Identification of a deep flow system in a dolomitic alpine aquifer – case study Wimmerbauern spring, Bad Ischl

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hydrochemical modelling
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Abstract

In the context of a regional study about the aquifer characteristics of dolostones along the northern margin of the Northern Calcareous Alps (NCA) some remarkable properties of the spring "Wimmerbauernquelle" (WQ) in Bad Ischl were detected. Moderately increased water temperatures of 11.0 to 11.5°C and Tritium values in the range of 4TU evidenced a significant contingent of deep circulating thermally influenced submodern waters. Comparably low electric conductivities in the range of 270 µS/cm and a hydrochemical characterisation as Ca-Mg-HCO_3-type water with a balanced Ca-Mg-ratio and a nearly complete absence of other major ions are a sign of a shallow pure dolomitic aquifer. The results seemed contradictory at first glance. Besides hydrogeological mapping and hydrochemical investigations inverse hydrochemical modelling was used to reconstruct the genesis of the spring waters and leads to a mix of 50% to ~85% of obviously deep circulating water, according to the assumed basic conditions. Interpretation of Tritium and SF_6 measurements leads to a composition of 69% (+/- 5%) of the spring water that showed a mean residence time of more than 60 years. A conceptual model of the aquifer combining the results of our study with the approach of various flow-systems leads to the interpretation that WQ can be seen as the geothermally influenced drainage of a deep aquifer.

Im Rahmen einer regionalen Studie über die Aquifereigenschaften des Hauptdolomits am Nordrand der Nördlichen Kalkalpen wurden einige bemerkenswerte Eigenschaften der Wimmerbauernquelle (WQ) in Bad Ischl entdeckt. Stabile und leicht erhöhte Wassertemperaturen zwischen 11 und 11,5°C und Tritium-Konzentrationen im Bereich von 4TU deuten auf einen signifikanten Anteil an tief zirkulierenden und daher geothermisch beeinflussten submodernen Wässern hin. Vergleichsweise geringe elektrische Leitfähigkeiten von ca. 270 µS/cm und eine hydrochemische Charakterisierung als Ca-Mg-HCO_3-Wasser mit ausgeglichenem Ca/Mg-Verhältnis und dem fast völligen Fehlen anderer Hauptparameter deuten auf einen seichten dolomitischen Kluftaquifer hin. Die Ergebnisse erschienen auf den ersten Blick widersprüchlich. Neben hydrogeologischer Kartierung und hydrochemischen Untersuchungen wurde die inverse hydrochemische Modellierung eingesetzt, um die Genese der Wässer zu rekonstruieren. Je nach Rahmenbedingungen ergab sich dabei ein Mischwasser, das zwischen 50 und 85% aus tief zirkulierenden Kluftgrundwässern aus einem reinen Hauptdolomitaquifer besteht. Die Auswertung von Tritium- und SF_6-Messungen führt zu einem Anteil submoderner Wässer von 69% (+/- 5%). Auf Basis der Ergebnisse sowie der Annahme verschiedener Fließsysteme konnte ein konzeptionelles Modell entwickelt werden, das die Quelle WQ als geothermisch beeinflusste Drainage eines Tiefenaquifers erkennen lässt.

1. Introduction

Groundwater circulation within the Earth crust generally occurs at different scales – local, intermediate and regional flow systems (Toth, 1999). Although the most important mechanism of groundwater flow is gravity driven, temperature induced upward flow controlled by fractures and faults also plays an important role especially concerning expanded flow systems (Toth, 1999). Due to deep and widespread karstification in carbonate rocks a conduit flow system allows groundwater infiltration into deeper parts of the aquifer affiliated with warming and followed by density induced upward flow of thermal waters. For this reason thermal karst is the most important thermal water resource outside of volcanic areas (Goldscheider et al., 2010).

However, most studies on karst hydrogeology deal with more or less shallow and fast flow systems. These environments can be investigated by means of tracer test, hydrographs, temperature development or chemographs (e.g. Birk et al., 2004; Goldscheider, 2005, Linan Baena et al., 2009). Springs in this environment are directly and strongly related to precipitation and the recharge situation in the catchment.

Because of the aquifer situation in complex conduit karst systems or dolomitic double porosity systems (Perrin et al., 2011), thermal waters from a deep flow system are often mixed with colder near surface circulating waters before emerging in springs. According to the mixing ratio of tempered and cold water and to the overlapping deep and shallow flow systems the presence of thermal water often remains undetected.

Pronk et al. (2006) described a karst system in Switzerland with two main springs that obviously drain the same aquifer. With regard to chemical and isotopic data four different components of the spring discharge were identified. Besides three local, shallow and fast flow systems, parts of the spring discharge origin in the inflow of thermal water from a regional deep flow system (several hundred meter depths). The content of thermal groundwater differs significantly between the two springs that are located nearly at the same altitude.

Our study also intends to show such a thermal influenced deep flow system discovered in the context of investigations about the special aquifer characteristics of a widespread dolostone formation "Hauptdolomit" (HD) as drinking water reservoir (Hilberg, 2007; Hilberg and Schneider, 2011). Compared to several other investigated springs in similar geological settings (HD facies and springs from fractures in dolostones), WQ shows different physico-chemical properties and discharge behaviour. On one hand, low electric conductivity and the hydrochemical signature of the water indicates pure dolomite influenced groundwater (Ca-Mg-HCO_3 water type, Ca-Mg ratio of about 1, no other ions) and obviously short residence times within a shallow aquifer. On the other hand, the observed stable water temperature of about 11.5 °C all year round and Tritium values in the range of 4TU are a sign of less surface influences and mean residence times exceeding some decades. We interpret the data as evidence for a significant share of deep circulating groundwater with longer residence times as a major part of the spring discharge.

2. Geographical, geological and hydrogeological setting

2.1 Overview

The investigated spring WQ is situated in the municipal area of Bad Ischl in Upper Austria. On the bottom of the southern slope of Leonsberg (L1) (1746 m asl.) with its eastern presummit Gspranggupf (L2) (1376 m asl.) the spring is situated at an elevation of 560 m asl. In E-W-direction the study area is delineated by the brooks "Enge Zimnitz" (B1) in the West and "Saiherbach" (B2) in the East of WQ. In the North of L1 and L2 the valley "Mitterweißenbach" (B5) and in the South the river "Ischl" are the delineations of the investigated region.

