ON THE HYDROLOGY OF THE PARTNACH AREA IN THE WETTERSTEIN MOUNTAINS (BAVARIAN ALPS)

With 13 figures and 2 tables

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Zusammenfassung: Zur Hydrologie des Partnach-Ursprungs im Wettersteingebirge

Die Hydrologie alpiner Einzugsgebiete ist auch heute noch sehr wenig erforscht. Gerade in Zeiten mit klimatischen Veränderungen ist es jedoch wichtig, ein besseres Verständnis der Wasserressourcen von Gebirgen zu erlangen, da diese Räume überproportional hohe Niederschläge erhalten und so für die Wasserversorgung großer Gebiete von Bedeutung sind. In den Sommermonaten der Jahre 1996 und 1997 wurden am Partnach-Ursprung Abflüsse, elektrische Leitfähigkeiten und Niederschläge registriert. Mit diesen Daten liegen erstmals fortlaufende hydrologische Daten zu Deutschlands höchstgelegenem Karstgebiet vor. In beiden Jahren wird der sommerliche Abfluss zu über 30% aus der Schneedecke gespeist. Im trockenen Herbst 1997 tritt der Schmelzwasserabfluss von den Gletschern im Gebiet deutlich hervor, über mehrere Wochen sind tägliche Schmelzhydrographen der Gletscher zu beobachten. Durch Konstruktion der Trockenwetterlinie konnte das allgemeine Speicherverhalten des Gebietes verdeutlicht werden. Rezessionsabschnitte von Hochwasserabflüssen als Folge von Niederschlägen bilden den obersten Abschnitt der Trockenwetterlinie, der Auslauf des Karstspeichers beginnt bei ca. 2 m^3/s. Mit graphischen und mit gewässerchemischen Methoden kann gezeigt werden, dass mehrere Karstwasserleiter mit unterschiedlichen Fließgeschwindigkeiten am Abfluss beteiligt sind. Neben dem Oberflächenabfluss können für den Partnach-Ursprung drei Karstwasserleiter nachgewiesen werden. Dabei handelt es sich offenbar um lösungschemisch erweiterte Hohlräume, um Kluftwasser- und Porenwasserleiter, die jeweils mit unterschiedlicher Verzögerung auf einen Niederschlagsinput reagieren. Bei allen drei Karstwasserleitern können Verdrängungsprozesse beobachtet werden, durch die altes, im Karstsystem gespeichertes Wasser mit hohem Elektrolytgehalt von frischem, ionenarmem Niederschlagswasser herausgedrückt wird und als erstes an der Quelle erscheint. Mittlere Fließgeschwindigkeiten von etwa 400 m/h (ca. 11 cm/s) können mit Hilfe der Analyse von Schneeschmelzhydrographen nachgewiesen werden, da durch das täglich abgegebene Schmelzwasser eine stufenweise Abnahme der elektrischen Leitfähigkeit im Abfluss aufgezeichnet wird. Im Vergleich mit Gebieten des Dinarischen Karstes liegen die Fließgeschwindigkeiten im Einzugsgebiet des Partnach-Ursprungs sehr hoch und deuten auf ein gut entwickeltes Karstsystem.

Summary: Until today there is still a deficit in understanding the hydrology of alpine environments. Especially in times with changing climatic conditions it is necessary to get a better knowledge of the water resources in mountainous areas, because these areas are receiving disproportionate amounts of rainfall and in consequence they have high significance for the fresh water supply of large areas. During the summer months of 1996 and 1997 runoff, electrical conductivity and rainfall have been measured at the Partnach spring (Wetterstein mountains with the Zugspitze 2,962 m a.s.l.). These data are the first continuous hydrological records of the Partnach spring in the highest situated karst area of Germany. During both years of measurement, about 30% of runoff in summer is constituted by snow-melt processes in the upper part of the catchment. In the dry autumn of 1997 snow-melt hydrographs of the glacier fields can be seen clearly over several weeks. With the construction of the recession curve the overall depletion behaviour of the catchment has been demonstrated. Recession limbs of several storm-induced runoff events constitute the upper part of the recession curve, depletion of the groundwater takes place if runoff reaches values lower than 2 m^3/s. With graphical and geochemical methods it has been shown that runoff is produced by different karst water systems with specific velocities of flow. Apart from overland flow, three components of groundwater flow have been detected. Flow in karst conduits, flow in fractures and diffuse Darcian flow in fine fractures are reacting with a different delay after storm precipitation. Displacement processes for all components of flow can be observed by means of electrical conductivity. Old pre-event water with a high electrical conductivity is pushed out of the aquifer before the new storm water can be detected by a falling electrical conductivity in the karst spring. Flow velocities in the karst conduits have been calculated during snow-melt. The rhythmic curve of the daily melting hydrographs is connected with a stepwise fall of the electrical conductivity at the karst spring because of dilution processes. New melting water arrives at the Partnach spring when the electrical conductivity is falling. By means of the electrical conductivity, mean velocities of flow of about 400 m/h (about 11 m/s) have been calculated. In comparison with Dinaric karst areas, these high values are pointing to a well developed karst conduit system in the underground of the Partnach area.

1 Introduction

Even today there is a deficit in knowledge of the high mountain areas of the earth. Hence the UN proclaimed the year 2002 as the "International Year of the Mountains". A special deficit exists in the knowledge of the hydrology of high mountain areas. Due to the observed and predicted climatic change, research on this topic has to be intensified (e.g. WISSENSCHAFTLICHER BEIRAT DER BUNDESREGIERUNG 1998; BENISTON 2002). A better knowledge of the hydrology of high mountain areas is so important, because these areas are receiving over proportional amounts of rainfall. Through this high mountain regions possess an abundance of water and after MESSERLI and IVES (1997) they are called the "water towers" of the earth. Even under humid climatic conditions high mountain areas are necessary for the water supply of large regions. About 50–60% of the annual discharge of the river Rhine for example is produced in the alpine part of the catchment, covering 11% of the total area. Hydrological research should be intensified because little is known about water balance and hydrological processes, despite the enormous hydrological potential of mountain areas. High mountain hydrology has been characterized by BANDYOPADHYAY et al. (1997, 131) as "the blackest of black boxes in the hydrological cycle" from which only the output is known with a satisfying accuracy.

The knowledge of the water balance of the Alps has first been summarized by BAUMGARTNER et al. (1983). Resulting from different reasons, the authors had many difficulties estimating aerial amounts of rainfall and evapotranspiration. Twenty years later only little has changed, rainfall and evapotranspiration are still remaining uncertain parts of the water balance in alpine areas (SPREAFICO 2001; DE JONG et al. 2002). Despite over 5,000 rainfall collectors in the Alps, rainfall amount can be calculated only with a considerable degree of inaccuracy. Even in Switzerland, which is known as the best investigated hydrological area of the earth with a dense network of meteorological stations and sophisticated procedures of rainfall corrections, an inaccuracy of rainfall amount of 14% is given in the Hydrological Atlas of Switzerland (SPREAFICO 2001). The same problems are concerning the Wetterstein Mountains although the meteorological service of Germany (DWD) maintains an observatory at the Zugspitze (2,962 m a.s.l.), the highest peak of the Bavarian Alps.

Also for wide areas of the Alps runoff is only estimated. The Partnach-Ursprung, one of the largest karst springs in the Bavarian Alps, is draining the area of the Zugspitze. But the discharge of the karst spring is rather unknown. After WILHELM (1997) mean runoff of the Partnach close beneath the spring is about 4 m^3/s. If a catchment area of 20 km^2 at the point of runoff measurement is assumed, the mean annual precipitation must be more than 6,000 mm! Taking the geological and geomorphological situation of the area into consideration, an underground influx has to be excluded and the current hydrological knowledge of even well known alpine areas is demonstrated by this value.

