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Effect of Alpine karst on the hydrology of the Berchtesgadener Ache basin: a comprehensive summary of karst research in the Berchtesgaden Alps

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Keywords: karst, tracer, isotope, groundwater flow, distributed water modelling, regional scale, integrated water resource management

Abstract

The Berchtesgaden Alps are situated in the Northern Limestone Alps, characterized by individual mountain plateaus and ridges in close proximity to each other, intersected by valleys, with an altitudinal gradient of 2100 meters. The limestone has been exposed to dissolution processes since the Cretaceous, leading to a massive karstified aquifer with a wide range of subsurface flow channels. There are hundreds of springs as groundwater recharge locations, feeding the seven rivers of the region that contribute to the Danube watershed. Several studies were conducted to examine the hydro-geological conditions and the resulting groundwater flow. This paper aims to evaluate and summarize research in the basin describing groundwater flow to identify the main drainage direction, travel times, spring dynamics and possible subsurface redistribution in the individual mountain ranges and the whole basin. To this end, we evaluate several tracer experiments, two isotope studies and a spring database. The tracer experiments are generating knowledge about flow directions in the individual mountain ranges, groundwater redistribution, water storage and mean travel times. Five experiments prove increased groundwater flow remaining within a valley and four experiments indicate groundwater redistribution through mountain ranges. The isotope studies indicate potential water storage in the Wimbach valley of an estimated 100×10^6 to 470×10^6 m^3 and mean transit times of about four years. The analysis of the spring database focuses on locations and discharge classification. Overall, there are 289 springs recorded in the spring database, distributed from 600 to over 2000 m altitude, with major springs at the northern base of the mountains Hochkalter, Watzmann and at the north shore of lake Königssee. The conclusion summarizes the effect of the karst aquifer on the hydrology of the region. The outlook introduces current research within the area and the distributed water balance modelling.

Profile

Protected Area

Berchtesgaden National Park

Mountain range

Alps

Country

Germany

Theoretical background

The Northern Limestone Alps are characterized by massive layers of dolomite and banked limestone, formed through sedimentation processes during the Triassic formation (Langenscheidt 1994). Alpine folding during the Cretaceous led to a typical arrangement of interfaces and joints. Postglacial ice covers and their movement shaped present day mountain ranges and plateaus and the valleys in between. With the lifting of the Alps, the soluble limestone was exposed to dissolution processes leading to the generation of subsurface pathways along the interfaces (karst). The main characteristic of a karst aquifer is that it consists of two components, the rock matrix and the conduits inbetween (Atkinson 1977; Bakalowicz 2005; Kiraly 2003; Sauter et al. 2006; Teutsch & Sauter 1991; White 2002). White (2003) describes fractures as a third component of karst aquifers. This leads to a broad field of hydraulic parameters and unknown boundary conditions, which form the main challenge of describing the groundwater flow in the existing approaches (Kiraly 2003; White 2002; Sauter et al. 2006). Atkinson

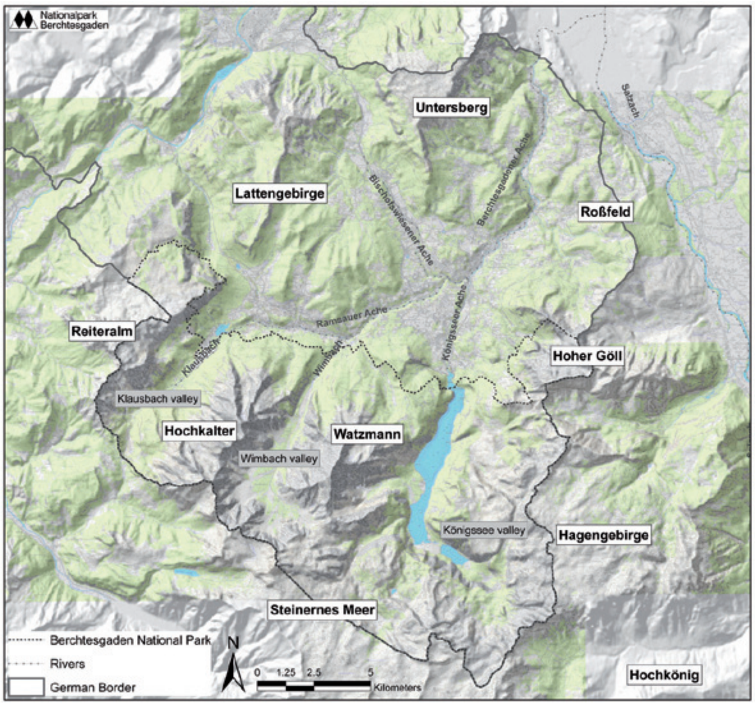

Figure 1 – Berchtesgaden Alps: mountain ranges and main rivers.

(1977) found for the Mendip Hills in Great Britain that the majority of the water is transported through enlarged conduits. The specific geomorphologic-geological structure produces the effect that the surface drainage basin differs from the groundwater basin because unknown underground flow channels lead to a redistribution of infiltration water across the boundary. This makes it difficult to quantify the amount of the redistributed water.