Figure 1 shows an overview of the study area and the regional setting.

The investigated area is part of the Tirolean "Stauffen-Höllengebirgs nappe" in the northern part of the NCA which consists of HD facies. The southern slope of L2 and the main part of the northern slope are completely built of dolostones, in wide areas overlain by glacial and postglacial sediments. In the south HD is covered by Jurassic calcareous units and Quaternary sediments. In the North, underlying Raibl Formation and Wetterstein dolomite delineate the occurrence of HD.

The known tempered (thermal) springs in the Upper Austrian karst region were described by Schauberger (1979). In most of the described cases high mineralised waters evidence the presence of a deep aquifer. Besides these wide spread saline waters, low mineralised spring waters with peculiar temperature curves are seldom observed in the region. One prominent example is a spring called "Warmes Wasser" (warm water) at the north-western margin of the lake "Hallstätter See" some tenth of km south of the study area. This spring yields water with temperatures of about 20°C combined with relatively low electric conductivity values. The water was classified as Ca-Mg-HCO_3 type (Schauberger, 1979). Historical reports and dating of timber found in a nearby gallery indicates the use of these thermal waters as baths as early as the 15th century (Schauberger, 1979). Nowadays, the spring is below the water level of the lake and historic galleries are not accessible anymore so that it is not possible to gain samples of this spring and to verify the data with recent measurements.

In the vicinity of WQ within the Ischl Valley no thermal influence is known to date. Schauberger (1979) describes the so called "Marie-Luisen spring" as a spring of saline but cold water. The spring flows out of sedimentary layers near the river Ischl as a result of an upward flow of high mineralised Na-Cl waters out of evaporitic units in unknown depth along existing fractures (Schauberger, 1979). With regard to the completely different hydrochemical composition it is assured that WQ and "Marie-Luisen spring" have nothing in common concerning their flow regime and must belong to completely different aquifers.

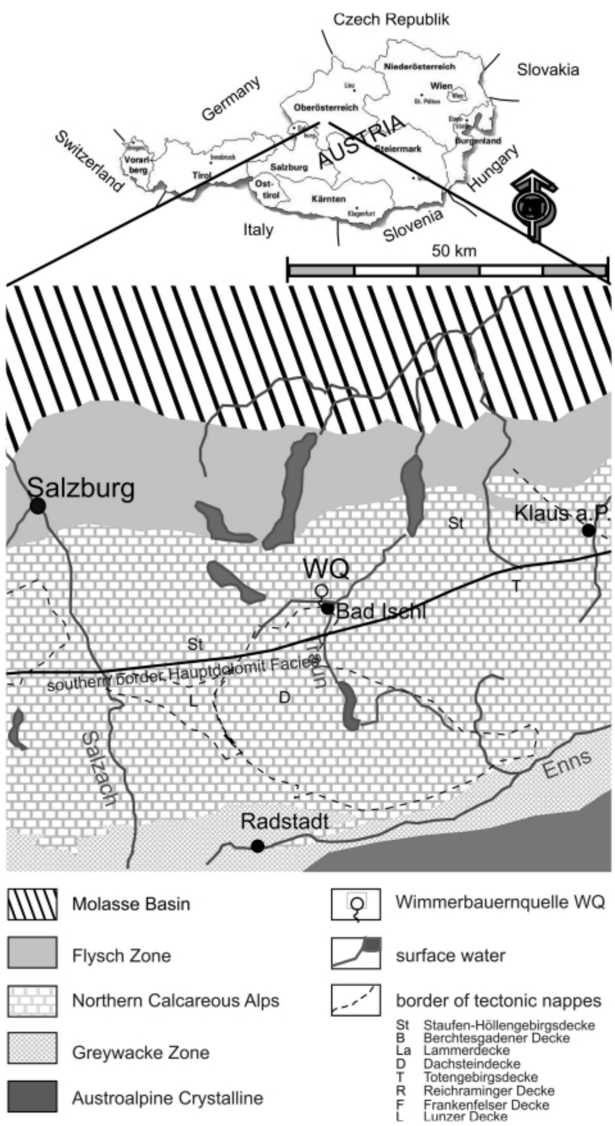
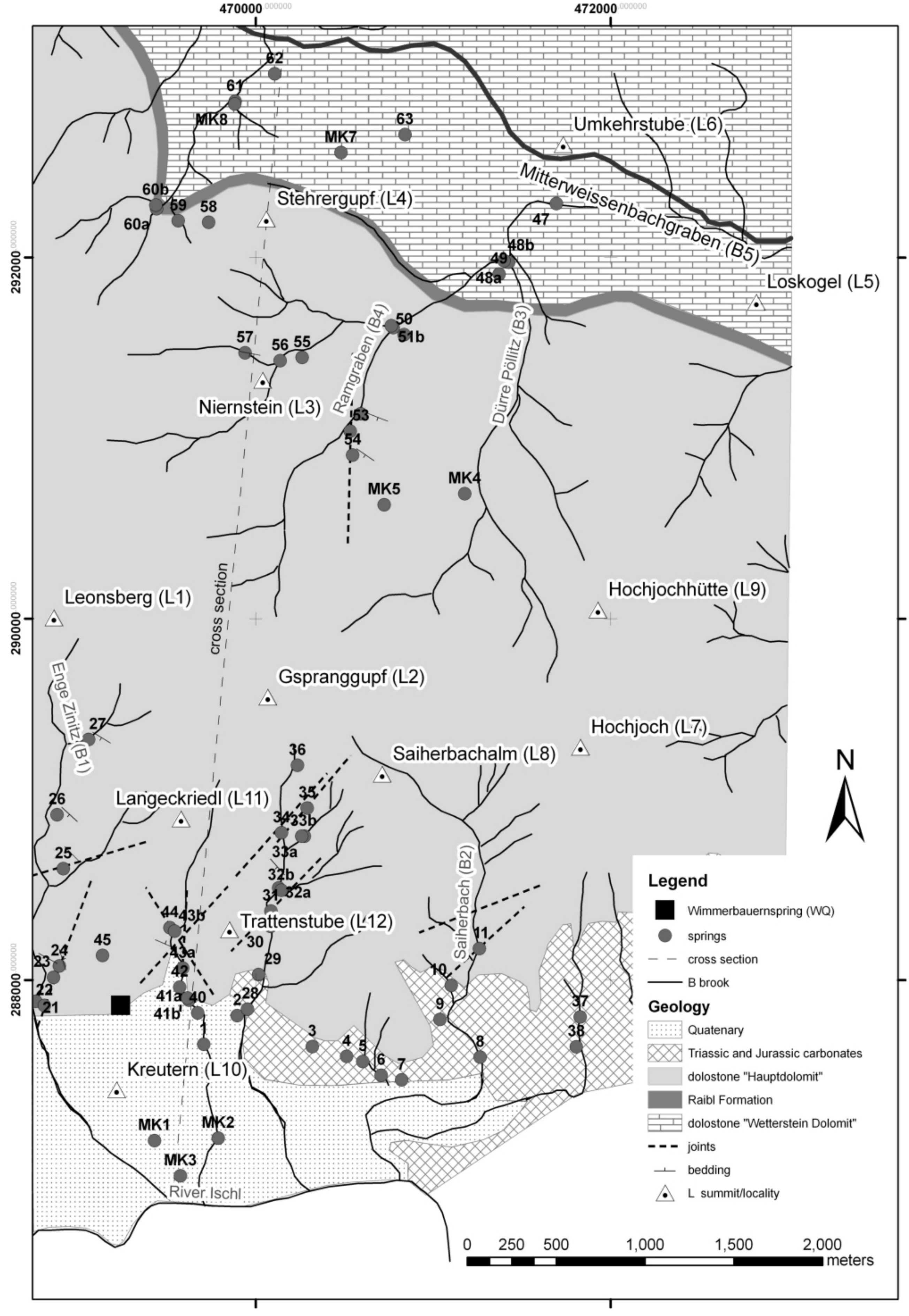