Hydrological investigations in the basin of the Partnach-Ursprung should not focus only on the parameters of the water balance. Several questions concerning the hydrology of alpine karst areas can be examined here. In the past different hydrological investigations even in alpine karst areas have been conducted. Most of the studies are dealing with tracer hydrology (cf. BÄUMLE et al. 2001; SEILER a. WOHNLICH 2001), but investigations of runoff production processes in alpine karst systems are rare. Above all HESS and WHITE (1988) and DREISS (1989) have shown that different processes in the karst aquifer can be examined by means of a combination of hydrological and geochemical analysis. As WHITE (1988, 136) pointed out, much more investigation on the base of geochemical analysis should be conducted in karst terrain. Therefore a gauge station has been installed close beneath the Partnach-Ursprung. During the summer months in 1996 and 1997 data on the water level, electrical conductivity of runoff and rainfall have been recorded at this station.

The hydrological investigations at the Partnach-Ursprung presented in this paper have four areas of concern. At first, runoff during the summer months as a consequence of snow melting, storm precipitation and glacier ablation should be registered, analysed and discussed in a regional context. Secondly, hydrological balances for the two measuring periods on the basis of meteorological and hydrological data should be calculated. An analysis of runoff production processes for the different types of runoff (e.g. snow melt and storm runoff) is a further focus of this paper. At least karst hydrological conditions should be examined by use of continuous records of water quality data.

2 The investigation area

The investigation area is situated in the western part of the Wetterstein Mountains culminating in the peak of the Zugspitze (Fig. 1). Crests of a westward-rising geological synclinal structure are bordering the surface catchment area of the Partnach-Ursprung (cf. Fig. 2).

The border runs along several peaks (e.g. Jubiläumsgrat, Zugspitze and Schneefernerkopf) following the circular-stretching geological structure. To the east, the catchment is opened like a horseshoe, so the catchment border cannot be determined by the topography of its surface. Here, S–N and SW–NE-running fault lines form the hydrogeological border. In the cross point of these fault lines the Partnach-Ursprung is situated. The central part of the catchment, the so-called "Zugspitzplatt", has a quite smooth eastward-falling surface (about 13°) which is overtopped by about several hundred metres by the peaks of the divide.

The geological ground of the Partnach area is formed by the 220 mill. year-old (Ladin) Wetterstein limestone, a pure white reef limestone with a thickness of about 600–800 m (Miller 1962). Karst landforms of different dimensions as karren fields and dolines can be found on the Zugspitzplatt. Under the Wetterstein limestone a marly claystone (Partnachschichten, thickness about 300–400 m) follows with a low hydraulic conductivity (Fig. 2), which acts as an aquiclude. The groundwater flow direction in the karst system of the Partnach-Ursprung basin is eastward (Wrobel 1980). At the fault lines which form the border of the groundwater basin in the east, the karst water is forced to well up and forms the Partnach spring. No indication for a leakage of the basin has been found by means of tracer studies (Wrobel 1980) and examinations of springs in the vicinity of the basin (Endres 1997). So it can be assumed that the Partnach basin works like a natural lysimeter and is especially suitable for studies on water balance. However, more hydrogeological investigations are necessary to be sure about a closed aquifer system and the hydrogeological conditions of the catchment.

The catchment of the Partnach source has an areal extent of 11.4 km^2. Between the highest point of the catchment (Zugspitze 2,962 m a.s.l.) and the Partnach source (1,430 m a.s.l.) a distance of 3.6 km and a vertical difference of 1,532 m exists. Beneath the Zugspitze the "Nördlicher Schneeferner" the largest glacier of the Bavarian Alps is situated. Today the glacier area has an extension of only 31 ha, because of a fast retreat in the last 20 years (Hera 1997). Together with some

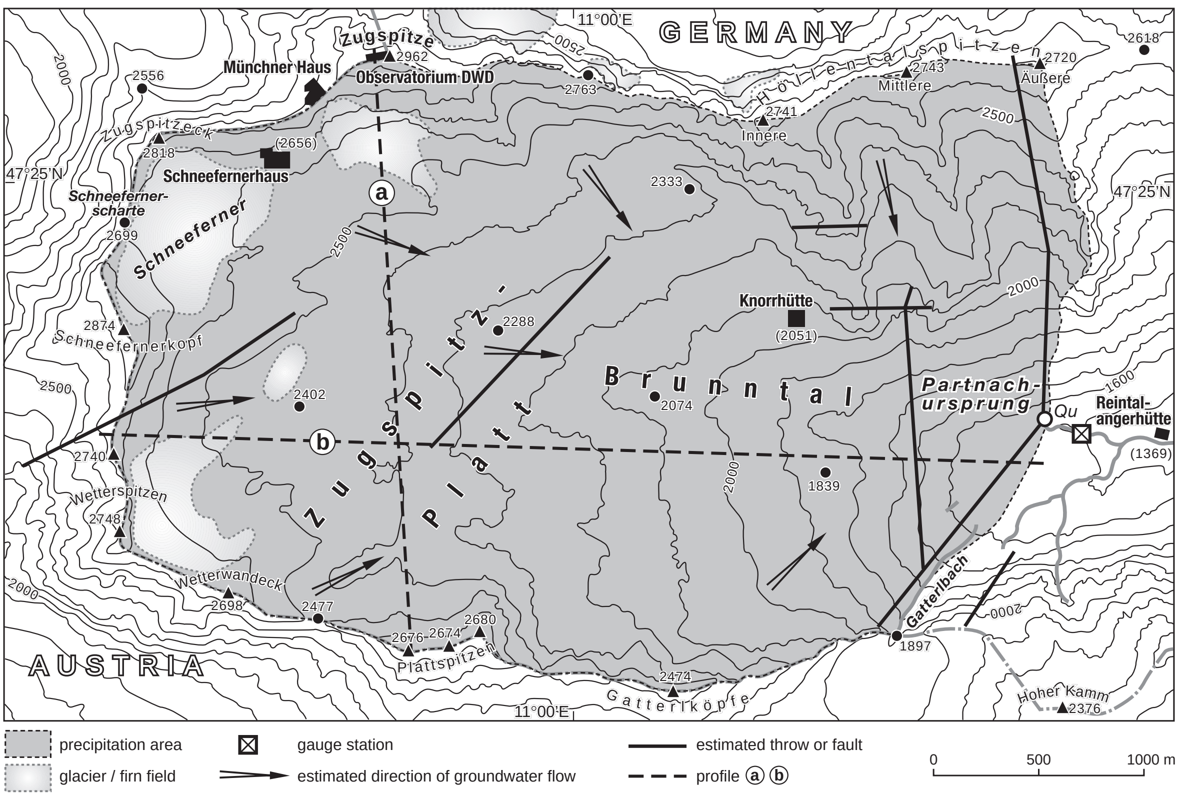

Fig. 1: The area of the Partnach spring, the estimated directions of groundwater flow after investigations of Wrobel (1980) and the location of the gauge station

Das Einzugsgebiet des Partnach-Ursprungs, angenommene Fließrichtungen des Grundwassers nach Untersuchungen von Wrobel (1980) und die Lage der Pegelstation other small glaciers in the Partnach catchment 54 ha or 4.7% of the total area is covered permanently by ice. The tree-line in the Northern Alps has an altitude of about 1,800 m. Because 90% of the catchment is situated in elevations over 1,800 m, alpine grassland partially used as pasture is the dominant vegetation cover. Alpine forests mainly consisting of spruce, fir, pine and some maple trees are growing in locations which are protected against rockfall and snow avalanches. More than 40% of the catchment is barren of vegetation because of the steep slopes and the resistance of the Wetterstein limestone.