Mountain massifs can be seen as lifted aquifers characterized by high altitudinal gradients and inclined stratification. The head difference between recharge area and springs is the primary driving force for the movement of water through the aquifer (White 2003). One can assume that groundwater flow in Alpine catchments is increased, as they consist of banked karstified limestone, the increased groundwater flow may even be additionally strengthened and redistribution processes may take place at the subbasin scale and affect receiving water courses in neighbouring Alpine valleys. However, in terms of sustainable water management, Alpine basins are the origin of large lowland watersheds, contributing with spring and surface water to brooks and rivers that in turn contribute to defined lowland river systems. Therefore, it is indispensible to understand the characteristics of subsurface water flow and its effect on the regional hydrology. Moreover, system understanding is absolute necessary to predict future changes in the light of climate change. Many studies in karstified areas focus on small-scale effects of karst conduits by examining spring hydrographs, chemographs and tracer breakthrough curves – to define the size and the characteristics of one individual spring aquifer (Birk et al. 2004; Bonacci 1993; Einsiedl et al. 2005; Geyer et al. 2008; Grasso et al. 2003; Hauns et al. 2001; Kovács et al. 2005; Smart 1988). Other approaches concentrate on karst genesis or theoretical conduit flow (Sauter et al. 2006; White 2002). Those studies do not provide answers to questions about karst effects on the comprehensive water balance of an Alpine headwater catchment. Questions remain: how much water redistributes from one subbasin (valley) to another through flow channels in mountain massifs? Can we quantify groundwater flow in karstified mountains?

This review paper summarizes all previous research in the study area with a focus on the water balance in the region. It aims to emphasize all outcomes indicating karst influence for the whole watershed or single subbasins. This knowledge provides profound insights into how the system is functioning and is the basis for the current research project in the Berchtesgaden watershed describing the water balance, with a focus on snow and groundwater storage, using the deterministic model WaSiM-ETH (Schulla & Jasper 2007). The outcome of this paper helps to improve the distributed model WaSiM-ETH for the area with respect to groundwater flow and its influence on the hydrology of the basin. The new model set-up will help to understand hydrological processes within the Berchtesgaden watershed, to gain more information about water storage in winter and summer and to predict future water availability and dynamics by performing climate impact scenarios. The overall aim is to improve hydrological modelling in karst-dominated catchments for integrated water resource management.

Site description

General

The Berchtesgaden Alps are situated in the Northern Limestone Alps in the southeast of Germany in the Federal State of Bavaria. Most of the area is part of Berchtesgaden Biosphere Reserve. Its core and buffer zone is Berchtesgaden National Park (Berchtesgaden NP; IUCN Category II) covering an area of 210 km^2.

Geology and geomorphology

The Berchtesgaden Alps can be seen as a geomorphologic unit. The mountain ranges are shaped as plateaus and ridges in close proximity (Figure 1). Three valleys (Klausbach valley, Wimbach valley and Königssee valley) stretch from south to north, separating four mountain massifs. Dominant rock formations are Triassic Dachstein limestone and Ramsau dolomite, whereas Jurassic and Cretaceous rock series are also present. The banked limestone with a layer thickness of up to 1 000 metres, on top of 300 metres of dolomite, reaches an altitude of up to 2 100 m. The three main tectonic units in the area are arranged in such a way that the base Tirolicum is covered by the Lower Juvavicum, which is itself beneath the Upper Juvavicum. Alpine orogenic processes have produced the typical slope and inclined stratification of the existing rock formations (Fischer 2005; Langenscheidt 1994). The soluble limestone was exposed to karstification processes since the Alpine thrust, which took place in different phases. Typical karst phenomena in the region are the presence of sinkholes, basins, dry stream beds, caves and furrows. An exceptional characteristic is the Wimbach valley, which is filled with 300 m thick layer of glacial deposits, consisting mainly of dolomite rock that forms a porous aquifer.

River hydrology

The rivers Klausbach and Wimbach and Königsseer Ache drain three parallel valleys stretching from south to north (Figure 1). The Klausbach is a sinking stream during low flow conditions and the Wimbach is only emerging at a dam in the Wimbachtal that restrains the glacial deposits. The Königsseer Ache is draining lake Königssee. The Klausbach, draining the most western valley and later called Ramsauer Ache, receives the Wimbach from the south, plus the Bischofswiesener Ache from a northerly direction. In Berchtesgaden, the Ramsauer Ache and Königsseer Ache together form the Berchtesgadener Ache which flows north. Further down, the Almbach and Rothmannbach drain into the Berchtesgadener Ache. In Salzburg, the Berchtesgadener Ache flows into the Salzach, which contributes to the Danube river system that drains an overall area of 795 686 km^3 to the Black Sea. There are nine lakes in the Berchtesgaden area: the Königssee, Obersee, Hintersee, Funtensee, Grünsee, Schwarzensee, Seeleinsee, Laubseelein and Blaue Lache.