Figure 1: Regional setting and overview of the investigated area on the northern range of the Northern Calcareous Alps.


470000
472000
292000
290000
288000
62
61
MK8
MK7
63
Umkehrstube (L6)
Mitterweissenbachgraben (B5)
60b
59
58
60a
Stehrergupf (L4)
47
49
48b
48a
Loskogel (L5)
Ramgraben (B4)
50
51b
57
56
55
Niernstein (L3)
53
54
Dürre Pöllitz (B3)
MK5
MK4
cross section
Leonsberg (L1)
Hochjochhütte (L9)
Enge Zinitz (B1)
Gspranggupf (L2)
27
Hochjoch (L7)
36
Saiherbachalm (L8)
N
26
Langeckriedl (L11)
35
34
33b
33a
25
32b
32a
31
Saiherbach (B2)
44
43b
Trattenstube (L12)
24
45
43a
30
29
11
23
42
10
22
21
41a
41b
40
2
28
9
37
1
3
4
5
8
38
6
7
Kreutern (L10)
MK1
MK2
MK3
River Ischl
0 250 500 1,000 1,500 2,000
meters
Legend
Wimmerbauernspring (WQ)
springs
cross section
B brook
Geology
Quaternary
Triassic and Jurassic carbonates
dolostone "Hauptdolomit"
Raibl Formation
dolostone "Wetterstein Dolomit"
joints
bedding
L summit/locality

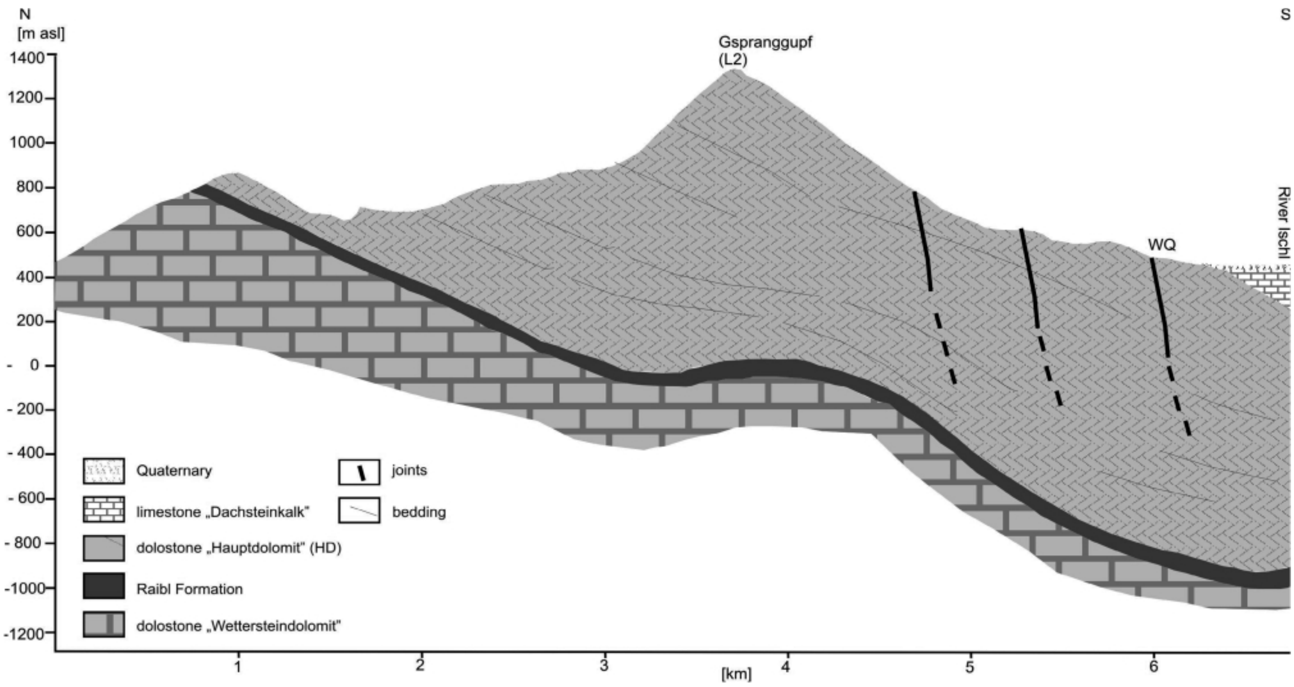


Figure 2: Hydrogeological map and cross section of the study area based on geological, structural and hydrogeolgical mapping of L2 and its southern foreland.