The climatic conditions of the area are monitored by the meteorological observatory at the top of the Zugspitze. Mean rainfall of a 30-year period (1961–1990) is 2003.1 mm, rainfall is equally distributed over the year, only in April a slight minimum can be observed (Müller-Westermeier 1996). In the same period a mean temperature of –2.8°C with the extremes 17.6°C and –32.7°C has been recorded. Because of the extreme relief and the different expositions the observations are only valid for the highest parts of the catchment of the Partnach-Ursprung.

3 *Methods and instrumentation*

Assessing the long-standing hydrological balance of a catchment measurement of at least two components of the balance is necessary. In this investigation, only short periods of observation have been carried out. Additionally snow cover outflow has taken into consideration, too, following that all components of the water balance should be measured or estimated. The geolog-

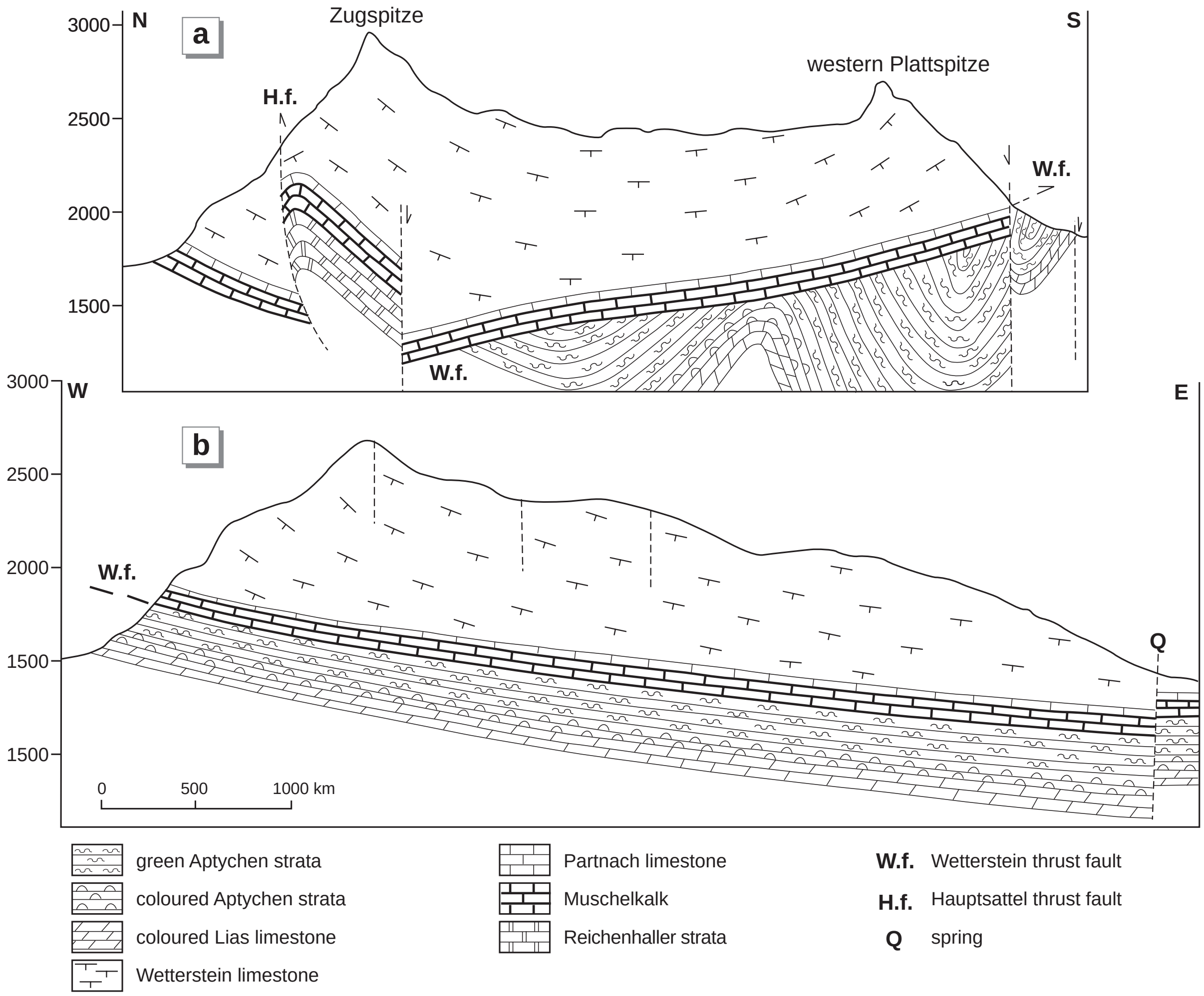

Fig. 2: Geological cross-sections through the Partnach area (after Endres 1997)
Geologische Profilschnitte durch das Partnach-Gebiet

ical and geomorphological conditions of the catchment of the Partnach-Ursprung lead to the conclusion that the total runoff of the basin can be recorded by means of a gauge station at the Partnach close to the spring. For an alpine catchment with relief conditions like the Partnach area rainfall and evaporation measurement cannot be conducted with the same accuracy as runoff. One problem is the calculation of the regional precipitation; the other is how to estimate basin-wide rates of evapotranspiration. The analysis of runoff production processes has been carried out by means of graphical separation and electric conductivity as an indicator for geochemical processes. In the following a discussion of the different methods applied in this investigation is presented.

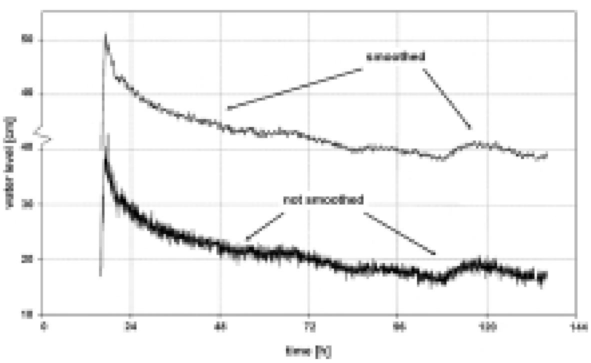

Fig. 3: The water level/runoff-relationship at the Partnach gauge station

Die Wasserstands/Abfluss-Beziehung der Pegelstation Partnach-Ursprung

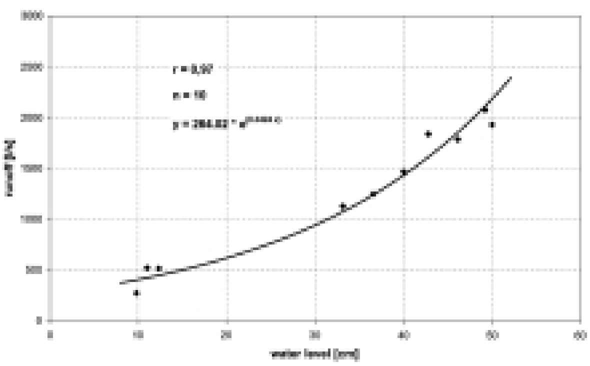

Fig. 4: The roughness of the water-level data as a result of the turbulent flow of the Partnach creek and the smoothed hydrograph

