Beiträge zur Hydrogeologie / 54 / Seiten 97–118 / Graz 2003

Application of Water Balance Analyses at Different Time and Space Scales at the Catchment Pöllauer Safen (Eastern Styria/Austria)

Wasserbilanzuntersuchungen in unterschiedlichen Zeit- und Raumskalen am Beispiel des Einzugsgebietes Pöllauer Safen (Oststeiermark/Österreich)

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1. Introduction

"Water is not a commercial product like any other but rather a heritage which must be protected, defended and treated as such." This quotation from in the European Parliament Directive 2000/60/EC summarizes in only few words the political perception about water and its vulnerability. One of the main purposes of this directive is to establish a framework for the protection of inland surface water, transitional water,

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coastal water and groundwater which promotes sustainable water use based on a long-term protection of available water resources. Mountainous water resources play in this respect a particular role because they cover the most vital functions of mountains and lowland people. But these benefits of mountain water are threatened by degradation of water quantity and quality and discontinuity of flow. The growing demand for water will make the preservation of these functions of paramount importance in the future.

Only distributed physically based hydrological models are theoretically able to provide answers to the water resource management demands. These models of the water cycle are very complex. They need parameters related directly to the catchment physical characteristics (e.g. topography, soil, vegetation and geology) and operate within a distributed framework to account for the spatial variability of both physical characteristics and meteorological conditions.

The authors J. C. Reefsgaard & B. Storm (1996) justify the use of such models by the demands for prediction of effects of such human intervention as landuse change, groundwater abstractions, wetland management, irrigation and drainage and climate change as well as for subsequent simulations of water quality and soil erosion. For these important purposes, the authors see no alternative to further enhancements of the distributed physically based model codes.

However, input time series and parameter values needed for such models are seldom available and simulation results for a spatial sub-division can generally not be validated. The authors S. Bergström (1991) and B. G. Grayson et al. (1992) argue that, at least with the present level of available field data, physically based distributed models are not realistic tools for practical water management purposes. In addition, as stated by K. Beven (1989), their overparameterization and their implicit lumping of sub-grid processes and heterogeneities mean that they are not fundamentally different, in some respects, from more classical lumped conceptual models.

Clearly, the use and the superiority of distributed physically based models are largely dependent on the data quantity and quality available for the system under investigation. But data scarcity represents a major problem especially in mountainous regions where topography together with the associated morphometry have a great effect on the water and energy input pattern, the spatial heterogeneity of the land surface and subsurface hydraulic properties. The result is very patchy soil moisture and water balance patterns, leading to large spatial variations in evapotranspiration and stream discharge (see B. Ambroise, 1995). Thus, even if the structure from a mountainous area under investigation can be defined with sufficient accuracy, there still remains the problem of the system inputs (precipitation) and outputs (discharge and evapotranspiration) patterns in time and space.

In this respect, the goal of this work is to gain more understanding of the water balance variations in different spatial and temporal scales. The water balance approach applied at the catchment and sub-catchment scale is a traditional method used by hydrologists to study the spatial and temporal variability of the main hydrological processes: precipitation, evapotranspiration and discharge.

Few conditions must be fulfilled to conduct a water balance study: (a) topographical and hydrogeological boundaries from the area and subareas under study must be identical, (b) the measurement network must be large enough to detect spatial variations, and (c) the time series must be long enough to eliminate storage effects in the water balance equation. The present study is conducted at the Austrian research catchment Pöllauer Safen and three sub-catchments based on the verification, analysis and interpretation of a large data set.

2. Methodology

2.1. Water balance concept

The basic concept of hydrology is the hydrologic cycle that can be described quantitatively by applying the principle of conservation of mass often referred to as a water balance or water budget. The statement of conservation of mass for any particular compartment is that the time rate of change of mass or of volume stored (dS/dt) within the compartment is equal to the difference between the inflow rate (I) and the outflow rate (O):

$$I - O = dS/dt. \quad \text{(Eq. 1)}$$

Hydrologists typically choose the control volume for application of eq. 1 to be a catchment (or watershed or drainage basin). Unfortunately, the volume of water that can be stored in a catchment is unknown and the watershed (three dimensional characteristics) is generally described with respect to its surface. The drainage basin is defined as the total topographical area drained into a stream and it is theoretically possible to delimitate such a surface all along a river channel. Thus the catchment is identified relative to a specific location along a watercourse and the associated land area that can vary considerably from catchment to catchment is considered to "catch" the water that flows past that point (the basin outlet).

Precipitation (P) represents catchment water inflow whereas runoff (R) and real evapotranspiration (Etr) compose the catchment water outflow. The water budget for a watershed without human perturbations is then written:

$$P - (E + Etr) = dS/dt. \quad \text{(Eq. 2)}$$

For a period long enough the change in net storage is usually small relative to the size of the other terms and can often be ignored:

$$P - R = Etr. \quad \text{(Eq. 3)}$$

The real evapotranspiration which is really difficult to determine comparing to precipitation and runoff can be well approximated with the use of eq. 2. If runoff is known and if precipitation can be regionalized with confidence, the water balance applied at a large time scale is very useful to compare the three terms for watershed displaying structural contrasts in size, altitude, slope, landuse, soil, geology and so on. The main factors affecting the water balance can be determined.

However, it should be remembered that the result from eq. 3 is assumed to be real evapotranspiration. In fact this term includes the entire water amount leaving a catchment due to other hydrological processes as discharge, e.g., deep percolation losses. This uncertainty cannot be ignored and the difference between precipitation and discharge is therefore, named "rest term" or "losses" in the section below.

2.2. Areas under investigation

2.2.1. Research catchment Pöllauer Safen (59.407 km^2)

In 1978 within the framework of the International Hydrological Program (IHP), the survey of a hydrological test area in Pöllau in Eastern Styria (see fig. 1) began under the