A third group of springs described by Schauberger (1979) should be mentioned because of their position on the northern slope of L2 in B5. The described hydrochemical setting of these springs identifies them as sulphur dominated springs, obviously influenced by gypsum or anhydrite. A direct context to the WQ aquifer is also not given.

The examples show, that deep aquifer draining springs are generally common in the investigated region. Because of the extended saline complex most of the deep circulating waters are influenced by halite or gypsum ("Haselgebirge") and show high mineralisation and Na-Cl water type or dominance of sulphate. The historically known spring "Warmes Wasser" is the only known example for a low mineralised tempered spring in comparable geological setting.

2.2 Geology and hydrogeology of the WQ catchment

Nearly the entire investigated area consists of the Triassic dolostone unit "Hauptdolomit" (HD). Only in the northernmost part along the northern slope of L2 Raibl Formation and Wetterstein dolomite were detected. Because of the hydrochemical composition of the spring the occurrence of Raibl Formation delineates the hydrogeological catchment of WQ.

Sampling of structural data within HD resulted in two dominant structures: (1) shallow to moderate (max. 30°) SW dipping beddings. Some outcrops show NE dipping beds which evidences flat folds in a km-wide range. (2) Steep (~ 80°) dipping NNE-SSW to NE-SW striking joints. These joints are responsible for significant scarps in the mapped region.

On both slopes, N and S of L2, the surface runoffs follow this major joint direction. The spatial distribution of the springs shows a significant spring horizon along the southern slope toe of L2 in the transition region between HD and Quaternary or Jurassic units, respectively. Further accumulations of springs were detected in the vicinity of surface forming joint structures. Only a very small group of springs, including WQ, is not clearly bound to a surface structure or to the slope toe but emerges in Quaternary sediments. In the vicinity of WQ no signs for calcite deposition as result of CO_2 degassing are observed.

Figure 2 shows the hydrogeological map and the resulting geological cross section of the investigated area.

3. Methods

Since the spring was part of the public drinking water supply of the city of Bad Ischl for the last decades hydrochemical data as well as monthly measurements of the spring discharge and water temperature were available and provided by the municipal water works. Discharge was measured by filling a graduated vessel within a defined time period. Temperature was measured with a usual thermometer. The samples for hydrochemical analysis were collected and the field data were measured directly at the tapping of the spring by the staff of an authorized laboratory and operators of the water works, respectively. These data represent a basic input for this study.

3.1 Hydrogeological mapping

Hydrogeological mapping involved the spatial documentation of HD outcrops and the Quaternary cover. Structural data were collected to explore the network of fissures in the catchment area. Dolomitic units on the northern margin of the NCA can be characterised as a double porosity medium (Kassebaum, 2006) consisting of oriented major fractures (conduits) and a network of ubiquitous interconnected micro fractures. Since the major fractures are considered to be responsible for temperature induced upward flow significant fault systems or large scale and deep reaching joints were of special interest.

Field parameters of springs and surface runoffs, e.g. temperature, electrical conductivity and pH were measured with multiparameter instruments. The discharge of each mapped spring was measured by filling a graduated vessel within a defined time period.

3.2 Hydrochemical modelling

For hydrochemical modelling data provided by the water works of Bad Ischl were used. The samples were taken between 2002 and 2010 by different laboratories in the context of drinking water quality monitoring. Besides 6 datasets of WQ hydrochemical analysis of two wells in the foreland of L2 were available.

Our study focused on the major ions Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Sulphate (So_4^{2-}), Chloride (Cl^{-}) and Hydrocarbonate (HCO_3^{-}) since those are the most common parameters within NCA aquifers. One important parameter was the Ca/Mg-ratio which should be near to 1 in a pure dolomitic catchment (Merkel 1983).

Other ions should not occur in significant concentrations in pure carbonate aquifers. Within the geological setting of the Northern Calcareous Alps appreciable concentrations of e.g. Na^{+} and Cl^{-} are indicators for halite. SO_4^{2-} would be a sign for gypsum or anhydrite. Such parameters could be regarded as indicators for an influence of “Haselgebirge” (formation of Permian to lower Triassic shale, gypsum and salt) which is common in the region as described in chapter 2.

Hydrochemical modelling using the software PhreeqC (Parkhurst and Appelo, 1999) was used to assess the data with regard to saturation indices and electrical balances and to calculate possible mixing ratios between deep circulating thermally influenced waters and input from a shallow aquifer. The water compositions of two wells MK1 and MK2 in the southern foreland of L2, a calculated composition of deep circulating tempered water and the mean hydrochemical composition of WQ were used for inverse modelling.

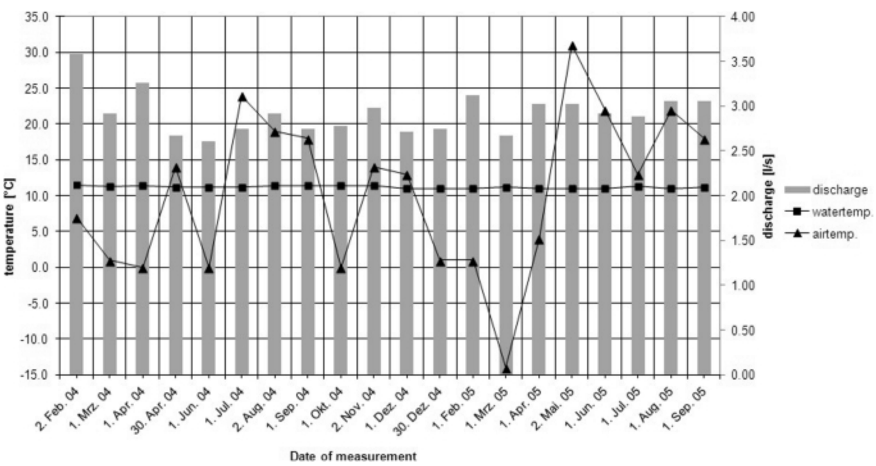


Figure 3: Hydrograph curves of temperature and discharge of WQ. The monthly measured values show a discharge in the range of 2.5 to 3.5 l/s and a very stable temperature of 11.0 to 11.5 °C independent of seasonal influences represented by the air temperature graph.