Schwankungsbreite von Pegelaufzeichnungen an der Station Partnach und die durch Glättungsroutinen gedämpfte Ganglinie

3.1 Runoff

In June 1996 a water level recorder has been installed about 200 m beneath the Partnach-Ursprung. Here, the intake of a small power plant for a nearby hut of the DAV (German Alpine Club) with a fixed cross-section of the Partnach creek is situated. Together with the electronic water level recorder a probe for electrical conductivity has been placed. The data of the probes have been recorded at intervals of five minutes by a data logger. Runoff measurements with the salt dilution method (Benischke a. Harum 1984; Käss 1992, 455) have been conducted at 10 different water-levels (Fig. 3). Some more runoff measurements in times of moderate runoff would be desirable but as a consequence of the difficulties in reaching the investigation area (several hours of walking) and the problems of salt transport (about 6 kg per measurement) no more data are available. Measurements with different probes in the cross-section of the Partnach creek with deviations of < 3% have shown the accuracy of the salt dilution method (Otzinger 1998). The best fit of the data is given by an exponential function with a coefficient of correlation of 0.97 and a mean deviation of ± 19% for the calculated runoff. A reason for the error of the regression model has to be seen in the difficulties of measuring exact water-levels due to the highly turbulent flow of the Partnach creek.

The turbulent flow of the Partnach with a high velocity is causing a rough surface of the creek. Resulting from the turbulent flow and from pressure pulses the water-level records are showing short termed oscillations and abrupt peaks and lows, as figure 4 demonstrates. Therefore smoothing of the data has been necessary. This has been done in two steps: at first all abrupt peaks and lows as a consequence of pressure pulses have been eliminated. In a second step a moving average over five values has been calculated. Moving average has been chosen for smoothing, because original data should be modified as little as possible. Figure 4 shows the course of the water-level during a storm event before and after the smoothing procedure.

3.2 Precipitation

The calculation of the mean regional amount of precipitation in alpine areas is very difficult, due to the spatial heterogeneity of rainfall. Growing problems occur if the regional amount of precipitation for single events should be estimated. This results from different directions of the wind field and from the increase of rainfall with height (Spreafico 2001). Also it can be observed that the gradient of rainfall varies from one rainfall to another in relation to the type of rainfall (convective or advective) (FELIX et al. 1988). As SEVRUK (1985) pointed out, any precipitation measurement has a systematic error specific to each type of rainfall collector and the wind field in the vicinity of the collector. For summer conditions this error is about 5–15% (cf. FELIX et al. 1988, 87) and has to be taken into consideration, too. The spatial and hypsometric distribution of rainfall can be measured if enough rainfall collectors are situated in the basin. Because of the limited financial budget of the current investigation, only data of one precipitation balance near the gauge station and precipitation data of the DWD from the Zugspitze have been used.

Due to the above mentioned, a calculation of the regional amount of precipitation for the Partnach area bears a lot of uncertainties. In this study the regional amount of precipitation has to be calculated I) assessing the seasonal water balances and II) for analysing runoff processes in the karst system. Assessing the seasonal water balance data of the DWD observatory at the Zugspitze should be used, too. Therefore the data have been corrected by adding 10% of precipitation amount if rainfall has occurred and 20% in the case of snowfall. Differentiation of snow and rain had already been conducted by the DWD. The correction is in accordance with the findings of SEVRUK (1985), MOSER et al. (1986) and FELIX et al. (1988). But a comparison with the writer´s own data recorded at the gauge station points to the problems of measuring precipitation in alpine areas. Only a small difference exists between the rainfall amount at Partnach station (1,430 m a.s.l) and Zugspitze (2,962 m a.s.l). Taking the geomorphological conditions of the catchment surrounded by high mountain ridges in the north, west and south into account a clear difference in rainfall amount between the valley station and the summit observatory should exist.

Table 1: Data of rainfall amount for the Partnach area during the investigation periods after different sources (Partnach = own data recorded at the gauge station, Zugspitze (corr.) = corrected data of the DWD, Partnach area = areal rainfall amount after own data)

Die Niederschläge im Partnachgebiet während der beiden Messkampagnen nach verschieden Quellen (*Partnach* = eigene Daten, *Zugspitze (korr.)* = korrigierte Daten des DWD, *Partnach-Gebiet* = selbst errechnete Gebietsniederschläge)

period	Partnach gauge [mm]	Zugspitze (corr.) [mm]	Partnach area [mm]
18.6.–30.8.96	491.9	576.1	629.6
14.6.–7.10.97	580.4	573.9	742.8

So calculation of the regional amount of precipitation has been calculated by means of the author's own data. But how is the increase of rainfall with elevation to be taken into consideration? An overview of different rainfall gradients in the northern Alps has been given by FELIX et al. (1988, 262) and for Switzerland a similar situation is presented by SPREAFICO (2001). After that any assumption of precipitation gradients is speculative. But as MOSER et al. (1986) pointed out, correction of rainfall data for the purpose of hydrological balances should be conducted. Hence the mean gradient of 65 mm/100 m given by BAUMGARTNER et al. (1983, 121) for the northern Alps has been adopted for the Partnach area. Because single events should also be corrected and gradients during summer are lower (cf. FELIX et al. 1988), a rainfall increase of 3% per 100 m seems to be a realistic approach for the Partnach area. Calculation of the regional precipitation has been done by use of a DEM, so the hypsometric distribution of rainfall has been taken into account, too.

3.3 Evapotranspiration

Due to the geographical heterogeneity of the different parameters influencing evapotranspiration rates, assessment of the regional distribution of evapotranspiration is difficult. Modelling of annual evapotranspiration rates of alpine areas can be performed quite well, but modelling accuracy of shorter periods of time is not sufficient (XU a. SINGH 2000). At the hillslope scale of hydrology of alpine areas most of the parameters affecting evapotranspiration are not available. New approaches have to be developed for the calculation of basin-wide evapotranspiration rates (DE JONG et al. 2002). Despite its having been shown that daily evapotranspiration rates of high alpine areas are higher as supposed, the daily net water vapour balance is lower resulting from nightly condensation processes as DE JONG et al. (2002) have pointed out. Because runoff production in a high alpine karst area is the main topic of this investigation and data for the research basin are rare, the simple approach after HAUDE (1958) for estimation of evapotranspiration rates has been chosen.

3.4 Runoff production and hydrology of the karst system

Different approaches are used in hydrological studies concerning runoff production processes for separation of the sources of discharge (e.g. CUI 1997). Runoff separation can be conducted by means of three methods: I) separation with the graphical method (MUTREJA 1990), II) separation by use of stable isotopes of the water cycle and III) geochemical separation where the different pathways of water during the process of runoff production are traced by ions specific to the sources of runoff (McDonnell 1990; Wels et al. 1991). In this study the electrical conductivity has been used as a tracer for Ca^{++} and Mg^{++} cations dissolved in the water by solution processes in the karst aquifer of the Partnach area. Electrical conductivity (EC) has been used successfully in several studies on runoff production (Kennedy et al. 1986; Kobayashi et al. 1999; Wetzel 2003) as well as in karst hydrologic investigations, if a shallow karst system exists (White 1988, Dreiss 1989). Due to the lithologic homogeneity of the catchment – all over the catchment Wetterstein limestone forms the ground – Ca^{++} and Mg^{++} are the dominant dissoloved cations, showing a relation of 4:1. As demonstrated in figure 5, a significant correlation exists between EC and the hardness of runoff water. Therefore in the results and discussion section only EC is used in explaining runoff production.