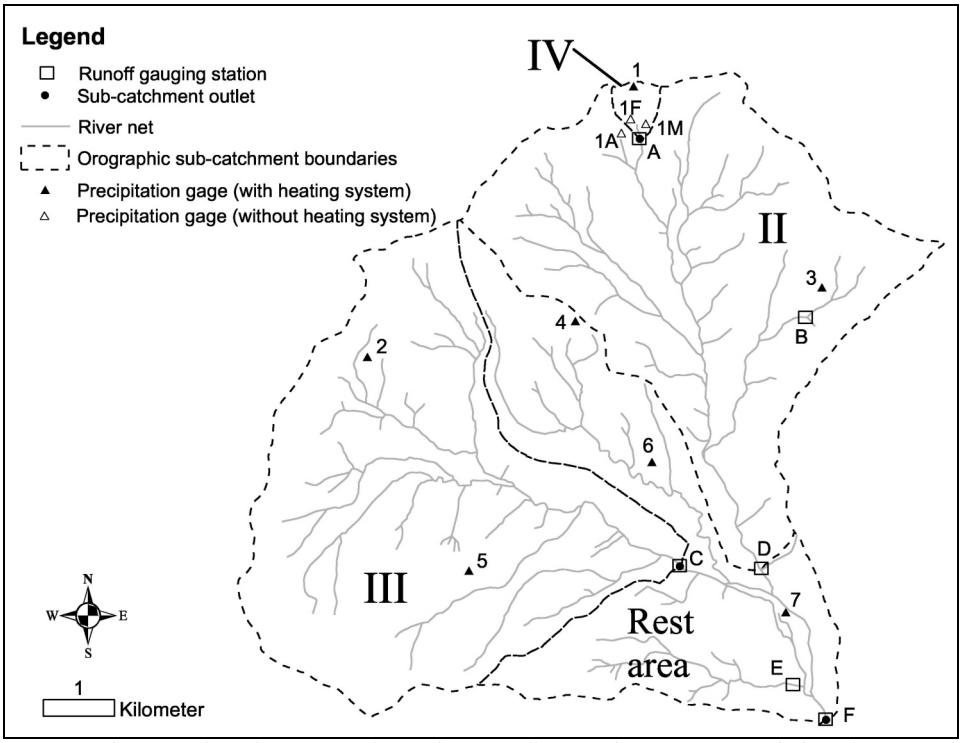

Fig. 1: Hydrometeorological survey at the catchment Pöllauer Safen in 1999. Hydrological units: I – catchment Pöllauer Safen (I = II + III + IV + rest area), II – Ölmühle, III – Pöllauer Safen Mitte, IV – Höhenhansl; runoff gages: A – Höhenhansl, B – Zeilerbach Mitte, C – Pöllauer Safen Mitte, D – Ölmühle, E – Mausbach, F – Pöllauer Safen; precipitation gages: 1 – Höhenhansl, 1A – Höhenhansl arable land, 1F – Höhenhansl forest, 1M – Höhenhansl meadow, 2 – Leitenbertl, 3 – Moyhoffer, 4 – Schule, 5 – Franzl, 6 – Heiling, 7 – Cividino.
Hydrometeorologisches Messnetz des Einzugsgebietes Pöllauer Safen 1999. Hydrologische Einheiten: I – Pöllauer Safen (I = II + III + IV + Restgebiet); II – Ölmühle, III – Pöllauer Safen Mitte, IV – Höhenhansl; Abflussmessstationen: A – Höhenhansl, B – Zeilerbach Mitte, C – Pöllauer Safen Mitte, D – Ölmühle, E – Mausbach, F – Pöllauer Safen; Niederschlagsstationen: 1 – Höhenhansl, 1A – Höhenhansl Ackerland, 1F – Höhenhansl Wald, 1M – Höhenhansl Wiese, 2 – Leitenbertl, 3 – Moyhoffer, 4 – Schule, 5 – Franzl, 6 – Heiling, 7 – Cividino.

direction of the Institute for Hydromechanics, Hydraulics and Hydrology of Graz Technical University (H. Bergmann, 1982) together with the Hydrographical Survey of the Government of Styria. The research catchment Pöllauer Safen is the second largest one in Austria (H. Holzmann & F. Nobilis, 2002). The Institute for Hydrogeology and Geothermics (JOANNEUM RESEARCH, Graz) has, since 1994, been contributing to the hydrological and meteorological investigations with the intensive survey of the Höhenhansl headwater sub-catchment (J. Fank et al., 1995) and the Zeilerbach Mitte unit.

The Pöllauer Safen catchment presents an important altitude gradient, which ranges from 398 m at the main outlet to 1271 m. Only 5 % of the basin surface is over 900 m. The watershed covers an area of 59.41 km^2 and presents a typical basin form. It is a well-drained catchment (around 1.9 km/km^2). The geological units are illustrated on fig. 2 whereas morphological information are presented in tab. 1. The watershed is de-

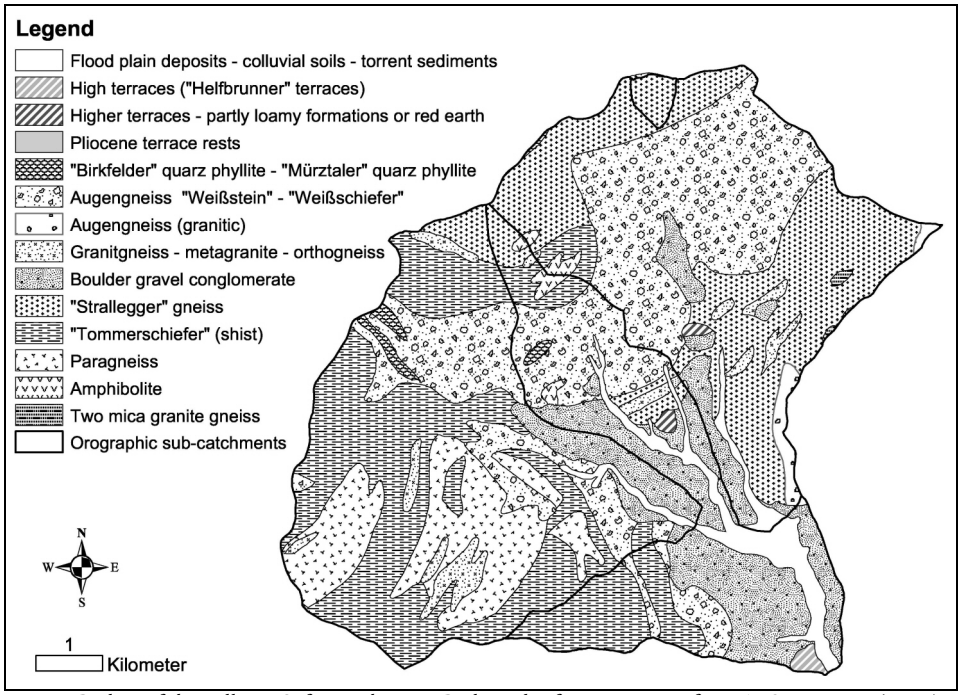

Fig. 2: Geology of the Pöllauer Safen catchment. Geological information issue from A. SCHWENDT (1998). Geologie der Pöllauer Bucht (nach A. SCHWENDT, 1998).

limitated on the W, N and E by crystalline basement rocks. They are built up by coarse gneiss series and by the Strallegg gneiss series. According to the mica richness, the weathering leads to less permeable loams or to higher permeable layers. The basin is filled up with Tertiary sediments, the characteristics of which differ strongly in space depending on their genesis. Quaternary sediments are of little spatial expansion and can

Tab. 1: Summary of the calculation of morphometric parameters from the four studied hydrological units (adapted from H. ZOJER et al., 1996). I – Pöllauer Safen, II – Ölmühle, III – Pöllauer Safen Mitte, IV – Höhenhansl.
Aufstellung der berechneten morphometrischen Parameter der vier untersuchten Einzugsgebiete (nach H. ZOJER et al., 1996). I – Pöllauer Safen, II – Ölmühle, III – Pöllauer Safen Mitte, IV – Höhenhansl.

	I	II	III	IV
Area [km^2]	59.4	21.1	22.9	0.39
Alt. min. [m]	398	415	455	778
Alt. mean [m]	710	706	859	963
Alt. max. [m]	1271	1055	1271	1067
Slope mean [°]	11.03	11.60	12.99	17.07
Slope max. [°]	34.63	29.09	34.63	29.96
Orientation [°]	142	184	100	164
Drai. Dens. [km/km^2]	1.87	1.80	1.82	0.47
Forest cover [%]	49	52	51	70

be found for example at the basin outlet where a pumping test carried out 500 m downstream revealed a hydraulic conductivity of 5.3×10^{-4} m/s. The amount of water leaving the watershed through the aquifer(s) is considered to be relatively small by comparison to the discharge because of the limited valley size at the outlet location.

The forest cover with dominating coniferous trees represents nearly half of the catchment landuse (49 %) while the urban areas, essentially the city of Pöllau located near the watershed oulet, can be considered negligible (0.3 %). Typical for the "hill country", the grass cover is important (35 %) and the cultivated areas represent only about 15 %. 94 % of the soils are non-calcareous. The permeability and the storage capacity of soils are classified according to range from high to moderate.