Hydrology of the mountain plateaus and ridges

Untersberg

Description: Separate geological unit; geologically part of the so-called *hochjuvavische Reiteralmdecke* (Upper Juvavicum Reiteralm cover).
Drainage direction: Former tracer experiments in 1967, 1986 and 1982 resulted in tracer peaks after 8 weeks and 11 days, respectively, at the Fürstenbrunn spring, indicating subsurface flow paths in a northerly direction.
Springs and caves: 188 springs and 306 caves.
(Klappacher & Mais 1975; Klappacher 1996)

Lattengebirge

Description: A ridge stretching from north to south. Dominant rock formations are dolomite and dolomitic limestone.
Drainage direction: 10 of 33 caves drain in a westerly direction to the river Schwarzbach.
Springs and caves: 33 caves at the base of the mountain in the north and west.
(Klappacher & Mais 1975; Klappacher 1996)

Watzmann & Hochkalter

Description: Both mountain massifs formed a vault of mainly dolomite and Triassic limestone subducting north beneath the Berchtesgaden Unit. The peak of the vault collapsed, which resulted in the Wimbach valley (rift valley).
Springs and caves: 11 caves in the Watzmann and 16 caves in the Hochkalter massif.
(Klappacher & Knapczyk 1977, 1979; Klappacher 1996; Langenscheidt 1994)

Hoher Göll

Drainage direction: Subsurface drainage mainly to the north to three big karst springs on Austrian territory.
Tracer experiments: Gollinger Wasserfall.
Springs and caves: 11 springs: 5 are within the watershed of the Berchtesgadener Ache (Alpeltal, Scharitzkehlalm, Ofner Alm). 221 caves.
(Klappacher & Knapczyk 1979; Klappacher 1996)

Hagengebirge

Description: Mountain plateau between the Göll massif and the Steinernes Meer. Two thirds are on Austrian and one third on German territory. Built of Triassic limestone and dolomite, part of the Tyrolean tectonic unit.
Drainage direction: The plateau is mainly drained through subsurface flow. Most relevant springs are in the north (Austrian Bluntautal).
Tracer experiments: Two former tracer experiments in 1976 and 1978 indicated subsurface drainage in a north-easterly direction to the spring Schwarze Torren in Austria.
Springs and caves: 15 important springs across different valleys. 446 caves, of which 18 are in the watershed of the Berchtesgadener Ache.
(Klappacher & Knapczyk 1979; Gerecke & Franz 2006)

Reiteralm

Description: A plateau of bowl-shaped rock layers, inclining in the southeast in a north-westerly direction, in the north in a northerly direction and in the northwest in a south-easterly direction. Max. elevation 2 230 m, northern part max. 1 600 m. Same geological stratification as Lattengebirge.
Drainage direction: Mainly north to the spring Schwarzbachloch Fischer (2005).
Springs and caves: 169 caves.
(Klappacher & Mais 1975; Klappacher 1996)

Steinernes Meer

Description: Strongly karstified plateau mountain of 62 km^2, most springs situated at spliced geological joints between mountain massifs: Schrainbach between Watzmann and Steinernes Meer; Röthbach between Steinernes Meer and Hagengebirge.
Springs and caves: 19 important springs and 552 caves. Springs: Grünseebrunnen and Schradlloch in the north at lake Königssee altitude. Lake Obersee probably fed by springs beneath the lake. In the south, on Austrian territory, major springs at the Dießbach reservoir, the Wallerquellen and the Labeckbach at the Saalachtal. Due to the northerly incline of the banked limestone, the springs in the south are situated in the dolomite. Large karst springs in the north are situated even beneath the bottom in Dachstein limestone.
(Klappacher & Knapczyk 1977; Klappacher 1996, Langenscheidt 1986)

Karst

According to Fischer (2005), the Berchtesgaden relief is characterized by bare karst, half-exposed karren, covered karst and subsoil karst. As Alpine orogenic processes have continued since the Cretaceous and there are several huge karst springs, mature karst with endokarst and exokarst characteristics is present. Poljen and uvalas exist at mountain plateaus and dolines are dominant at geological faults (Langenscheidt 1994).

Research development

Tracer experiments

From 1987 to 2008, tracer experiments were conducted to detect the direction of underground flow paths of each mountain complex to quantify groundwater flow and to find out about transit times and water storage (Table 1). The experiments were all carried

Table 1 – Tracer experiments conducted in the Berchtesgaden Alps (modified from Plassmann 1998; GLA 1999; Apel et al. 2001 & 2005; Delannoy et al. 2001; Maloszewski et al. 2005; Kosak & Krafft 2006; Kraller 2008); d.n.a. = data not available