3.3 Isotope Hydrology

In combination with geological and hydrogeological data the effect of fractionation with altitude of the stable isotope ^{18}O was used to determine the mean elevation of the infiltration areas. Six samples (each 500ml polyethylene bottles) were taken directly at the spring at various seasonal conditions in the period 2005 to 2007 and were analysed for oxygen isotopes. 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 longer residence times (some years) attenuates any seasonal effects (Moser and Rauert, 1980; Schneider et al., 2003).

To determine mean residence times of WQ-waters in detail the radioactive isotope Tritium (^{3}H) (half life 12.32 years +/- 8 days) (Clark and Fritz, 1999) was used. Samples for Tritium analysis were taken four times at various seasons. Each sample consists of 1000ml spring water, stored in a polyethylene bottle and was analysed by the mentioned isotope laboratory. Isotope analysis techniques are described e.g. in Moser and Rauert (1980). Because of the extreme man-made increase of ^{3}H concentrations in the atmosphere in the 1950s and early 1960s (Clark and Fritz, 1999) detailed knowledge of the input concentration is of importance for calculating the age distribution. Therefore, weighted long-term measurements of ^{3}H in precipitation were used as input function. Data of the Austrian Network of Isotopes in Precipitation (ANIP station N-36 Feuerkogel) published in Umweltbundesamt (2012) were used for creating an input function for the Ischl Valley region. To determine mean residence times a flow model considering the mixing processes in the aquifer must be defined. According to the results of hydrogeological mapping and the characterisation of HD as double porosity medium an exponential model was assumed for the shallow flow system. With regard to the expected long residence times of deep circulating waters they are supposed to be free of Tritium. Thus it is appropriate to use a piston flow model to determine the component of submodern waters (deep flow system). Both models were combined to explain the measured Tritium values.

To verify the interpretation of isotope measurements the micro pollutant sulphur hexafluoride (SF_6) was used. The world wide concentration of this micro pollutant in precipitation has increased since the 1950s. The development is known by international long-term measurements (Oster, 2002) which were used as the input function in the present study. To avoid atmospheric contamination with recent SF_6-concentrations the sample (500ml) was taken directly at the spring tapping without atmospheric air contact.

Geology	HD					Quaternary foreland		
Station	WQ					MK1		MK2
Date	05.11.2004	24.05.2006	29.05.2008	16.10.2008	26.02.2009	23.10.2002	28.11.2008	20.10.2010
pH	7.7	7.6	8.0	8.1	8.0	7.7	7.7	7.7
Temp [-C]	11.7	11.3	11.3	11.8	11.6	10.5	9.3	7.8
Cond. [µS/cm]	256.0	291.0	263.0	259.0	253.0	309.0	330.0	341.0
Na [mg/l]	0.1	0.3	0.3	0.3	0.3	0.1	0.1	0.9
Mg [mg/l]	19.3	18.0	19.2	17.8	17.1	19.0	18.0	20.5
Ca [mg/l]	37.5	35.0	36.2	33.6	36.5	42.0	41.0	49.3
Cl [mg/l]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.0
SO4 [mg/l]	0.0	1.7	1.8	2.0	2.5	2.3	2.4	2.5
HCO3 [mg/l]	200.1	195.3	210.0	190.0	184.0	240.0	240.0	238.0
NO3 [mg/l]	0.1	0.1	1.4	1.5	2.2	3.9	4.4	3.8

Table 1: Hydrochemical data of WQ and porous groundwater from the L2-foreland

Tritium based residence times and the adjustment via SF_6 were calculated using the program MULTIS by Richter and Szymczak (1992). Combination of both data in a so called harp diagram was based on a method described e.g. in Bauer et al (2002).

4. Results

4.1 Time series of WQ field data

As shown in figure 3 WQ is characterised by a discharge varying between 2.5 and 3.5 l/s and stable temperature values between 11 and 11.5°C hardly influenced by air temperature or season, respectively. With regard to the annual mean air temperature of 8,7°C in Bad Ischl (469m asl) and the mean elevation of the catchment area between 800m and 1200m asl (approximately 7°C mean air temperature) the detected water temperature is 4°C higher than it should be. Electrical conductivities in the range of 270 µS/cm are comparably low with regard to other investigated springs in comparable geological settings (Hilberg and Schneider, 2011).

4.2 Water chemistry

Hydrochemical characteristics of WQ (major parameters) are dominated by a nearly balanced Ca/Mg-ratio and considerably lower concentrations of other cations like Na^+ and K^+. On the anion-side the dominance of HCO_3^- is significant. Cl^- and SO_4^- were detected only in minor concentrations. The waters of WQ can be classified as alkaline-earths-carbonatic (Ca-Mg-HCO_3) water type referring to the classification by Furtak and Langguth (1967).

The chemical composition of WQ waters compared to hydro-chemical data of two wells (MK1 and MK2 in figure 2) delivering pore groundwaters from the alluvial foreland is shown in table 1 and in the diagrams in figure 4. The hydrochemical composition of WQ can be interpreted as evidence for a pure dolomitic aquifer without any contact to saline units and only low influence of shallow waters circulating within the Quaternary cover.

4.3 Hydrochemical modelling

One purpose of hydrochemical modelling was to verify the plausibility of the data with regard to the electrical balance of the solutions and to the saturation indices (SI) of the most important mineral phases calcite and dolomite. The SI of these phases are expected to be close to zero since assuming adequate mean residence times the hydrochemical system is supposed to reach equilibrium conditions. To prevent falsifications due to degassing of carbondioxide (CO_2) while sampling, CO_2 partial pressure is also calculated in each sample. Low CO_2 partial pressure near to atmospheric conditions is evidence for degassing affiliated with consecutive reactions. In table 2 the results of the plausibility check are shown.