The solution content of runoff and therefore the EC, results from a mixture of three components of runoff: I) precipitation water with a low solute content and a typical EC of 15 µS/cm (± 10 µS/cm), II) overland flow with an EC of about 80–100 µS/cm varying with the intensity of rainfall and III) the karst water component with an EC of up to 140 µS/cm. The EC of rainfall has been measured in various studies in the Bavarian Alps (cf. Wetzel 2001, 2003). Overland flow and the karst water component have been sampled during field trips. In the course of the dry autumn of 1997 the EC and the solute content of the Partnach spring rose to the highest values observed in the investigation period. During this

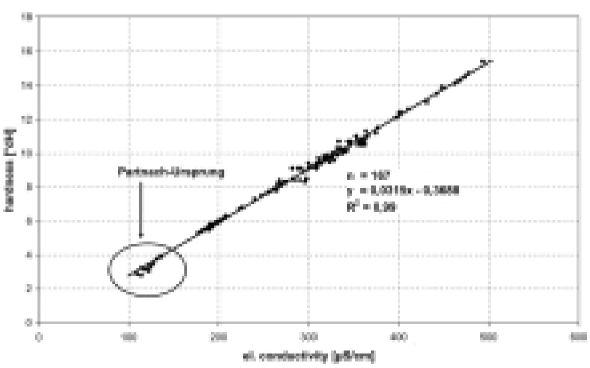

Fig. 5: The correlation of electrical conductivity and hardness for the Partnach-Ursprung in comparison with other measurements in the Bavarian Alps
(Source: own data)

Der Zusammenhang von elektrischer Leitfähigkeit und Gesamthärte für den Partnach-Ursprung im Vergleich mit anderen Gewässern der Bayerischen Alpen

time only small amounts of glacier runoff led to a dilution of the karst water and an EC of nearly 140 µS/cm has been measured. Probably in the winter, highest solute concentrations near the equilibrium should be observed at the Partnach spring, but due to the risk of avalanches the spring is not reachable. Therefore an EC of karst water of 140 µS/cm has been assumed. Despite the concept presented above, which mixes three components, precipitation is not used as a separate source of runoff in the following text. As pointed out before, due to the karst processes no perennial running water can be observed in the Partnach basin. The entire precipitation falls to the ground and immediately solution processes are starting (Hüttl 1999). Because of the high velocity of the solution processes during rainfall only overland flow with a typical EC of 80–100 µS/cm in the Partnach area enters the karst system via joints, sinkholes or dolines. Once entered the karst system further solution takes place in the aquifer. In relation to the occurrence of wide karst conduits, one part of the water leaves the system without reaching solute equilibrium; the other part has longer retention periods in the karst aquifer and therefore a higher solute concentration (Atkinson 1977; Hess a. White 1988; Ford a. Williams 1989). Hence, spring runoff has to be seen as a mixture of two components: fresh overland flow with low solute concentrations transported quickly through the karst conduits and highly concentrated old water of the karst aquifer.

Additional to the tracer approach, the traditional graphical method of hydrograph separation has been used recognising different sources of runoff in the karst system. According to Chow (1964) and Mutreja (1990) separation of runoff has been conducted. The underlying principle of the graphical method is the assumption that storage depletion can be described by an e-function:

$$Q_t = Q_0 \cdot e^{-\alpha t}$$

where:

Q_t → runoff at time t after runoff Q_0
α → empirical recession constant
t → time interval between runoff Q_0 and Q_t

In a semi-logarithmic diagram the slowest component of runoff building up the hydrograph will be changed to a straight line (Matthess a. Ubell 2003, 407). The point "k" where the recession curve breaks to the straight line defines the moment after that runoff is constituted only by the slowest component of flow. The separation of the slowest component is accomplished by constructing a straight line from the beginning of storm runoff to point "k" on the recession curve representing the end of faster components of flow (cf. MUTREJA 1990). Subtracting the slowest component will lead to a new hydrograph and the procedure can be repeated. By means of graphical separation methods, the course of runoff components during the rising part of the hydrograph is speculative (MATTHESS a. UBELL 2003, 408). Thus, the application of graphical separation techniques should be restricted to the recession part of the hydrograph and quantitative conclusions should be drawn with care. In this study the graphical method has been used only for the detection of different karst aquifers constituting spring discharge.

4 *Results and discussion*

4.1 The hydrographs of the two investigation periods

With this paper the first runoff records of the Partnach spring over a period of several months are presented. The hydrographs of the two periods of investigation show a quite similar course (cf. Fig. 6 and 7). During both years a "baseflow", as the result of snow melt runoff in the upper part of the basin, can be observed, which is superposed by rainfall induced runoff. The storm hydrographs at the Partnach spring are showing well developed peaks of runoff and recession limbs similar to those of surface watercourses. After FORD a. WILLIAMS (1989, 195) this can be seen as typical for vadose and shallow karst systems respectively. Despite the behaviour of the hydrographs, parts of the system have to be termed as a phreatic or deep karst system respectively, because the aquiclude (Partnach layers) is situated beneath the level of outfall. As a result up-welling of water can be observed in the Partnach spring, indicating a piecometric surface higher than the level of the spring. Accordingly a well-mixed karst reservoir should exist at the Partnach spring and the geochemical composition of runoff should correspond to the mean solute concentrations of the aquifer (cf. ZÖTL 1974, 100).

In both investigation periods the same fluctuations in the course of the hydrographs can be observed. The general behaviour of the hydrograph can be seen clearly in 1997 and with some restrictions the basic characteristics in 1996, too. At the beginning runoff is falling to values of about 1 m^3/s according to a cold snap occurring regularly in the middle of June. Snow melt stops and new snow is often falling beneath the tree-line. In July temperatures are rising and snow-melt runoff is showing a daily oscillation and in general an increase up to the end of July. After snow-melt has reached its maximum at the beginning of August, runoff is falling. During July and August most of the storms with high rainfall intensities are occurring leading to peaks of runoff of more than 5 m^3/s. Analysing the hydrographs in detail leads to results presented in the following.

The water equivalent of the snow cover at the end of the winter is determining depth of runoff during the first half of the summer. In the year 1997 depth of snow cover was nearly as twice as high at the beginning

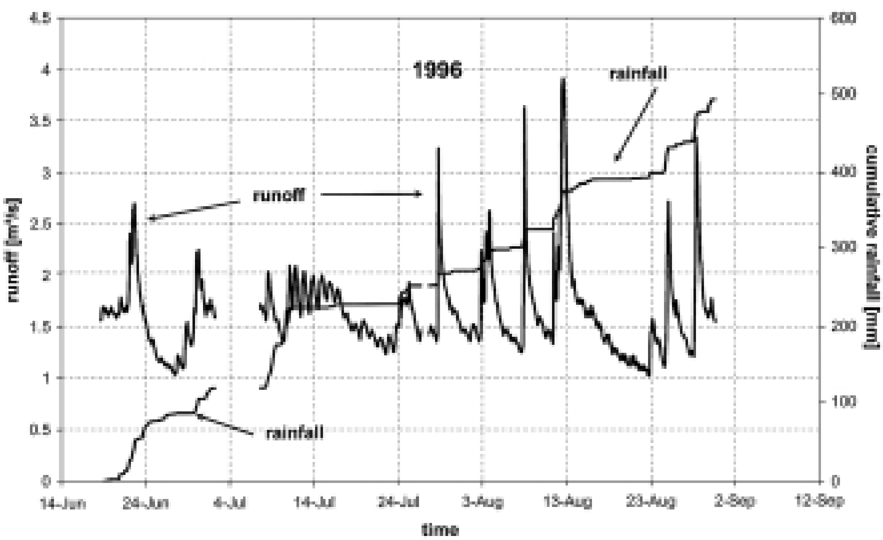

Fig. 6: Rainfall amount and runoff during the 1996 measuring period at the Partnach spring