Location (year)	**Injection places**	**Tracer**	**Amount tracer [kg]**	**Number of sampling sites**	**Sampling sites with tracer breakthrough**	**Flow velocities [m/h]**	**Single tracer indications**	**Main drainage direction**
Gotzenalm (1987 & 1988)	Gotzenalm	Eosine (E)	2	11	4/2 (U/E)	~ 41.7	4/0	South-west
		Uranine (U)	2		3/0 (U/E)	10.8–83.3	8/0	
Wimbach (1990)	Sailergraben	Tritium Eosine, Pyranine ^{18}H	d.n.a.					
	Hochalm Water supply Wimbachgrieshütte							
Salzgrabenhöhle (1997)	Grünsee in the cave	Uranine	1	9	7	252–450	None known	North
	Waterfall	Sulforhodamine B	1		d.n.a.			
Steinernes Meer (1998)	Funtensee	Eosine	2	17	3	174–348	1	North
	Schwarzensee	Amidorhodamine	1		3	2.0–94		
	Grünsee	Uranine	2		7	2.9–42		
Göll (1999)	Christpherusschule, wastewater	Amidorhodamine	0.5	11	3	5.4–63	None known	West
	Scharitzkehlalm, wastewater	Eosine	0.5		3	0.3–26		
	Göllfuß	Uranine	0.5		10	4.6–307		
Hochkalter (2001)	Glacier runoff	Uranine	1	25	6	870	5	North
	Blaueishütte, wastewater	Eosine	1		6	0.7–662	7	
	Schärtenalm, wastewater	Sulforhodamine B	0.75		3	3.33–445	3	
Watzmann (2002)	Watzmannkar	Amidorhodamine	1	37	3	14.7–18.46	7	North
	Kühroint, wastewater	Eosine	1		0		1	
	Watzmannhaus, wastewater	Uranine	1		3	21.05–247.8	12	
Reiteralm (2004)	Hirschwiese	Natrium-Naphtionate	20	53	0			North
	Reitertrett	Amidorhodamine	2		1	14	1	
	Mühlsturzkar	Eosine	4		2	17–125	2	
	Häuslhorn	Uranine	2		1	74	3	
Reiteralm (2005)	Hirschwiese	Uranine	3	37	1	20.32	None known	North
	Erdgrube	Eosine	5		2	8.7–16.3		
Wimbach (2008)	Hochalm	Uranine	2	11	ongoing analysis			
	Hochgraben	Eosine	2					
	Mitterfleck	Amidorhodamine	2					

out within the borders of Berchtesgaden NP and are mainly named after the examined mountain (Figure 2). Each test was done using mainly the fluorescent dyes uranine, eosine, amidorhodamine, sulphurhodamine B and natrium-naphtionate (Plassmann 1998; GLA 1999; Dellanoy et al. 2001; Apel et al. 2001, 2005; Maloszewski et al. 2005; Kosak & Krafft 2006; Kraller 2008). The number and location of injection and detection places and the amount of injected tracer varied according to the research approach. As the NP administration is also interested in the flow paths of wastewater of Alpine huts, not only natural sinkholes were chosen as injection places but also the wastewater treatment plants of the huts. Sampling locations were mostly natural springs and streams but also springs that are used as water supply for Alpine huts, and pastures were sampled because they provide important ecosystem services in the area. The tracers were all injected at once and sampling, with a defined sampling program carried on for at least one year after injection (Plassmann 1998; Apel et al. 2001, 2005; Dellanoy et al. 2001; Maloszewski et al. 2005; Kosak & Krafft 2006; Kraller 2008). The samples were analysed at facilities of the former Bavarian Geological Survey (now Bavarian Environment Agency) and the Helmholtz-Zentrum Munich.

Results

Results of tracer tests have been described by Plassmann (1998), GLA (1999), Apel et al. (2001, 2005), Delannoy et al. (2001), Maloszewski et al. (2005), Kosak & Krafft (2006) and Kraller (2008). The results are presented in Table 1 and Figure 2.

The experiments in the Wimbach valley in 1990 and 2008 do not provide adequate results for further evaluation. No reliable data are available for the experiment of 1990, and the experiment of 2008 is still being analysed. As the rationale of the two approaches was to find out about travel times and water storage in the porous aquifer of the Wimbach valley, no karst influence (groundwater redistribution, increased groundwater flow) is expected.

The experiments from 1987 to 1999 were all conducted in the south-easternmost subbasin of the Königssee valley. They show high flow velocities in each preferred direction. The tracer tests of 1987 and 1988 showed flow velocities of up to 83 m/h in a westerly direction. The tracer breakthrough curves

*Table 2 – Quantitative modelling of the main flow paths of the tracer experiments at Göll, Steinernes Meer and Hochkalter (modified from Maloszewski et al. 2005). * in the investigated period*

Injection place	**Detection place**	**Distance [m]**	**Flow rate [m³/d]**	**Tracer**	**Number of flow paths**	**Velocities [m/h]**	**Volume of water [m³] ***
				Endstal valley			
Göllfuß	Königssee (well)	2000	100	Uranine	4	0.73–2.75	4600
	Scharitzkehlquelle (spring)	1000	1700	Uranine	4	4.2–44.2	28200
Scharitzkehlalm	Königssee (well)	370	100	Eosine	4	0.05–0.38	17000
				Hochkalter massif			
Glacier runoff	Gletscherquellen (spring)	3790	2160	Uranine	4	11–39	17700
Blaueishütte		2340	2160	Eosine	2	1.7–2.5	93600
Schärtenalm		1440	2160	Amidorhodamine	4	3.33–12	19000
				Steinernes Meer mountain range			
Funtensee	Schradlloch (spring)	4000	10600	Eosine	4	82–275	11100
	Kastl (spring)	3925	9500	Eosine	4	90–335	11200
Grünsee	Schradlloch (spring)	2750	10600	Uranine	3	275–655	2500
	Kastl (spring)	2650	1730	Uranine	4	209–575	400
	Grüne Brunnen (spring)	2425	1900	Uranine	4	27.1–127	2770
	Lagune (spring)	2150	260	Uranine	4	26–104	400
Schwarzensee	Grüne Brunnen (spring)	1925	1900	Amidorhodamine	4	25–83.3	2460
	Lagune (spring)	1525	260	Amidorhodamine	2	39–75	250
Salzgrabenhöhle	Schradlloch (spring)	870	4800	Uranine	4	47–182	1020
	Kastlquelle 2 (spring)	800	4320	Uranine	4	65–212	750
	Kastlquelle 3 (spring)	840	3600	Uranine	4	58–195	700
	spring between Schradel and Kastl	840	2160	Uranine	3	48–226	400