2.2.2. Data availability

In 1999, the instrumentation comprised (see fig. 1 and tab. 2):

- Ten precipitation recorders. Seven of them were installed between 1980 and 1981. Snow is recorded "immediately" because of the integrated heating system. The precipitation gage Heiling (6) is part of a complete meteorological station whereas the precipitation gage Cividino (7) is installed in the city Pöllau. The three other stations, installed since August 1995, have no heating system.
- Six runoff gauging stations. It should be noted that no rating curves exist for the gauging stations Pöllauer Safen Mitte (C) and Mausbach (E).
- Different instrumentations concerning primarily the unsaturated zone, are located at the Höhenhansl headwater sub-catchment – stations: arable land (1A), forest (1F) and meadow (1M).

The gauging station installed at the Mausbach river (E) is working only since 1998. Information gained at this station is not used in this work because the measurement period is too short. Also information from the Zeilerbach Mitte catchment (B) are not used in this study. Furthermore, as already mentioned, water stages are recorded at the Pöllauer Safen Mitte (C) outlet but no rating curves are defined. Fourteen-day runoff measurements have been made between 22/04/98 and 01/09/99 to determine the rating curve for this sub-catchment. All in all, 33 discharge measurements have been conducted (C. A. Ruch, 2002, for details). The rating curve calculated for this period has been used to reconstruct the discharge since 1996. It is clear that the water balance analysis made below for the Pöllauer Safen Mitte is uncertain because no discharge measures are made for high stage level and also because no information has been available about the river profile modifications since 1996.

Due to the data availability, the water balance from four hydrological units can be analysed in this study:

- the entire catchment Pöllauer Safen (59.407 km^2);
- the Ölmühle sub-catchment (21.1 km^2) that drains the east part; it should be noted that a retention basin exist few hundred meters upstream the gauging station;
- the Pöllauer Safen Mitte sub-catchment (22.9 km^2) that drains the west part;
- the Höhenhansl headwater sub-catchment which is the smallest studied unit with an area of less than one square kilometre (0.392 km^2).

It should be noted that the Höhenhansl, the Ölmühle and the entire hydrological units form a nested structure.

Tab. 2: Main information concerning the hydrometeorological survey in 1999 at the Pöllauer Safen catchment.
Basisinformationen über das hydrometeorologische Messnetz des Einzugsgebietes Pöllauer Safen 1999.

	Runoff gages	**Altitude [m]**	**Data used in this study**
A	Höhenhansl	778	1991–1999
B	Zeilerbach Mitte	646	–
C	Pöllauer Safen Mitte	455	1996–1999
D	Öhlmühle	415	1991–1999
E	Mausbach	410	–
F	Pöllauer Safen	398	1991–1999
	Precipitation gages	**Altitude [m]**	**Data used**
1	Höhenhansl	1058	1991–1999
1A	Höhenhansl arable land	762	–
1F	Höhenhansl forest	855	–
1M	Höhenhansl meadow	875	–
2	Leitenbertl	822	1991–1999
3	Moyhoffer	772	1991–1999
4	Schule	758	1991–1999
5	Franzl	725	1991–1999
6	Heiling	525	1991–1999
7	Cividino	424	1991–1999

Data availability not only limits the number of hydrological units and their location but also the period that can be analysed. Logically, the shortest time series from the variable (rainfall and discharge) used in eq. 3 determines the period for the water balance analyses. In this respect,

– for the entire catchment, the Ölmühle and the Höhenhansl headwater subcatchment a common period of nine years (1991–1999) is retained,
– whereas for the Pöllauer Safen Mitte unit only four years (1996–1999) are studied.

The precipitation data available for this study are characterized by (a) a great uncertainity before 1991 and (b) many gaps. Therefore only data since 1991 are used for the present work. Moreover, simple regressions are used at the month scale to fill up the gaps. This time scale enables the analysis of the statistical relationship between two stations with good sample size and amplitude. Furthermore, the correlation coefficient is "high enough" to ensure that the data reconstruction is done with relative good confidence. Only the rain gauges installed in the early instrumentation phase are used for the water balance analysis because (a) only these stations are equipped with heating systems and snow is recorded immediately, (b) one "older" station is installed near the three "younger" stations so that their information are to a large extent already taken into account, and (c) using the same rain gauges type avoids measurement differences due to the apparatus.

It should be noted that the maintenance of these stations as well as the data acquisition and correction is done by the Institute of Urban Water Management and Landscape Water Engineering at TU Graz.

3. Results

3.1. Precipitation characteristics

The different precipitation amount measured every year since 1991 at the station Höhenhansl (1) are presented on fig. 3. It should be remembered that missing data have been entered on the month scale using the information from the gage network installed in the Pöllauer Safen catchment.

The precipitation amount always exceeds 800 mm. Since measurements have been made, 1996 (1110 mm) was the most humid year. It is characterized by extreme snow cover (until 0.70 m at the Höhenhansl headwater catchment, personal communication M. and B. GRABNER). Due to the conjunction of important snow melt and heavy rainfalls, April 1996, with a total of 217 mm, is over the whole period the most humid month.

In 1997, 995 mm is calculated. The precipitation in this year is characterized by numerous convective rain events during the summer. 1997 is in this respect an exceptional year. At the rain gauge station meadow (1M) installed since 1995 (Fig. 1), a 47.8 mm storm rain was measured on 16th June (maximum intensity: 8.2 mm/15 min), on 23rd July, 63.4 mm (maximum intensity: 11.8 mm/15 min), on 18th August 69.20 mm (maximum intensity: 12.4 mm/15 min) and on 6th September, 48 mm (maximum intensity: 13.6 mm/15 min). This last intensity is also the highest ever measured at this station, whereas the events from June, July and August constitute the highest daily values measured for these months in the period 1995–1999.

The mean annual precipitation values calculated for the period 1991–1999 for each station are presented on fig. 4. Over the nine years studied, the average values ranged from 820 mm for the lowest station Cividino (7) to 910–920 mm for the Höhenhansl (1), Franzl (5) and Leitenbertl (2) stations. Although these three stations display a similar mean annual precipitation amount for the period 1991–1999, they display an important altitude gradient of 300 m. In contrary, the stations Franzl (5), Schule (4) and Moyhoffer (3) have approximately the same altitude but display an important gradient W–E of 100 mm. The mean annual precipitation amount decreases from W (Franzl (5), 870 mm) to E (Moyhoffer (3), 770 mm).

This shows that for this watershed no apparent relation between precipitation and altitude can be defined. This is confirmed by the determination coefficient (R^2) calculated between altitude and amount of precipitation equal to 0.46 only (Tab. 3). However, this coefficient displays a considerable variability (from 0.80 in 1996 to 0.13 in 1992) when each year is analysed separately. In 1998, precipitation and altitude are even inversely correlated. This is due to the very local effect of convective rainfalls centred on the city of Pöllau in 1998.