The mixing ratio between waters from a shallow and a deep aquifer was determined by means of inverse modelling. As ini-

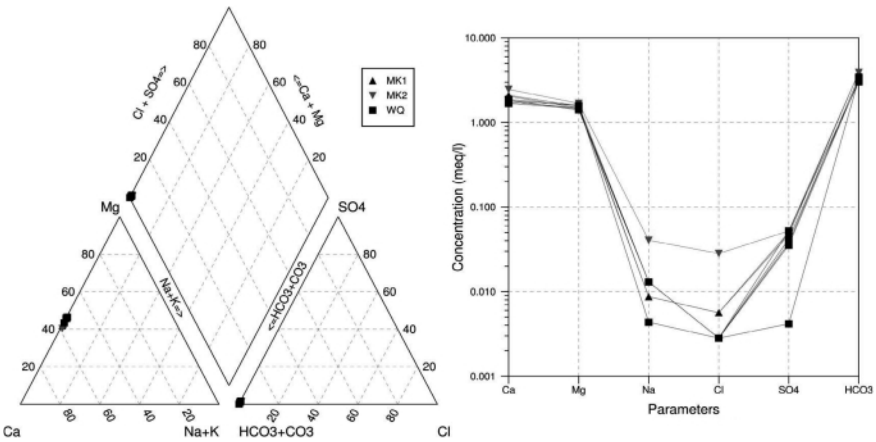


Figure 4: Hydrochemical composition of WQ and the wells MK1 and MK2. All analysed waters are of Ca-Mg-HCO_3-type with a more or less balanced Ca-Mg ratio and low concentrations of other NCA common ions, e.g. Na, K, SO_4 or Cl. As shown in the Schoeller plot, Na and Cl concentrations are significantly lower in WQ than in the two wells.

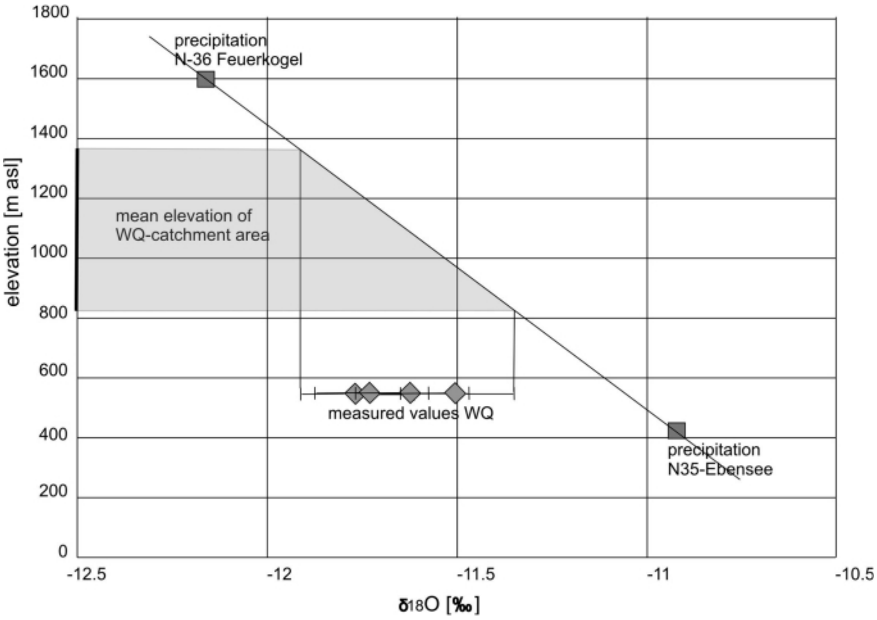


Figure 5: Elevation versus measured ^{18}O values of WQ and precipitation at different elevations. The mean elevation of the WQ catchment is in the range of 800m to 1200 m asl.

tial solutions the following two components were used: Solution 1 matches the major ion composition of the wells MK1 and MK2 in the southern foreland of L2. These waters are removed from the porous groundwater body and are supposed to represent the water composition of the shallow flow system. Solution 2 is a modelled composition of deep circulating water within a pure dolostone aquifer in equilibrium with calcite and dolomite. With regard to the thickness (~1400m) of the aquifer estimated by the results of geological mapping and structural data (Fig. 2, cross section) a mean circulation depth of about 500 m seems to be appropriate. To evaluate the influence of circulation depth and temperature (based on a gradient of 3K/100m) on the mixing ratio three scenarios of circulation depth were modelled: (A) mean circulation depth 300m, warming up to 20°C, (B) mean circulation depth 500 m, warming up to 26°C and (C) mean circulation depth of 700 m, warming up to 32°C.

(3) As resulting solution the mean composition (generated from 5 samples, taken between 2004 and 2009, table1) of WQ was used. Table 3 shows the results of inverse modelling and the possible mixing ratios with regard to various temperatures, and the most probable models for each temperature scenario are documented. Temperature as result of circulation depth of solution 2 has an important influence on the resulting mixing ratio. Since this comparably wide range of mixing ratios is not a really sufficient result another method is needed to come to more precise findings.

4.4 Isotope hydrology and trace element analyses

Isotope concentrations of ^{18}O and ^{2}H are very stable over the hydrographical year and variations do not exceed the measurement error. This leads to the assumption of mean residence times of at least some years since seasonal variations in precipitation are attenuated completely. To determine the mean elevation of the catchment area of WQ ^{18}O data were combined with isotopic input in precipitation using the stations Ebensee (N-35, 425 m asl) and Feuerkogel (N-36, 1.598 m asl) which are parts of ANIP. The mean elevation of 800 to 1200 m asl is in agreement with the topographic situation along the southern slope of L2.

sampling date	percent error	SI Calcite	SI Dolomite	si_CO2(g)	CO2 Partial Pressure [Vol%]
11-May-2004	5.04	-0.06	-0.26	-2.50	0.31
24-May-2006	-1.80	0.19	0.26	-2.73	0.20
5-Sep-2008	-1.29	0.23	0.34	-2.86	0.14
16-Oct-2008	1.05	0.15	0.12	-2.78	0.17
26-Feb-2009	2.88	-0.21	-0.56	-2.42	0.38

Table 2: Plausibility check of WQ analysis. The charge balances are in a tolerable range, SI of calcite and dolomite are more or less in equilibrium and CO_2 partial pressure is approximately ten times higher than under atmospheric conditions.