of uranine and eosine from the experiments of 1997 and 1998 indicate that the high-alpine lakes Funtensee, Schwarzensee and Grünsee are connected with lake Königssee via one huge subsurface cave with flow velocities of up to 348 m/h, with a stream velocity from the cave to the receiving lake Königssee of up to 450 m/h (Plassmann 1998; Delannoy et al. 2001; Maloszewski et al. 2005). The approach in the Göll area in 1999 showed rather low flow transport velocities in the porous aquifer, but the partly karstic aquifers are indicated by groundwater flow through karst conduits with flow velocities of up to 307 m/h detected for the tracer uranine (Apel et al. 2001; GLA 1999).

The experiments from 2001 to 2005, conducted at the huge mountain massifs of Hochkalter, Watzmann and Reiteralm, resulted in the detection of different groundwater flow directions (Figure 2). Experiments show that groundwater flow within a subbasin took place but also detected subsurface flow paths redistributing water between valleys. The experiment from 2001 returned low velocities, ranging from 0.7 to 662 m/h (Maloszewski et al. 2005; Kraller 2008). The tracer experiment in 2002 revealed several groundwater flow paths with flow velocities from 14–248 m/h. Both approaches show tracer spreads in an easterly and westerly, but predominantly northerly direction. The experiments at the Reiteralm in 2004 and 2005 reveal a drainage of this mountain plateau in a northerly direction, with water emerging mainly at one big karst spring. The flow path detected by eosine in 2004 to the karst spring showed flow velocities up to 125 m/h. Also single tracer indications were proven, noted as intermittent flow. No tracer test led to an evidence of groundwater transport out of the watershed towards the south.

Maloszewski et al. (2005) and Kraller (2008) applied the conceptual model FIELD and DIFFER (Maloszewski 1981; Maloszewski et al. 1992), developed at GSF-IfH (IGOE), to find hydraulic parameters of every single karst-hydrological connection between injection place

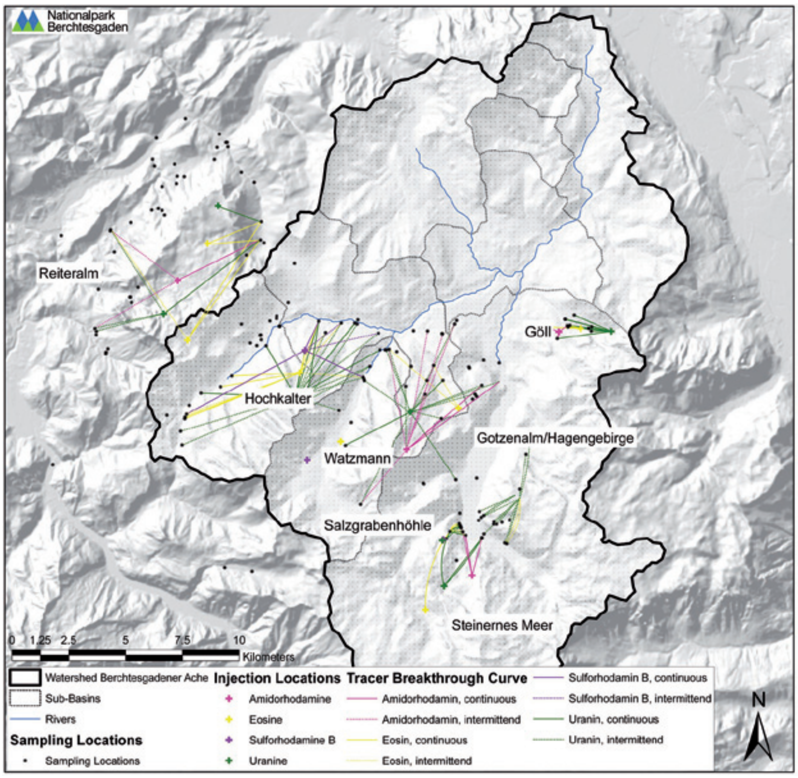

Figure 2 – Results of the tracer experiments conducted in the Berchtesgaden watershed.

and sampling site that result in different water volumes and flow rates. The model was applied to main flow paths from experiments at Endstal / Göll, Steinernes Meer and Hochkalter. The differences in flow velocities of Table 1 and Table 2 result from the approaches used. Table 1 summarizes flow velocities of all karst-hydrological connections detected for each tracer used in the tracer experiment. Table 2 presents results for selected tracer breakthrough curves from injection point to sampling point. The modelling results are presented in Table 2 and Table 3. According to the tracer breakthrough curve, every transport from sinkhole to

*Table 3 – Result of the quantitative modelling of the main flow paths detected by the Hochkalter tracer experiments (Kraller 2008). * in the investigated period*