From the rainfall characteristics described above it can be deduced that any regionalization is accompanied with much uncertainty. For this reason the THIESSEN polygon method that has the favourable propriety of being straightforward and fast is used to determine the spatial precipitation. This method relates rainfall distribution in space to the gage locations only. However it can be applied in this work because of (a) the dense measurement network and (b) the large time scale under consideration. The spatial weight from the precipitation gages over the entire catchment ranges from 0.09 for the Höhenhansl (1) station to 0.22 for the Franzl (5) station. The other five stations have a spatial weight near 0.14. The calculated mean annual precipitation over the nine years

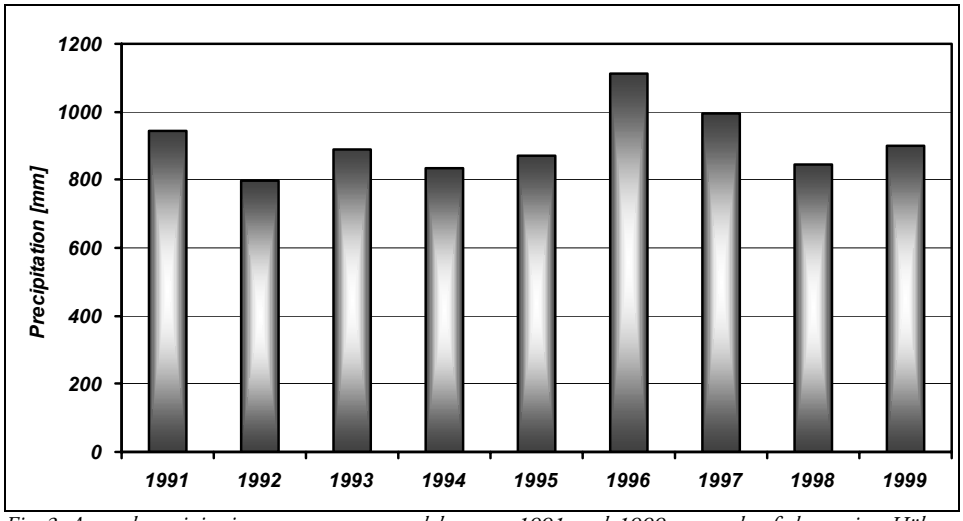

Fig. 3: Annual precipitation amount measured between 1991 and 1999; example of the station Höhenhansl (1).
Jahresniederschlagshöhe gemessen zwischen 1991 und 1999; Beispiel: Station Höhenhansl (1).

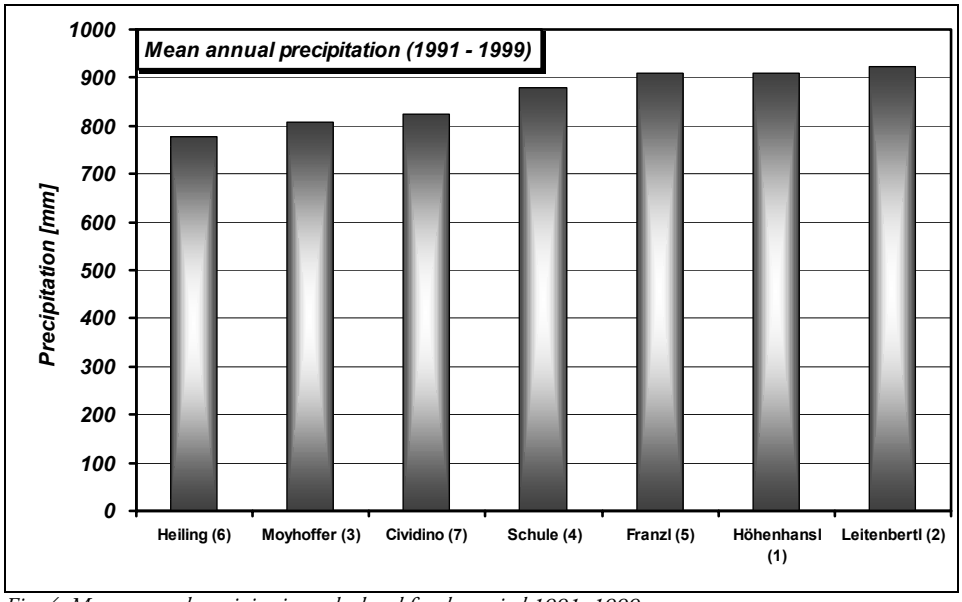

Fig. 4: Mean annual precipitation calculated for the period 1991–1999.
Mittlere Jahresniederschlagshöhe berechnet für den Zeitraum zwischen 1991 und 1999.

Tab. 3: Determination coefficient between the variables altitude – precipitation calculated for the seven precipitation gages at the catchment Pöllauer Safen.
Bestimmtheitsmaß der variablen Seehöhe und Niederschlag berechnet für die sieben Niederschlagsstationen des Einzugsgebietes Pöllauer Safen.

Years	1991	1992	1993	1994	1995	1996	1997	1998	1999	Period
Coef.	0.32	0.13	0.62	0.41	0.23	0.80	0.59	0.33	0.48	0.46

represents 860 mm and is only a few millimetres higher than the arithmetic mean value. 1993 is a really dry year (precipitation below 760 mm) whereas 1996 is the wettest year with nearly 1000 mm.

It should be noted that during these two years the best determination coefficient is obtained between altitude and precipitation amount (Tab. 3). Thus, the relation quality between altitude and precipitation at the year scale is not dependent from the precipitation amount but much more from the rainfall type. Only for the stations Cividino (7) and Schule (4) the highest annual precipitation amount is not recorded in 1996 but in 1998 and 1991 respectively.

In tab. 4 the cumulated spatial precipitation amount for each hydrological unit over the period 1991–1999 and 1996–1999 is presented. Precipitation for the headwater catchment Höhenhansl corresponds to the precipitation measured at the Höhenhansl station (1) when the THIESSEN polygon method is used. Precipitation amounts are for both periods the most important at this unit. It is remarkable to see that the precipitation gradient recognized for the precipitation gages Franzl (5) and Moyhoffer (3) has significantly diminuished when the spatial precipitation from the units Pöllauer Safen Mitte and Ölmühle are compared. However "W precipitation" is still higher as for the "E side" because of the important spatial weight (0.22) of the precipitation station Franzl (5).

Tab. 4: Cumulated spatial precipitation amount [mm] calculated for each hydrological unit. (*) Precipitation amount measured at the station Höhenhansl (1).
Kumulierte Niederschlagshöhe [mm] berechnet für jede hydrologische Einheit. (*) Niederschlagshöhe gemessen an der Station Höhenhansl (1).

	1991–1999	1996–1999
Pöllauer Safen	7940	3820
Ölmühle	7840	3780
Pöllauer Safen Mitte	8280	3930
Höhenhansl	8330 (*)	4000 (*)

The amount of precipitation per month calculated as a mean value from regionalized precipitation between 1991 and 1999 for the entire catchment is presented on fig. 5. On this figure, it can be clearly seen that precipitation follows a symmetric distribution centred on the summer months. During the period from May to September, the precipitation for all the stations represents always 63–68 % of the annual precipitation. This is clearly due, in this catchment, to the high frequency of convective rainfalls (H. Bergmann et al., 2000, H. Stubenvoll, 1993, T. Zeyringer, 1993) as already recognized in 1997 for the Höhenhansl stations. June and August are for every station the wettest months (14–15 % from the year amount), whereas January and February are the dryest (2–4 %) for every station. This indicates that the precipitation pattern within the middle year will be similar for each station and thus, logically, also for the regionalized precipitation.

This is a really important piece of information for the water balance because (a) evapotranspiration is really high during the summer months and (b) intensive rainfalls are generally accompanied by overland flow. Both processes reduce the amount of water infiltration. Thus, only a low part of the annual precipitation must be available for groundwater recharge in the Pöllauer Safen catchment and an important rest term (precipitation minus discharge) can be expected in the water balance equation.