Die Summenkurve des Niederschlags und der Abfluss während der Messkampagne 1996 am Partnach-Ursprung

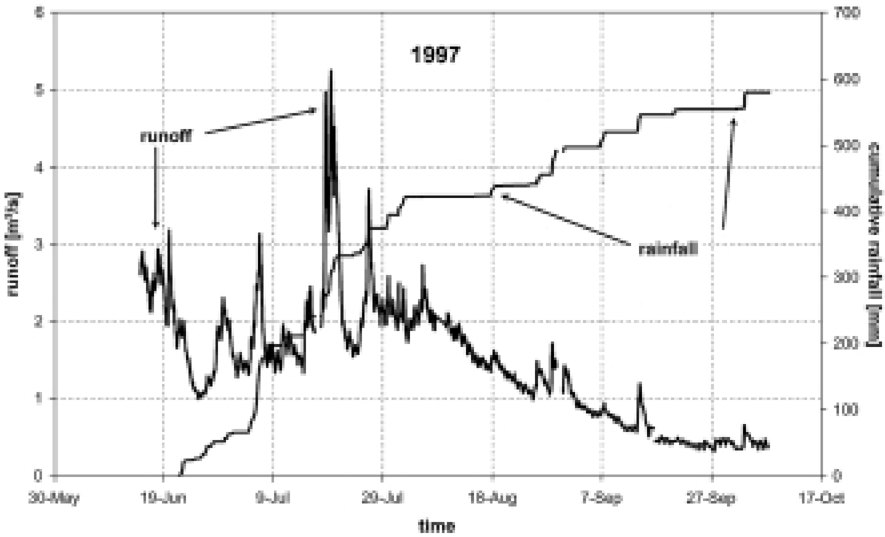

Fig. 7: Rainfall amount and runoff during the 1997 measuring period at the Partnach spring

Die Summenkurve des Niederschlags und der Abfluss während der Messkampagne 1997 am Partnach-Ursprung

of the record (May, 1st) as in 1996, resulting in runoff about 0.5 m^3/s higher during the ablation period (Fig. 8). The high proportion of snow-melt runoff in the summer season becomes clear in both hydrological balances (cf. Tab. 2). Notwithstanding that the amounts of precipitation and the depth of evapotranspiration have been nearly equal in both years, the depth of runoff in the same period of time is 16% higher in 1997. Snow depth has been about 3 m in the upper part of the area at the beginning of the 1997 investigation period. About 30% of the amount of runoff, namely 247 mm (1996) and 379 mm (1997), has been delivered

Fig. 8: Snow height at the Zugspitzplatt during the measuring periods of 1996 and 1997 after data of the DWD

Die Entwicklung der Schneehöhe am Zugspitzplatt in den Sommermonaten der Jahre 1996 und 1997

by snow cover outflow. Classically shaped snow-melt hydrographs in consequence of hot weather conditions in July of 1996 can be seen in figure 6. Daily snow-melt fluctuations also can be observed in 1997, but snow-melt runoff has been interrupted by several storm events. The main difference between the two investigation periods exists in August. While August of 1996 has been characterized by several storms with high amounts of rainfall, the late summer of 1997 was very dry and only a few showers of low intensity and small amounts of rainfall have been recorded. Hence, in 1997, runoff decreased after snow-melt has reached its maximum and after September, 12th daily hydrograph fluctuations have been produced by glacial ablation.

The construction of the recession curve by use of different falling hydrograph segments (MATTHESS a. UBELL 2003) allows estimation of the storage behaviour of the karst reservoir. Above all the dry late summer of 1997 has led to a very low runoff so the recession curve encloses a wide range of different levels of runoff (Fig. 9). A distinct difference can be seen in the recession curve between storm runoff and depletion of the karst aquifer starting below 2 m^3/s of discharge. A recession constant for the depletion of the karst aquifer cannot be given, because recession is not only due to aquifer depletion. Snow-melt runoff and runoff from glacier ablation are superposing the karst aquifer depletion, so an interpretation of the recession curve should be done with care.

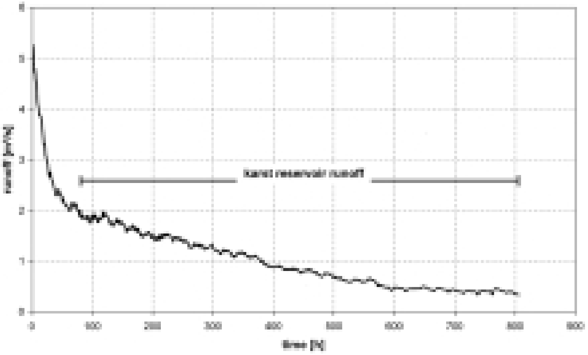

Fig. 9: Depletion line of the Partnach spring constructed on the base of the measuring periods 1996 and 1997

Die Trockenwetterlinie für den Partnach-Ursprung auf Basis der beiden sommerlichen Messperioden.

4.2 Analysis of single events

Water circulation in karst systems is characterised by different kinds of flow (cf. ATKINSON 1977; BONACCI 1988; KLIMCHOUK a. THOMAS 2000). Turbulent flow occurs in karst conduits widened by solution activities. In small joints and fissures flow is laminar and in the pores of the limestone water movement is best described by the Darcian law. Each of the three kinds of aquifer has a specific velocity of water flow, whereby in karst conduits and in joints and fissures solute processes are taking longer as the flow of water through the aquifer (HESS a. WHITE 1988). By that, geochemical signals of each aquifer can be observed in spring runoff. This has been done at the Partnach spring for different kinds of storm events to get some evidence about runoff generation in the karst aquifer.

Most appropriate for demonstrating the different processes contributing to runoff is the hydrograph of the storm which occurred at July, 28th 1996. As figure 10 shows, the storm hydrograph has been triggered by a short duration rainfall of 14.9 mm at the gauge station. Due to the hypsometric gradient the regional amount of rainfall for the Partnach area has been calculated at 19.1 mm. The highest rainfall intensity exceeded 10 mm/15 min and already 10 minutes after the onset of rainfall a rapid rise of runoff had been observed. Runoff peak has been reached about one hour after the beginning of rainfall and 40 minutes after rainfall has exceeded its highest intensity. The falling limb of the hydrograph shows the pattern of a nearly perfect recession curve. Despite the uneven course of the hydrograph in consequence of the turbulent flow of the Partnach creek, similarities with hydrographs from non-karstic catchments can be observed; a feature described by GUNN a. TURNPENNY (1986) for New Zealand karst areas. Indications on karst-specific runoff production processes as rhythmic fluctuations of the hydrograph resulting from water-trap depletion cycles cannot be recognised.