Nr.	Sampling location	Tracer	Distance [m]	Flow rate [m^3/d]	Flow channels	Flow velocities [m/h]	∑ Volume per sampling location [m^3] *
1	Blaueis-Hütte	Uranine	523	1300	5	40–331	99905
2	Schärtenalm	Eosine	942	12.2	1	662	17
		Uranine	2020	12.2	2	870	28
5	Klauswandl 1	Eosine	4533	203.8	1	1.9	24456
6	Klauswandl 2	Sulforhodamine	4837	4147	3	42–445	84828
7	Eiswand	Uranine	4150	1296	2	17.5–33.3	10208
8	Ragertalm	Eosine	3324	666.9	1	1.1	80028
9	Schwarzbrunn	Eosine	2951	18975.6	1	0.7	3187900
11	Auzinger	Uranine	3078	33	2	1–1.3	6440
13	Gletscherquellen	Eosine	2340	2160	2	1.76–46	17700
		Uranine	3790	2160	4	11–38.5	93550
		Sulforhodamine	1440	2160	4	3.33–12.5	19050
21	Wimbachtal Infoträger	Uranine	4275	289.2	2	1.5–1.8	33429
23	Wimbach-Fassung	Sulforhodamine	2804	112320	2	130–289	178764
26	Engerdiensthütte	Eosine	5879	2077	1	1.6	268036

Table 4 – Sampling location and methods, method of analysis and model approach used in the isotope studies conducted in the Wimbach valley (Maloszewski et al. 1992; Einsiedl et al. 2008). d.n.a. = data not available

Isotope studies	Sampling			Methods	Model
	Location	Time period	Examined tracer		
Maloszewski et al. (1992)	5 sites at Wimbach river, 15 springs, 1 precipitation station	3 year time series (1988–1991)	Tritium ^{18}O	d.n.a.	Lumped parameter model (Maloszewski & Zuber 1982 & 1985)
Einsiedl et al. (2008)	Wimbach river (2 sites and 6 springs)	November 2006 March 2007 July 2007	^3H, $\delta^{18}H$, δ^2H Water chemistry Groundwater sulfate	Ion chromatography (Dionex DX 100) SHIMA-DZU TOC-VCPH Sulfate according to Silva et al. (2000) and Einsiedl & Mayer (2005 & 2006) Tritium: Liquid scintillation (Eichinger et al. 1980)	Lumped-parameter model (Maloszewski & Zuber 1982; 1985 & 1996)

Table 5 – Main results of the isotope studies conducted in the Berchtesgaden watershed (Maloszewski et al. 1992; Einsiedl et al. 2008). EM = Exponential model; DM = Dispersion model

	Maloszewski et al. (1992)		Einsiedl et al. (2008)
Mean discharge Wimbach river		1.75 m^3/s	1.75 m^3/s
Mean transit time	Gauge station, Wimbach river	4.15 years	4.50 years
	Springs	main spring (Wimbach spring): 3.9 years (EM) 3.7 years (DM)	4 springs: mean transit time: ~ 4 years
			1 spring: mean transit time: 7 years
			1 spring: mean transit time: 12 years
Resulting groundwater volume		220×10^6 m^3	250×10^6 m^3
Resulting groundwater depth		6.6 m	7.5 m
Estimated storage volume		2000×10^6 m^3	10^9 m^3
Porosity		0.3	0.3
Potential water storage		600×10^6 m^3	3×10^8 m^3
		2/3 saturated 1/3 unsaturated	1/3 saturated 2/3 unsaturated
Estimated potential water volume		470×10^6 m^3	100×10^6 m^3
Result	The water volume computed from isotopic data is only about half that estimated. Based on isotopic results, Wimbach river and spring water (Wimbach spring) originate from the same source.		The water volume computed from isotopic data is more than double that estimated.

karst spring consists of up to two flow paths leading to different flow velocities. For the tracer experiments within the Königssee valley, groundwater quantities during the experiment period could be estimated to 28 200 m^3 for the Endstal valley and up to 11 200 m^3 for the drainage of the high-mountain lakes to lake Königssee (Maloszewski et al. 2005). The tracer transport from the eosine injection location to the spring Gletscherquellen at Mount Hochkalter indicated that transported groundwater quantities could be estimated at 93 000 m^3. Kraller (2008) applied the model FIELD and DIFFER (Maloszewski 1981; Maloszewski et al. 1992) for all tracer breakthrough curves for the experiment at Mount Hochkalter in 2001. In this experiment, the transported water volumes flow within 1 – 5 flow channels from the injection places to the springs was found to be 3 187 900 m^3 (Table 3).

Isotope experiments

In 1992 and 2008, two isotope studies were carried out in the Wimbach valley (Einsiedl et al. 2009; Maloszewski et al. 1992). In 1992, measurements of tritium and ^{18}O concentrations in precipitation and runoff were used, in a simple hydrological dispersion model and an exponential model to find mean transit times. In 2008, ^{3}H, δ^{18}O and δ^2H measurements were used to determine the origin and mean transit times of groundwater using a lumped parameter approach. Furthermore, chemical and isotope analyses on groundwater sulphate were used to describe mean transit times of the groundwater (Table 4).