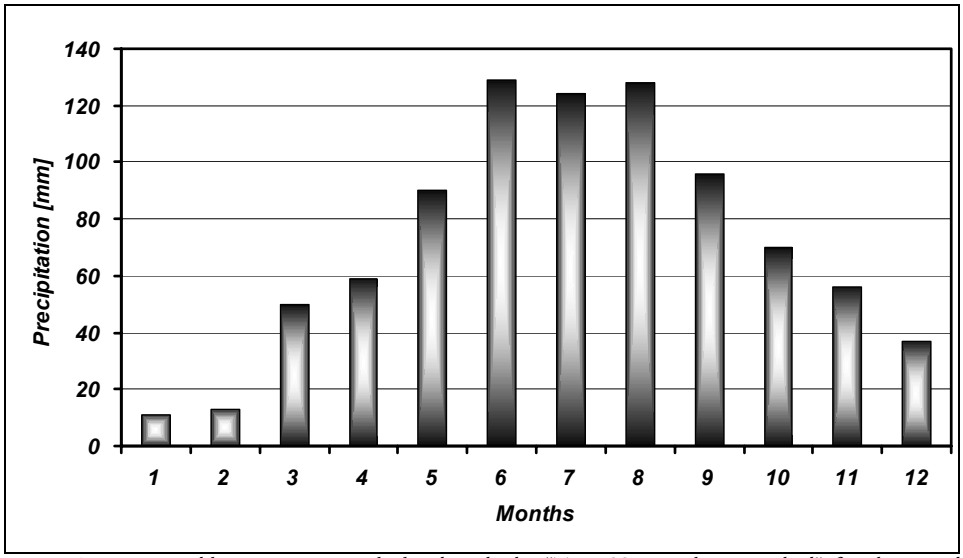

Fig. 5: Average monthly precipitation calculated with the "THIESSEN polygon method" for the period 1991–1999 at the catchment Pöllauer Safen.
Mittlere monatliche Niederschlagshöhe berechnet mit dem „THIESSEN-Polygon-Verfahren" für die Periode 1991–1999 im Einzugsgebiet Pöllauer Safen.

3.2. Discharge characteristics

On fig. 6a and fig. 6b it can be recognized that the total discharge during 1996 is the most important for each hydrological unit (500 mm, 440 mm, 560 mm and 700 mm for the Pöllauer Safen, the Ölmühle, the Pöllauer Safen Mitte and Höhenhansl catchments respectively). The average discharge amount per year over the period 1991–1999 represents 270 mm, 230 mm and 400 mm for the entire catchment, the Ölmühle and Höhenhansl catchments respectively. The annual discharge amount for the entire catchment is larger than the mean value only in 1991, 1996 and 1998. It should be noted that in 1996 the discharge amount is 80 % over the mean value. In contrary, 1993 is a very dry year with a discharge amount equal to 160 mm only. These results are in good accordance with the rainfall temporal repartition found in the section above.

The runoff fraction at the Höhenhansl headwater catchment is over this average value only for 1991, 1994 and 1996. Discharge in 1997 represents only 380 mm although 1997 is the second most humid year for this catchment (Fig. 3). Because most of the precipitation amount is recorded during the summer months it can be assumed that the plants have used a high fraction of this water or that water evaporated directly. In contrast to the really important runoff part from 1996 the years 1998 and 1999 have a ratio discharge/precipitation between 35 and 38 %. Only 1993 the year with the lowest precipitation amount has a smallest fraction with 34 %.

Over the period 1996–1999 the mean discharge values are 320 mm, 260 mm, 390 mm and 420 mm for the entire catchment, the Ölmühle, the Pöllauer Safen Mitte and Höhenhansl catchments respectively. The difference between both periods due to the extremely wet year 1996 is especially recognizable for the entire catchment (plus 20 %) and the Ölmühle catchment (plus 10 %).

The decreasing trend for annual discharge amounts since 1996 is well documented on fig. 6a and 6b. However, the total discharge amount calculated for the entire catchment for 1998 is larger than for 1997. This is due to the numerous convective rainfalls registered during the summer 1998 at the station Cividino (7) located in the city Pöllau. It should be remembered that for this year precipitation and altitude are inversely correlated, i.e. precipitation decreases with altitude. Thus, the rainstorms centred on the city Pöllau caused a large overland flow generation process (paved areas) explaining that in 1998 discharge amount increases for the entire catchment whereas it decreases for the other units.

The runoff reconstruction for the sub-catchment Pöllauer Safen Mitte (22.9 km^2) allows to analyse the discharge distribution for the four hydrological years 1996–1999 by

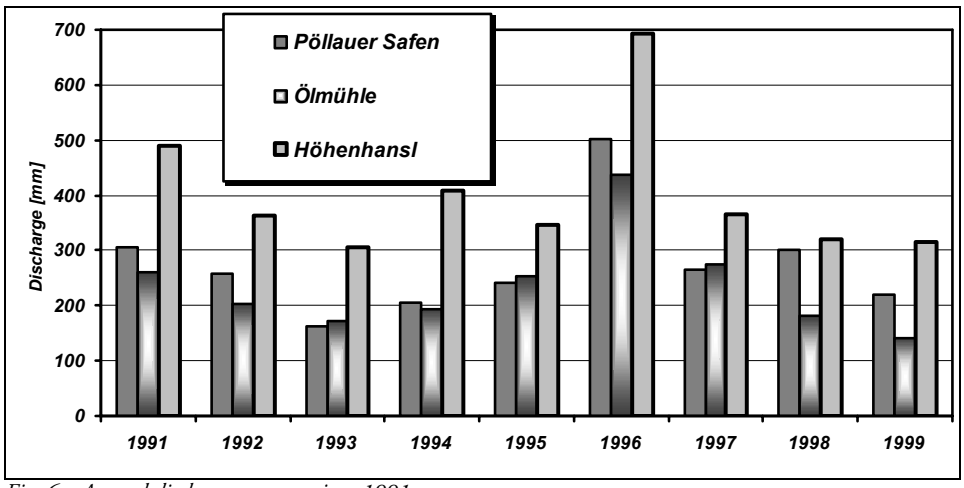

Fig. 6a: Annual discharge amount since 1991.
Jährliche Abflusshöhe seit 1991.

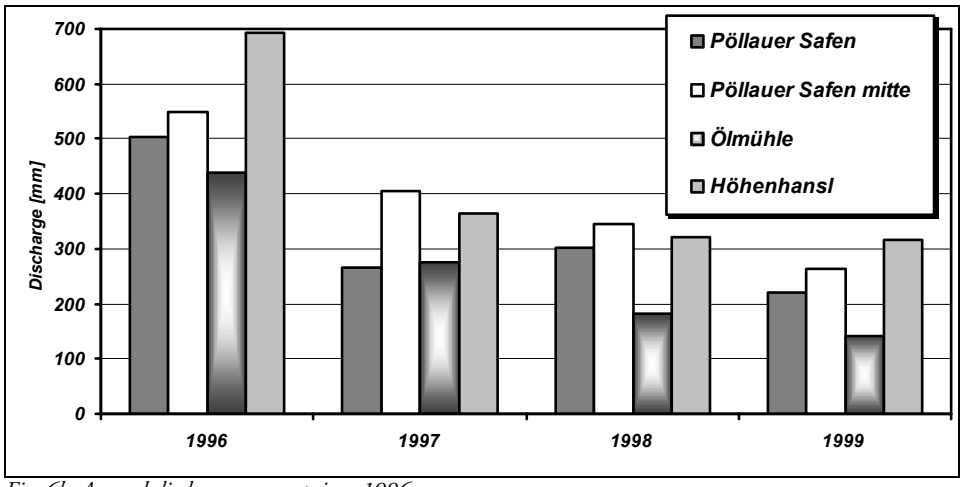

Fig. 6b: Annual discharge amount since 1996.
Jährliche Abflusshöhe seit 1996.

comparison with the data recorded at the Ölmühle station (21.1 km^2) and at the entire watershed. Together these two sub-catchments represent around 75 % of the entire area.