By means of the traditional hydrograph separation method according to CHOW (1964) and MUTREJA (1990), three segments with a different slope can be dis-

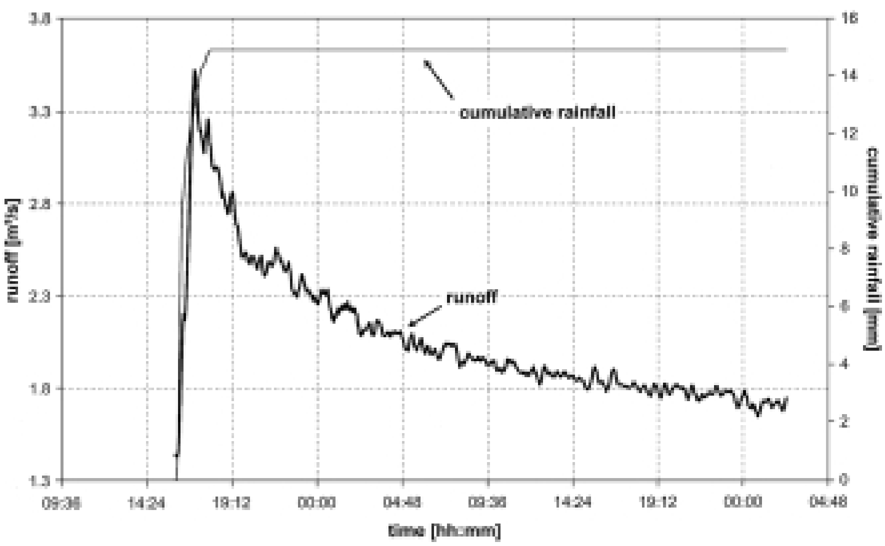

Fig. 10: Runoff and rainfall amount during the event of July 28th, 1997 at the Partnach gauge station

Der Verlauf des Hydrographen und die Summenkurve des Niederschlags am 28. Juli 1997 an der Pegelstation Partnach tinguished in the falling limb of runoff, as figure 11 demonstrates. According to studies by ATKINSON (1977), HESS and WHITE (1988) and BÄUMLE et al. (2001) towards karst hydrology it has to be assumed that besides overland flow, at least two further sources of runoff as flow in conduits and flow in pores should be participated in karst systems. At the Partnach spring a surface flow component has been observed during field investigations. As a result of storm precipitation with high rainfall intensities surface flow on bare rock surfaces is generated rapidly. The surface flow now concentrates in erosion scars, forming cascades of water reaching the Partnach within a few minutes. The high velocity of flow recession of the surface reservoir leads to a steep slope in the hydrograph of the Partnach (part 1). Taking the velocity of flow in the karst system into consideration, the other sources of runoff must be conduit flow (part 2) and a slow flow component (part 3) in small joints and fissures (Fig. 11). The reaction of the pore aquifer – theoretically forming a fourth component of flow feeding baseflow during winter and in periods of drought – cannot be detected by means of the graphical method. Calculating the portion of the two fastest components of flow about 16% of total storm runoff at the Partnach spring have been delivered by quick surface flow and flow in karst conduits.

The question arises whether runoff has been produced by new precipitation water delivered by fast conduit flow through the karst system or by displacement of old water stored in the aquifer. Separation of new and old components of runoff is not possible by use of the graphical method. As MCDONNELL (1990) and CUI (1997) have shown, separation of old and new flow components by means of isotopic methods will lead to reliable results. A very similar evidence of runoff production mechanisms can be reached by use of geochemical tracers and EC (e.g. KENNEDY et al. 1986; WELS et al. 1991; WETZEL 2003). At the Partnach rapid rises and falls of EC can be observed during the event of July, 28th standing in no relation to the hydrograph (Fig. 12). At the beginning of the storm runoff EC is falling rapidly from 108 µS/cm to values of about 92 µS/cm whereby runoff is rising as fast as EC decreases. The recorded decrease of EC is in accordance with the onset of surface flow with a low solute content now reaching the spring. Hence the fast response to the precipitation input of the Partnach at the gauge station first of all results from surface water influx.

After EC has reached its minimum, a synchronous increase of discharge and EC can be observed until the starting value of EC has been reached again. The increase of EC is a result of a rising spring discharge and a decreasing surface flow because maximum rainfall intensities have already occurred more than 30 minutes before. As nearly constant values of EC during the time of peak discharge are indicating, no variance of the chemical composition of spring discharge takes place although runoff is rising. This is in accordance with the model of a well-mixed karst reservoir existing at the Partnach spring. But the following observations do not match with the model of a well-mixed reservoir. Soon after runoff has begun to fall the EC increases to 120 µS/cm, so solute concentrations now have been higher than at the starting point of the hydrograph (flow system 1 in Fig. 12). Obviously water with higher solute concentration begins to leave the karst system. Due to the high solute concentration the water now leaving the karst system cannot be new precipitation water. Time for reaching near equilibrium carbonate concentrations is much longer, as residence time of the new precipitation water would be (BÖGLI 1978; HESS a. WHITE 1988). Therefore old water with a residence time long enough to reach high solute concentrations has been pushed out of the karst system and begins to predominate in spring discharge. This part of the chemograph corresponds with recession part 1 after graphical hydrograph separation in figure 11. But where does the old water came from? The enormous volume of water delivered by this source gives evidence of conduit flow. In karst conduits numerous water traps do exist and due to the dry pre-storm weather conditions, water with high solute concentrations has been stored there. During the storm event new precipitation water fills the karst conduits via sinkholes and dolines and flushes the old water out of the traps. Like a wave, the old water is pushed out of the karst system before the new water arrives. After that new precipitation water with a low solute content predominates conduit flow as the falling EC after the 120 µS/cm peak is indicating. Similar find-

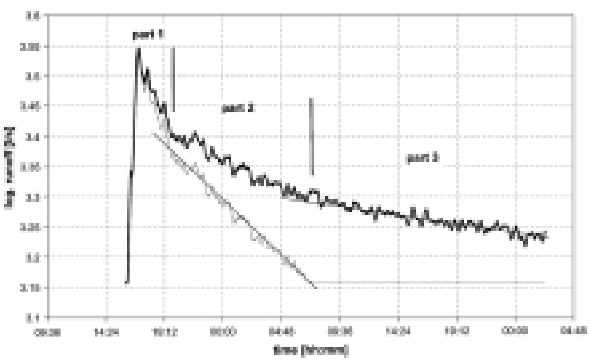

Fig. 11: Graphical separation of runoff components during the event of July 28th, 1997

Graphische Separation von Abflusskomponenten während des Ereignisses vom 28. Juli 1997

Table 2: Values of the hydrological balance for different periods of time for Partnach area (after own data and data of the DWD)
Die Größen der hydrologischen Bilanz für unterschiedliche Zeiträume des Einzugsgebietes ‚Partnach'

period	runoff [mm]	precipitation [mm]	evaporation [mm]	storage [mm]
18.6.–30.8.96	889.5	629.6	12.9	247.0
18.6.–30.8.97	1.026.2	635.7	12.0	378.5
14.6.–7.10.97	1.260.7	742.8	36.8	481.1

ings have been made by DREISS (1989) in karst areas of southeast Missouri (USA) and by HESS and WHITE (1988) in Kentucky. In both studies the role of displacement processes in spring discharge generation has been examined and flushing of old water with high solute contents over the level of pre-storm conditions has been proven as an important contributor to storm response of karst springs. More recent studies on physical and chemical responses of karst springs in Tennessee have been conducted by DESMARAIS and ROJSTACZER (2002). They also demonstrated the occurrence of flushing effects in consequence of storm precipitation by means of EC data.

After new water has begun to feed the Partnach spring, a rise of EC up to 108 µS/cm can be observed again. Obviously discharge of another karst system responding more slowly to precipitation input is starting now, with similar flushing processes (flow system 2 in Fig. 12). Just as new water of the second flow system begins to predominate spring feeding EC decreases and over a time span of four hours EC remains nearly constant at 99 µS/cm. The signals of EC with a slight rise (101 µS/cm) and an ensuing fall to 94 µS/cm may indicate a third flow system (Fig. 12). The signals of EC are in accordance with the results of the graphical separation method, showing a beginning of discharge of the slowest component of flow at the same time. Analysis of other storm hydrographs leads to similar results, but results become more uncertain if precipitation amount decreases.