Results

The experiments were published by Maloszewski et al. (1992) and Einsiedl et al. (2009) and are summarized in Table 5. Both approaches were conducted to gain better insight into groundwater storage properties of the Wimbach valley. Both studies show that the mean transit time of tritium for the whole subbasin was around 4 years, resulting in a groundwater volume of 230 to 250 x 10^6 m^3. Regarding the potential groundwater storage, the approaches differ in the assumption of the proportion of unsaturated zone and saturated zone. Maloszewski et al. (1992) assumed 470 x 10^6 m^3 and Einsiedl et al. (2009) 100 x 10^6 m^3. Compared to the modelled results, the previous approach probably underestimates and the latter over-estimates the potential water storage. Maloszewski et al. (1992) refer to tracer tests to find an explanation and Einsiedl et al. (2009) argue that the rest of the water (150 x 10^6 m^3) is stored in the remaining catchment (mountain slopes).

Spring Monitoring Program (SPM)

Springs are locations of groundwater exfiltration and represent unique ecosystems. To examine these habitats and to determine possible climate impacts, a long-term spring monitoring project has been implemented over the last 16 years. Investigation parameters are location, altitude, discharge rates, as well as dynamics, chemical, physical and structural parameters, and the mapping of flora and fauna.

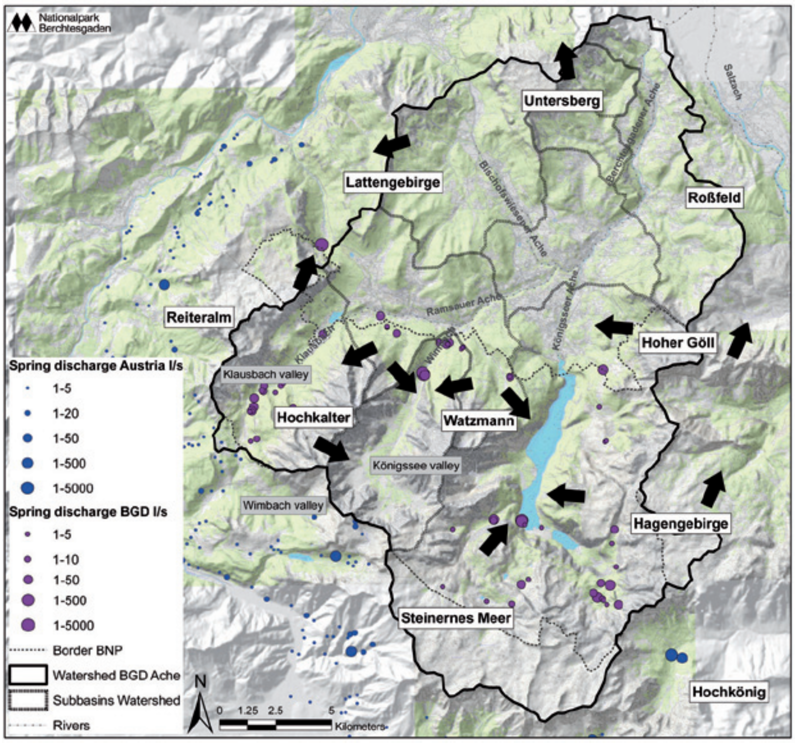

Figure 3 – Spring locations and discharge classification in the Berchtesgaden Alps. Black arrows indicate the direction of groundwater flow. BGD = Berchtesgaden, BNP = Berchtesgaden National Park

Results

A total of 413 spring locations are registered within the watershed Berchtesgadener Ache. The area of Berchtesgaden NP is characterized by 289 spring locations. A further 185 springs are situated in close proximity to the watershed in the south, in Austria. They indicate possible flow paths in a southerly direction. The springs in Berchtesgaden NP are distributed across an altitudinal range from 600 to over 2 000 m (Gerecke & Franz 2006) and have a discharge range from 0.1 l / s to 5 m^3 / s. The main springs occur at the northern base of the mountains Watzmann and Hochkalter and at the southern shore of lake Königssee, with discharge rates up to several m^3 / s (Figure 3).

Effect of the karst aquifer on the hydrology of the Berchtesgaden watershed

Karst

The basin is a highly karstified area due to a 1 000 m layer of banked limestone rock, which was lifted by Alpine orogenic processes, formed by ice ages and exposed to dissolution processes for 100 million years. The mountains are characterized by bare karst and endokarst and exokarst formations. We assume that evaporation over bare karst is minimal, as infiltration is more pronounced due to karst fractures and sinkholes. We take this into account when modelling karst conditions for infiltration.

A result of this karstification process are springs, spatially and altitudinally distributed and characterized by different discharge regimes. Most of the springs are situated at heights of 1 400 – 1 850 m and are not in contact with large receiving waters. Mostly they emerge at the border between dolomite and limestone, with dolomite being the aquiclude. They often react in a highly dynamic manner to precipitation events and snowmelt, which is typical for a minimal groundwater storage capacity. This indicates that shallow karst is dominant in the Berchtesgaden Alps, where the local and periodic groundwater aquifer is situated above the spring niveau and belongs to the vadose zone. Many spring locations do actually shift vertically depending on the amount of infiltrating water.