Total annual discharge values from the Ölmühle catchment are always less than for the entire catchment. If measurement errors can be excluded, another main sub-catchment must register larger discharge values compared to the entire catchment. This is effectly the case: the Pöllauer Safen Mitte catchment displays every year higher values than the entire catchment. Over the period 1996–1999, only 1040 mm is flowing out at the Ölmühle sub-catchment whereas at the Pöllauer Safen Mitte sub-catchment and at the entire watershed 1560 mm and 1290 mm are respectively calculated. The average monthly values calculated between 1996 and 1999 for these three units are presented on fig. 7. Except for October, the same pattern is always recognizable: The Pöllauer Safen Mitte sub-catchment has the highest amount, the Ölmühle sub-catchment the lowest one and the entire catchment an intermediate value. On fig. 7 it can be recognized that the huge difference existing between the discharge amounts calculated for the Ölmühle and the Pöllauer Safen Mitte sub-catchments is principally built during the summer months (the wettest months in the year). This difference is difficult to interpret without complementary investigations. However, few reasons can be mentioned to explain this phenomenon:

– The data accuracy for the catchment Pöllauer Safen Mitte discharges is low and the values are overestimated. However, the total discharge value for the entire catchment is higher than for the catchment Ölmühle. Therefore, if the data from these two stations are of good quality it is normal that another important sub-catchment has

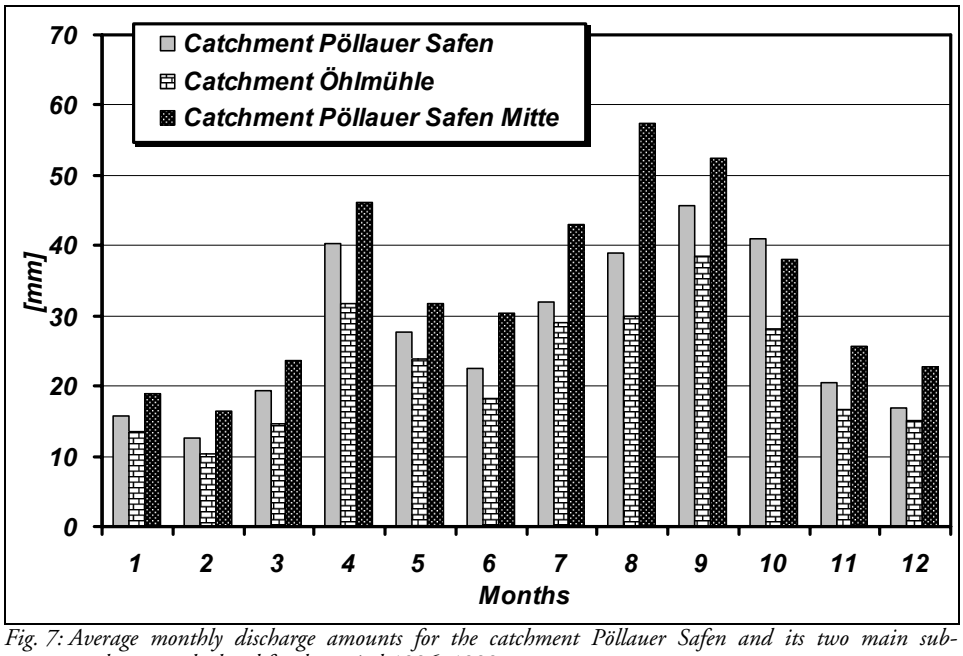

Fig. 7: Average monthly discharge amounts for the catchment Pöllauer Safen and its two main sub-catchments calculated for the period 1996–1999.
Mittlere monatliche Abflusshöhe des Einzugsgebietes Pöllauer Safen und seiner beiden Hauptteileinzugsgebiete berechnet für die Periode 1999–1999.

a higher total amount in comparison to the main outlet. The data accuracy is certainly a problem, but it cannot be the main explication for the difference mentioned above.

- The recharge area is smaller than the orographical catchment area for the Ölmühle unit or inversely the recharge area is larger than the orographical catchment area for the Pöllauer Safen Mitte unit.
- Deep percolation losses for the Ölmühle catchment. This process is difficult to verify. However, no major geological feature (e.g. fracture) is recognized for the studied areas so that it can be assumed that this phenomenon must be of minor importance.
- Losses in the Tertiary and/or Quaternary sediments. Outlets from the Ölmühle and the Pöllauer Safen units are located in the Quaternary and Tertiary sediments respectively. Furthermore few hundred meters upstream the Ölmühle gage station is located a retention basin that could also favour higher infiltration amount in the Quaternary sediments. An important amount of water could therefore flow out the basin without being recorded at the Ölmühle station. However, these processes are also very difficult to verify.
- Water is leaving more rapidly (e.g., surface runoff is much more important) the Pöllauer Saffen Mitte sub-catchment than for the Ölmühle unit and less water is therefore available for evapotranspiration processes.
- Difference in spatial precipitation. It should be remembered that the mean annual precipitation amount calculated at the station Franzl (5, Pöllauer Safen Mitte unit) is around 100 mm larger than for the station Moyhoffer (3, Ölmühle unit). In contrary, spatial precipitation calculated with the THIESSEN polygon method is quasi similar for both units although spatial precipitation is affected by a large uncertainty.
- Precipitation shortage on the E side is reinforced by the sub-basin exposition. A higher evapotranspiration is expected for slopes exposed to the S and SW, i.e. the evapotranspiration losses are higher for the Ölmühle sub-catchment (see tab. 1 for exposition values).

The forest cover fraction, the drainage density, and the soil formations are for both systems comparable. Therefore, if the very important discharge difference is due to natural causes, it seems that the exposition is the main explanation and that higher evapotranspiration processes for the Ölmuhle sub-catchment reinforce the rainfall gradient.

3.3. Remaining term: precipitation minus runoff

Over both studied periods (1996–1999 and 1991–1999) it can be assumed that the cumulated water storage for each hydrological unit is really small compared to the cumulated discharge amount (data from the different gages) and precipitation (spatial precipitation). Therefore, storage effects can be neglected. Differences between precipitation and discharge are considered to include primarily evapotranspiration processes as well as unrecorded discharge at the gauging stations. The part of each process that effects the difference between precipitation and discharge cannot precisely be identified, and this difference is named “rest term” in the following. However, it can be assumed that evapotranspiration processes constitute the main share of the rest term. It should also be remembered that the topographical and recharge areas are assumed to be equal for each unit.

From 1991–1999, the total rainfall, runoff and losses for the entire catchment represent 7940 mm, 2465 mm and 5475 mm respectively (see tab. 4, 5 and 6). This leads to the rainfall repartition in 31 % runoff and 69 % losses. Whereas for the Ölmühle unit 7840 mm, 2120 mm and 5720 mm, for the Höhenhansl 8330 mm, 3610 mm and 4720 mm are found for the total rainfall, runoff and rest term. This leads to the rainfall repartition in 27 % discharge and 73 % rest term for the Ölmühle unit, 43 % discharge and 57 % losses for the Höhenhansl unit.

The rest term share for the Pöllauer Safen Mitte sub-catchment (period 1996–1999) is equal to 60 % (40 % discharge) whereas the shares for the three other units stay quasi constant for the shorter period.

The fact that the highest located unit has the lowest lost term confirms with the general view in hydrology describing the rainfall amount to increase and the evapotranspiration amount to decrease both with altitude. But it is very interesting to see that this difference is principally build by the discharge difference. The cumulated rain amount is only 390 mm lower for the entire watershed but the cumulated discharge amount is already 1145 mm lower. This illustrates that the water balance difference between the headwater catchment and the Pöllauer Safen basin are primarily due to different runoff generation processes.

