of a deeper range of the aquifer, strongly influenced by a thermal gradient but already cooled while rising to the surface. Because of the contrary proportion of temperature and solubility of carbonates (Plummer and Busenberg 1982) the water is in equilibrium with carbonate phases in the deeper and therefore warmer parts of the aquifer. During a relatively fast rising to the surface cooling is faster than the hydro-chemical reactions. The consequence is subsaturation in calcite and dolomite. In the spring called Wimmerbauernquelle a deep reaching aquifer delivers warmed-up water from greater depth which is mixed with a small amount (max. 25%) of relatively younger surface waters.

To examine this interesting measuring point more detailed investigations are necessary and will be part of future studies on this topic.

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