The presence of huge karst springs at the shore of the receiving water Königssee, however, indicates deep karst at the southern shore of the lake. As their groundwater aquifer lies beneath the receiving water, those springs are fed by water of the phreatic zone, but also of precipitation and snowmelt. Both the absence of huge karst springs at the base of the Watzmann and the geological stratification indicate the existence of subsurface springs beneath the water surface of the Königssee. A pronounced karst landscape in the area with typical surface morphology points to long and intensive karstification processes. The number of springs and their discharge regimes indicate a mature path with many continuous underground pathways.

Hydrology

This section draws together the main outcomes of this comprehensive summary with initial results of the distributed water modelling in the area.

There are indications that the region is generally draining in a northerly direction and groundwater flow channels enable groundwater inflow, outflow and redistribution of groundwater between subbasins. Figure 3 summarizes assumed subsurface flow directions based on the evaluated research.

Tracer experiments from 1987 to 1999 in the Königssee valley resulted in high flow velocities between sinkholes and sampling points. All of the detected underground pathways are situated within the Königssee valley. Therefore, increased groundwater flow is given within the valley, but no criterion for groundwater redistribution through mountain ranges could be found. Klappacher (1979) describes groundwater flow in an easterly direction, which would imply water leakage for the subbasin and the whole drainage basin of the Berchtesgadener Ache itself. To underline the assumption of increased groundwater flow within the valley, Figure 3 shows high quantities of groundwater draining high-Alpine lakes through a huge karst cave and emerging at phreatic karst springs at the southern shore of lake Königssee (tracer experiments of 1997 / 1998). Initial model runs suggest that modelled discharge underestimates measured discharge within this subcatchment. Increased groundwater flow to the north may be the reason for underestimating runoff, as increased groundwater flow in high quantities has so far not been considered during model performance.

The results of the tracer experiments in 2004 and 2005 at the plateau mountain Reiteralm indicate groundwater flow in a north-westerly direction (Kosak & Krafft 2006). This subsurface connection is also described by Klappacher (1975, 1996) and Fischer (2005). We found strong indications of a leakage out of the drainage basin, as water infiltrating on that part of the region is not contributing to the river Berchtesgadener Ache. Model results with WaSiM-ETH so far show that there is a systematic overestimation of modelled discharge in the relevant basin, which could be explained by the fact that no leakage was considered in the model from the outset.

The dye experiment on Hochkalter can be associated to the Hintersee valley and Wimbach valley. The results show subsurface flow paths with some high flow velocities. For the mountain massif Hochkalter, the valleys between the drainage basin and the groundwater basin differ, resulting in groundwater redistribution. Due to high flow velocities and consequent transported water volumes, the hydrology of neighbouring subbasins may affect each other. However, no underlying evidence could be found in the literature. The location of the tracer test on Watzmann 2002 could be assigned to the subbasins Wimbach valley and Königssee valley. Similar to the experiment on Hochkalter, the detected underground flow directions passed the subbasins drainage borders. Groundwater flow took place in various directions and at different flow velocities.

The Untersberg is described as draining to the north and the Lattengebirge, according to the geological structure, is draining west to the river Schwarzbach (Klappacher 1975, 1996). Both flow directions mean a leakage of groundwater for the watershed of the Berchtesgadener Ache.

The water storage in the porous aquifer, assumed by two isotope studies (Einsiedl et al. 2009; Maloszewski et al. 1992), is about half of the volume of the Königssee. This groundwater body may buffer karst conduit flow in the Wimbach valley. As it is difficult to consider this extraordinarily porous aquifer within the model set up of WaSiM-ETH, the outcomes of the isotopes studies may help to understand probable discharge curve mismatches in the relevant subcatchment. The approaches showed not only increased groundwater flow within a subbasin, but also groundwater flow between subbasins. So far it is not clear how strong the impact of the redistributed water is on the hydrology on the region, but the increased groundwater flow within valleys and the detected outflow of several m^3 / s indicate some impact. We assume that the effective incoming precipitation (precipitation minus evapotranspiration) to relevant basins is not represented by measured discharge, as the extraordinary storage element karst can systematically lead to groundwater inflow or outflow from subbasins. This behaviour may then affect the hydrology of the whole region. Within the distributed modelling with WaSiM-ETH, this effect can be detected, as model algorithms do not consider redistributed water quantities.

Outlook: current research

To determine total water resources, the NP authority assigned two research institutes to describe the water balance using a distributed hydrological model at basin and subbasin scale (Kraller 2010). An ongoing research collaboration is jointly adopting and using the deterministic hydrological model WaSiM-ETH (Schulla & Jasper 2007) to describe the water balance for the watershed of the river Berchtesgadener Ache, which includes nine mountain ranges of the Berchtesgaden Alps and covers 432 km². The nine existing river gauges subdivide the basin into nine subcatchments.

The focus on the storage elements karst and snow should provide information about groundwater redistribution, inflow and outflow induced by each element. In addition, detailed evaluation of modelled and measured runoff curves during and after rainfall events may provide information on increased groundwater flow or water storage due to karst characteristics. Further aims will be to estimate systematic water redistribution, inflow and outflow between the subbasins of the area and to define limiting values for the respective processes.

The final question is: how do changing climatic conditions change subbasin drainage and discharge and how does this affect the overall basin hydrology?

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