4.3 The estimation of velocities of flow in the karst system

Because EC has not to been seen as a conservative tracer in karst systems an increase of EC during later recession of storm hydrographs should be explained by

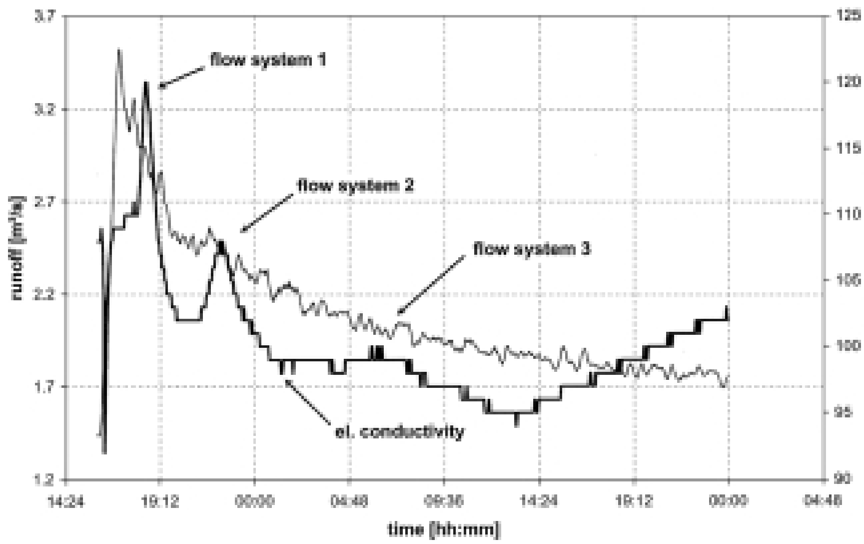

Fig. 12: Runoff and electrical conductivity and the reaction of different sources of flow in the karst system during the event of July 28th, 1997

Der Verlauf von Abfluss und elektrischer Leitfähigkeit sowie die Beteiligung verschiedener Karstwasserleiter während des Ereignisses vom 28. Juli 1997 solute processes in consequence of longer contact times of the water. Therefore quantitative approaches to the different flow systems have not been realized. Also determination of flow velocities in the karst system is difficult because it is not known where infiltration of precipitation water takes place. During the snow-melt period the location of meltwater infiltration in the karst system is known. With the progress of snow-melt and an increasing altitude of the snow-line the area of water infiltration can be defined with high accuracy.

During the week of July, 12th 1996 ideal snow-melt hydrographs with daily peaks of runoff have occurred. The daily amplitude of snow-melt runoff has been about 0.5 m^3/s and the peak of runoff has been shifted about 6 h in relation to the maximum temperature. As figure 13 indicates, by decreasing values of EC, a progressive dilution of the karst aquifer as a consequence of steady meltwater input can be observed. After HÜTTL (1999) especially snow cover outflow is characterized by a low solute content. It can be seen that decreasing of EC during snow-melt is not a continuous process; on the contrary decrease is concentrated during the time of daily peak runoff. Hence, the geochemical signal is just in time with the course of daily snow-melt and 6 h after snow-melt has reached its maximum, new meltwater with low EC can be observed at the Partnach spring, leading to a further dilution of the karst reservoir beneath the spring. So velocities of flow in the karst system can be calculated by means of EC data and knowledge of the altitude of the snow-line. At July 12th 1996 the snow-line has risen up to a level of 2,400 m a.s.l., so a minimum distance between meltwater infiltration and Partnach spring of 3,200 m can be assumed, if a difference in altitude of 1,000 m is taken into consideration. Supposing that intensive snow-melt begins to start two hours before the daily maximum temperature has been reached, a mean travel time of the karst water of about 8 hours and a velocity of 400 m/h (about 11 cm/s) can be calculated. Theoretically, travel times of 24 + 8 hours are possible, but after the findings of WROBEL (1980) mean travel times in the karst conduits of the Partnach area are significantly shorter than 24 h. Therefore, a field velocity for the Partnach area of about 400 m/h can be assumed. In comparison with field velocities measured in 281 Dinaric karst areas (cf. MILANOVIC 1981, 134), only 10% of the areas reach similar values. Even if the alpine relief is taken into consideration, after MILANOVIC (1981) field velocities of 400 m/h point to a well developed karst system.

5 Conclusions and outlook

The investigations on the hydrology of the Partnach area have been conducted with methods commonly used in the hydrology of running waters. Records of rainfall, runoff and EC, in combination with chemical analysis of spring discharge, have given insight in the karst hydrological processes in the underground of the Partnach area. The concept of the investigation has been proven in studies of runoff production (cf. MCDONNELL 1990; WELS et al. 1991; WETZEL 2003) as well as in other examinations concerning the hydrology

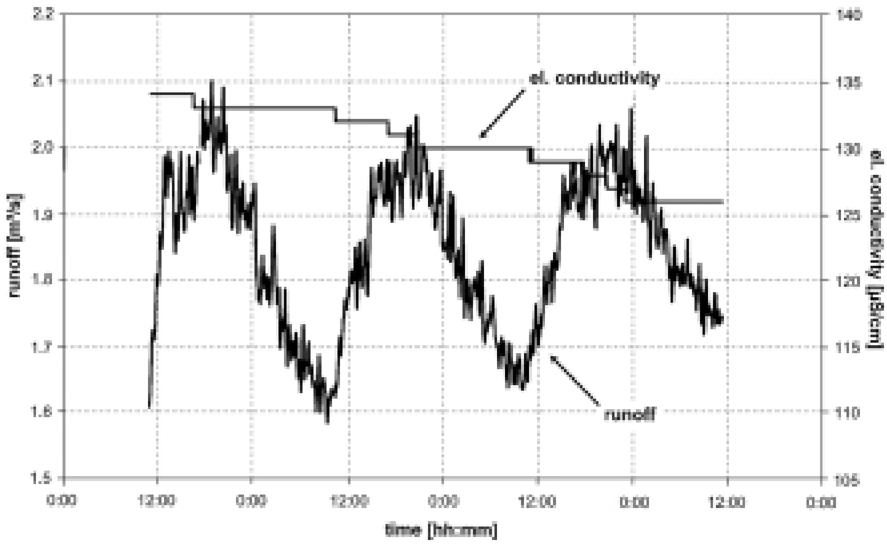

Fig. 13: Runoff and electrical conductivity during snow melt runoff around July 12th, 1996

Der Verlauf von Abfluss und elektrischer Leitfähigkeit während der Schneeschmelzperiode um den 12. Juli 1996 of karst springs (HESS a. WHITE 1988; DREISS 1989; DESMARAIS a. ROJSTACZER 2002). By use of comparatively simple methods, results on such different topics as recession behaviour, components of flow in the karst system, runoff production mechanisms and flow velocities have been obtained. Therefore this methodological concept is especially qualified for investigations in alpine areas difficult to reach.

Further investigations in the Partnach area should be conducted to validate the results of the geochemical approach by means of dye tracer tests and isotopic methods. Additionally, monitoring of spring discharge should be carried out during winter, because baseflow conditions in the karst system without the influence of snow melt can be observed. Finally, the question has to be examined whether the area has a groundwater leakage or not. The Partnach area is an excellent choice for investigations concerning the hydrologic cycle in alpine areas if the basin is a closed system.

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