The cumulated rest term amounts conform logically with the results found in the precipitation and discharge sections because the rest term is calculated as the difference between precipitation and discharge. Therefore, when the water balance is applied every year it can be recognized that the rest term share is very variable throughout the period (see fig. 8a for the entire catchment and fig. 8b for the Höhenhansl unit). A great difference appears between the behaviour of the Höhenhansl and the Pöllauer Safen unit, especially during humid years. For example in 1996, the year with the highest discharge amount, only around 50 % from the precipitation is flowing out for the entire watershed and more than 60 % is leaving the headwater catchment.

Tab. 5: Cumulated discharge amount [mm] calculated for each hydrological unit.
Kumulierte Abflusshöhe [mm] berechnet für jede hydrologische Einheit.

	1991–1999	1996–1999
Pöllauer Safen	2465	1290
Ölmühle	2120	1040
Pöllauer Safen Mitte	–	1560
Höhenhansl	3610	1690

Tab. 6: Cumulated rest term amount [mm] and share (rest term divided by spatial precipitation) calculated for each hydrological unit.
Kumulierte „Verlustkomponente" Menge [mm] und Anteil („Verlustkomponente" dividiert durch räumliche Niederschläge) berechnet für jede hydrologische Einheit.

	1991–1999	Share	1996–1999	Share
Pöllauer Safen	5480	0.69	2570	0.66
Ölmühle	5720	0.73	2750	0.73
Pöllauer Safen Mitte	–	–	2370	0.60
Höhenhansl	4730	0.57	2300	0.58

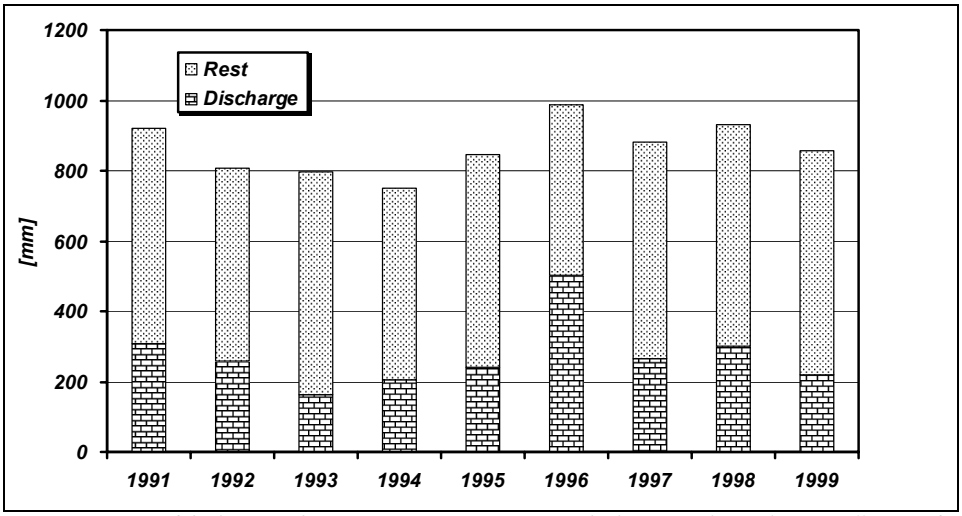

Fig. 8a: Amount of discharge and rest term (precipitation minus discharge) at the catchment Pöllauer Safen for the period 1991–1999.
Abfluss und „Verlustkomponente" (Niederschlag minus Abfluss). Menge für das Einzugsgebiet Pöllauer Safen in der Periode 1991–1999.

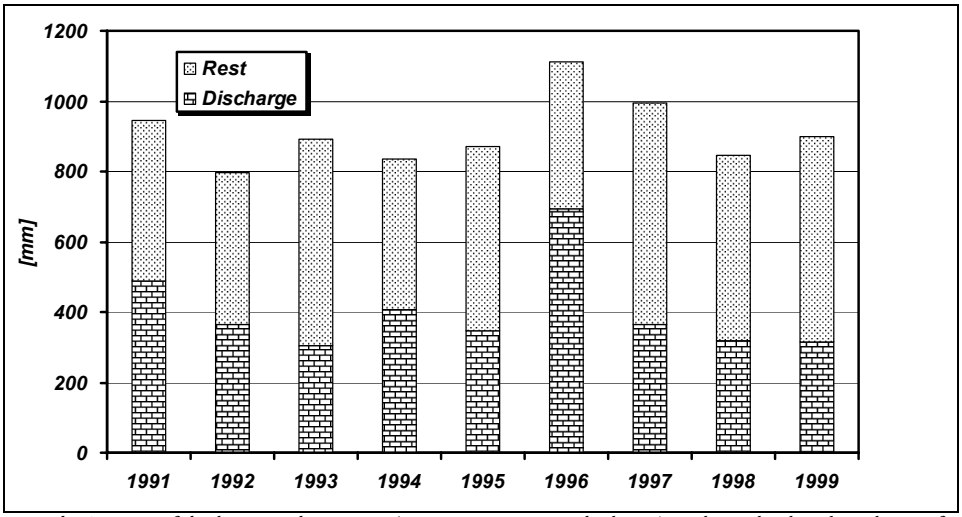

Fig. 8b: Amount of discharge and rest term (precipitation minus discharge) at the Höhenhansl catchment for the period 1991–1999.
Abfluss und „Verlustkomponente" (Niederschlag minus Abfluss). Menge für das Einzugsgebiet Höhenhansl in der Periode 1991–1999.

This discrepancy between rainfall amount and discharge amount is well documented on the fig. 9a and fig. 9b. As shown on these figures, the rest term share (rest term/precipitation) is very variable on the month scale. It should be noted that January is a special month because the discharge amount is higher than the precipitation amount. The rest component for June, July and August is larger than 75 % of the preci-

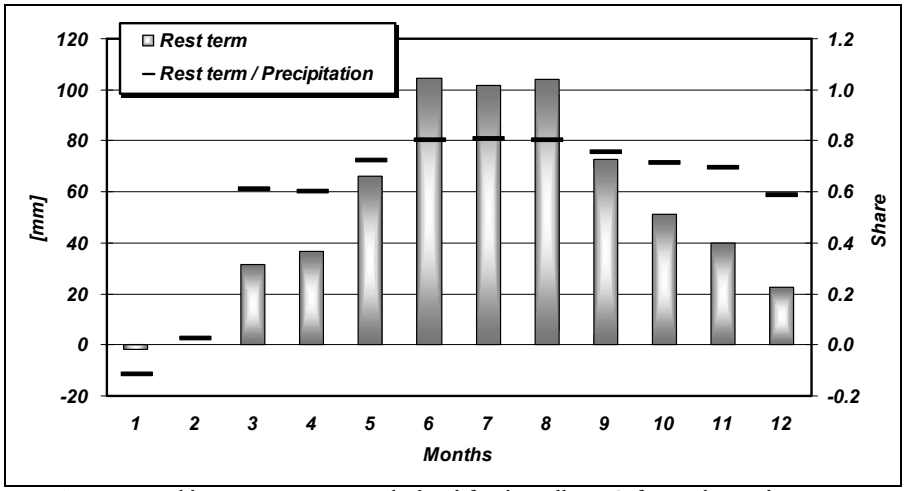

Fig. 9a: Average monthly rest term amount calculated for the Pöllauer Safen catchment between 1991 and 1999 and its share compared to the monthly average precipitation amount.
Mittlere monatliche „Verlustkomponente" des Einzugsgebietes Pöllauer Safen, berechnet zwischen 1991 und 1999, und sein Anteil verglichen mit der mittleren monatlichen Niederschlagshöhe.