Scenario	mean circulation depth [m]	Temperature [°C] of deep aquifer component	shallow aquifer fraction [%]	deep auifer fraction [%]	dissolution (-) / deposition (+) of Calcite [mol/l]
A	300	20	15.3	84.7	4,47E-06
B	500	26	39.6	60.4	-7,62E-05
C	700	32	51.2	48.8	-1,00E-04

Table 3: Results of inverse modelling. Within the assumed circulation scenarios the content of deep circulating waters is in the range of 50% to 85% and depends strongly on the increase in temperature with circulation depth. In scenario A slight deposition of calcite is modelled. This is not observed in the spring vicinity.

To determine mean residence times ^3H concentrations of the spring were measured in the period of 2005 to 2006. The measured values are in the range of 4 TU which is interpreted as a sign for a significant contingent of submodern (older than 60 years) water. To assure that WQ is the only spring in the region with significantly low ^3H values further springs were analysed. Since the ^3H values of all other samples are in the range of 8 to 10 TU they can be intepreted as post bombing test precipitation and so were not investigated further on. Amongst others the two wells MK1 and MK2 (input for inverse hydrochemical modelling) were detected as recent waters. For calculating the resulting mean residence times of WQ waters the measured data were calculated with ^3H input data of the station N-36 by using a combined pistonflow-exponential model (see chapter 3). Because of the small variations in Tritium input in the last years, dating based solely on ^3H data is ambiguous. The micro pollutant SF_6 was used as a second tracer to verify the findings based on ^3H. The harp diagram in figure 6 shows the results of the integrated dating method combining both parameters. It shows that 69% (+/- 5%) of the discharge is older than 60 years and refers to a deep flow system.

The results of groundwater dating are in agreement with those of inverse hydrochemical modelling since the age distribution and the ratio of shallow and deep aquifers of model B (500 m mean circulation depth) are in a comparable range.

4.5. Conceptual hydrogeological model

To verify the above described division in two different flow systems drained by WQ a conceptual hydrogeological model was developed. The particular purpose of the model is to verify the findings of hydrogeological mapping, hydrochemistry and isotope hydrology. The main question is: Are mean residence times of more than 60 years for nearly two thirds of the WQ discharge possible with regard to the necessary reservoir capacity in the aquifer? To answer this question all data based findings and some assumptions that are not really assured but probable are taken into consideration.

The following results and assumptions are considered in constructing the conceptual model:

- The mean elevation of the catchment is determined as 800m to 1200m asl which is in agreement with the elevation of L2 (1348m asl).
- The maximum thickness of HD is 1400m (result from geological mapping). Considering the cross section in figure 2 the maximum depth of HD bottom beneath the spring is approximately 1000m.
- To sustain the observed stable water temperature of 11.5 °C in the modelling process the deep water temperature was estimated as 26°C based on a mean circulation depth of 500 m below WQ. This is based on the assumption that only parts of the deep circulating component actually reach the bottom of the deep aquifer.
- The integrated approach of hydrochemical modelling and isotope hydrology leads to a distribution of approximately 26% - 39% shallow and young water (17 to 30 years mean residence time) and 61% - 74% deep and submodern water (precipitation before 1953).
- With regard to the results of hydrogeological mapping we assume that WQ is the only spring draining the deep aquifer while numerous other springs drain the shallow flow system.

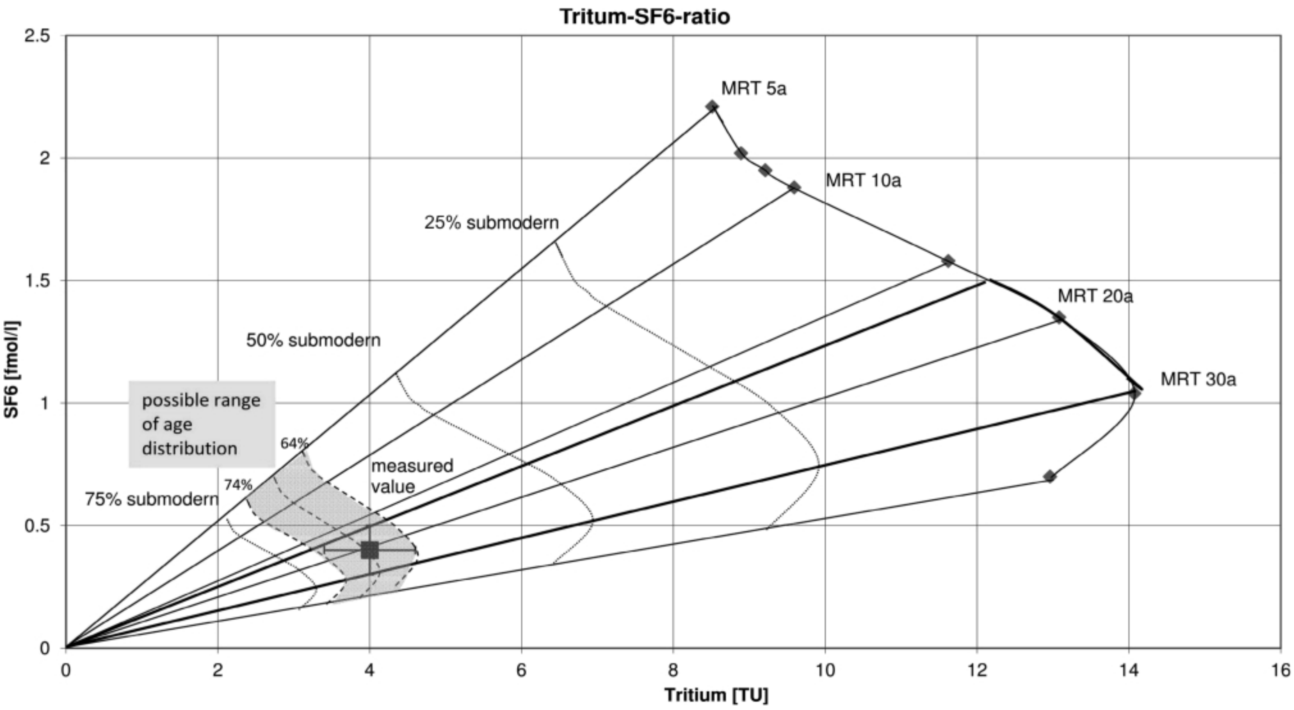


Figure 6: Integrated dating combining ^3H and SF_6 in a harp diagram after Bauer et al.(2002) to determine mean residence times. 31% (+/- 5%) of WQ discharge consists of “young” water with mean residence times in the range of 15 to 30 years whereas the main part, 69% (+/- 5%) of the discharge is older than 60 years and free of bombing test ^3H and anthropogenic SF_6.

- The mean residence time of submodern waters is not known and cannot be determined by means of the available data. For further calculations of the required reservoir capacity we use a mean residence time of 100 years. Since the calculation only serves the purpose of checking the plausibility of our findings this procedure seems adequate.
- We also do not have detailed information about the mean porosity of the HD aquifer. For further calculations we used a mean porosity value of 0.5% to determine the necessary aquifer volume.

Using a deep aquifer fraction of 61% to 74% of the mean spring discharge of 3l/s, a mean residence time of approximately 100 years, a porosity of 0.5% and a mean circulation depth of 500m the recharge area that supplies the deep aquifer is in the range of 2.6 to 2.8 km². These results are not in contradiction to the common recharge rates of some litres per km² that we expect in alpine environments. The calculation considers just one of two existent flow systems. Like it is shown in figure 7 besides the deep regional flow system drained by WQ another important local flow system is active in the catchment area and is drained by many other springs and surface streams. The flow regime considering all findings of our study is visualised in the modified cross section in figure 7.

5. Summary and Conclusions

At first view, WQ is an ordinary spring within "Hauptdolomit" as the dominant unit at the northern range of the NCA.

- Comparably low electric conductivities, the ion-composition of the solution, and the relatively small and clearly delimited orographical catchment area justify the prediction that the spring drains a common shallow groundwater body.
- The predicted mean elevation of the catchment area implies that orographical and hydrographical catchments are identical.

A closer look into the physico-chemical and isotopic setting shows noticeable properties that are in contradiction to the characterisation as an ordinary shallow local flow system:

- very stable temperature curve on a comparably high level of 11.5 °C.
- long residence times of more than 60 years for approximately 65% of the discharge.

Those findings can only be explained by a deep circulating flow system as it is constructed in chapter 4.5 and shown in figure 7. We are aware that the conceptual model considers some assumptions that are not assured. Nevertheless we justify the approach as a plausibility check of our data based findings. It involves a mean residence time of 100 years, mean circulation depth of 500m and a mean porosity of 0.5%. These assumptions, in combination with the results of hydrogeological mapping, hydrochemical modelling and isotope hydrology, lead to a possible area of recharge that is in the range of 2.6 to 2.8 km² which is plausible for the regional situation and shows that the characterisation of WQ as thermally influenced spring issue is reliable.

The case study shows a thermal karst spring that is masked by shallow waters and so remained undetected. Springs draining deep flow systems and emerging thermal and submodern waters in comparable geological settings may be much more frequent than is known as yet.

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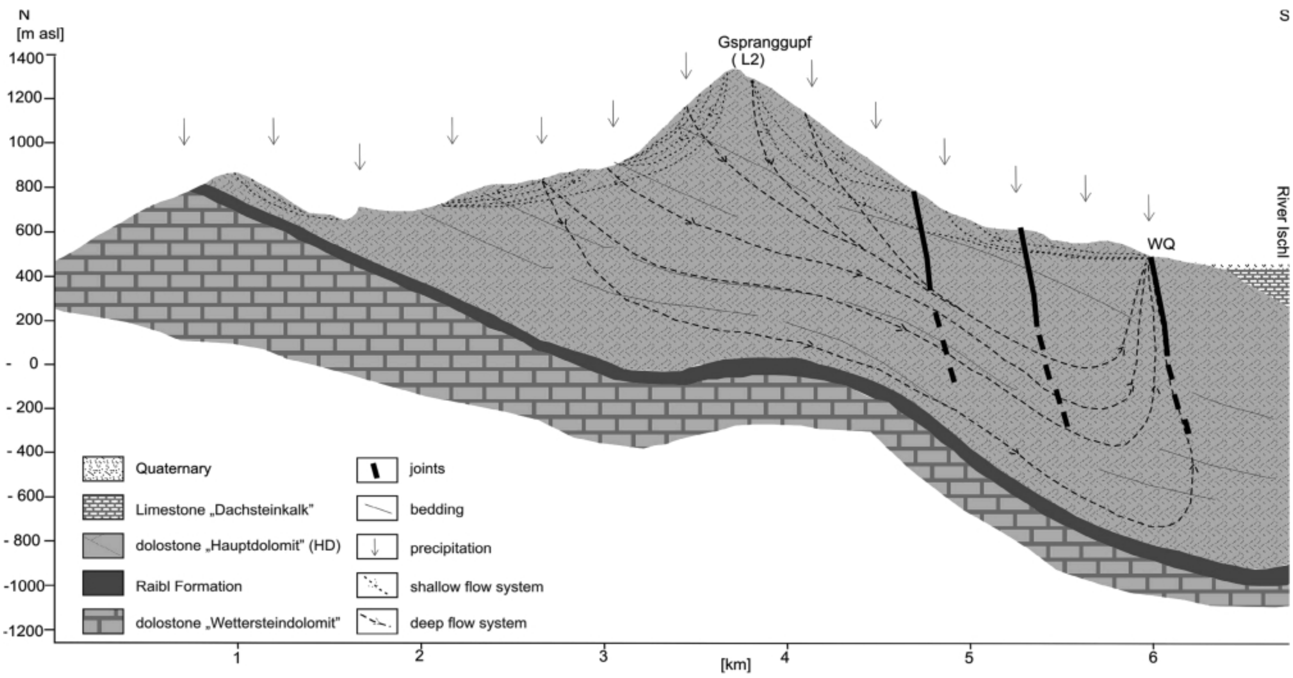

Figure 7: Modified cross section as conceptual hydrogeological model of the WQ catchment area and the possible flow regime. Two main flow systems are active in the investigated aquifer. The shallow flow system with recent waters is drained by many springs and surface streams on the southern and northern slope of L2. The deep flow system is drained only by WQ as result of thermal induced upward flow.

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