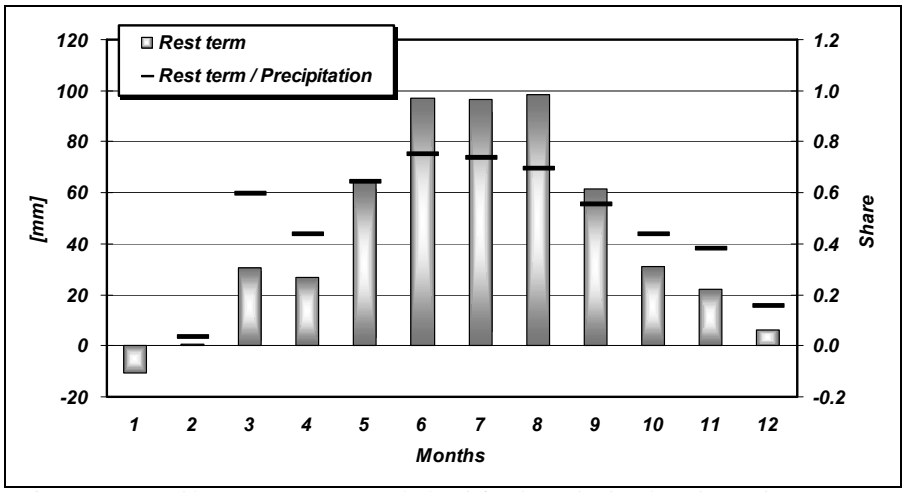

Fig. 9b: Average monthly rest term amount calculated for the Höhenhansl catchment between 1991 and 1999 and its share compared to the monthly average precipitation amount (the share in January is equal to minus 0.7).
Mittlere monatliche „Verlustkomponente" des Einzugsgebietes Höhenhansl, berechnet zwischen 1991 und 1999, und sein Anteil verglichen mit der mittleren monatlichen Niederschlagshöhe. (Der Januaranteil ist gleich minus 0.7).

pitation amount and more than 70 % in May and September. The fact that the percentages are for every month larger than those calculated for the Höhenhansl catchment (Fig. 9b) confirms that water is leaving the system faster at the Höhenhansl catchment. Although the drainage density for this unit is much smaller than for the entire catchment, the water residence time for the latter is much larger because of its much larger area.

4. Discussion and conclusion

This work conducted at the catchment Pöllauer Safen (around 60 km^2) is based on the verification, reconstruction, analysis and interpretation of a large data set: seven precipitation gages and four discharge gages. The dense hydrometeorological equipment allows to study the water balance terms at different temporal and spatial scales. Unfortunately only parts of the time series could be used in this work. Especially precipitation data before 1991 display large differences with gages installed nearby and are therefore not used. Many lacks in the precipitation and discharge time series are present between 1991 and 1999. Missing data have been reconstructed at the month scale using simple regressions between measured data from the gage network installed in the catchment. The discharge data used for Pöllauer Safen Mitte before 1998 are uncertain because no rating curve is available for this period.

Because of the many reconstructed data, the results presented in this work should not be overvalued. However, spatial and temporal patterns of the main water balance terms could be examined and these analyses should be considered as a first step that can give impulses for further inquiries.

The different water balance analyses made in this study are essential to understand the rainfall, discharge and lost terms temporal dynamic and spatial distribution for the watershed Pöllauer Safen. This study highlights the major role played by the loss processes. The type of rainfall and its temporal repartition is a key factor in explaining that the runoff part over the period 1991–1999 is only equal to 31 %. Nearly 2/3 of the rainfall amount is recorded between May and September when the water uptake of plants is the most pronounced. During this period, most of the rain events are convective with very local effects, high intensity and high amount. Therefore it can be assumed that overland flow processes are generated and less water can infiltrate. A larger overland flow generation should occur near the catchment outlet because the paved areas increase in percentage (city Pöllau). The high losses share must also be favoured by the large forest coverage, which represents nearly 50 % of the basin land cover. The runoff component rises until 50 % in 1996, a particularly humid year characterized by an important snow cover. This illustrates evidently the major role played by winter precipitation for recharge conditions.

In 1996 a large determination coefficient is found between the station altitude and the precipitation amount. But this good result is an exception for the period under investigation. For most of the years and also for the average value no relation is found. This seems to be due to the important precipitation gradient that exists between the W slopes and the E slopes. Mean annual rainfall amount calculated over the nine years (1991–1999) at the station Moyhoffer (3) is 100 mm lower than on the station Franzl (5). Also the large number of convective rainstorms with very local extension is an explanation for this low determination coefficient value. For example in summer 1998 rainstorms were concentrated on the city Pöllau (near the basin outlet) so that precipitation amount is found to decrease with altitude.

Evident spatial heterogeneities could also be recognized for discharge amounts when the two main sub-catchments (Pöllauer Safen Mitte and Ölmühle) are compared to the entire basin. A huge difference appears between the two sub-catchments. The Pöllauer Safen Mitte presents a clear surplus in comparison to the entire watershed, whereas the Ölmühle shows an important deficit. This result is only true as long as the topographical catchment area and the recharge area are equal. The precipitation gradient men-

tioned above must be a key factor to explain these spatial discrepancies although spatial precipitation is similar for both units. Nevertheless, reliability of the calculated spatial precipitation is unknown. The fact that the difference is primarily built in summer leads to the assumption that two other factors could play a significant role for the discharge difference mentioned above. The S and SW exposition favours greater evapotranspiration losses for the Ölmühle unit and/or, the flow generation processes favour a faster water transit (and therefore a lower evapotranspiration amount) at the Pöllauer Safen Mitte sub-catchment.

Finally, the comparison between the entire catchment and the headwater catchment Höhenhansl give valuable information about the runoff generation processes and the water residence time in the systems. All in all, 31 % and 43 % of the rainfall amount are found as runoff components in the water balance made from 1991–1999 for the entire basin and the Höhenhansl catchment respectively. On the one hand, this difference is primarily built during wet years, and on the second hand, the precipitation share found as runoff component is for every month higher at the headwater catchment. This leads to the conclusion that the runoff generation processes at the latter unit are more effective involving a faster water transit through the catchment. It is assumed that the main explanation factors for these differences are the slope system and the water transit time in the river channel. A steeper slope involves a larger gravitational gradient and consequently a larger and faster lateral water movement than for gentle slope. Furthermore the river channel for the entire catchment is logically much longer and flatter as for the Höhenhansl catchment. Globally water needs therefore a much longer time to leave the entire catchment as the Höhenhansl unit. These results conform with the view of V. K. Gupta & D. R. Dawdy (1995) that suggest that hillslope runoff processes may dominate the response at sub-catchment scale whereas the channel network geometry becomes more important in larger basins.

Thus, different physical processes dominate at different scales (G. Blöschl, 1996). At the sub-catchment scale, morphometric characteristics are decisive factors that control hydrological processes distribution in space and flow generation processes. Studying the relationships between the physical characteristics and hydrological processes of drainage basins is a common approach in hydrology. The main limit for such a study is the low density of rainfall gages and the data accuracy (C. S. Melching, 1995).

The exceptional network density from the Pöllauer Safen catchment gives a formidable example for hydrological processes variation in time and space. The present study has evidenced the large spatial heterogeneity of precipitation in a mountainous area of 60 km^2 only. Thus, ignoring this variability conducts inevitably to overestimate other factors affecting the water balance terms distribution in space. Runoff gauging stations are also numerous at the catchment Pöllauer Safen. Discharge spatial variability could not be explained only by precipitation heterogeneity. Catchment exposition, slope and river channel length seem to be the main morphometric factors explaining these disparities. Exposition controls the potential evapotranspiration whereas steep slopes and short river channels favour a rapid water transit limiting the amount of water available for evapotranspiration processes.

All in all, it can be said that the results presented in this work are ambivalent. On the one hand this detailed study was possible only because of the dense measurement network. Large research catchments like the Pöllauer Safen catchment deliver invaluable hydrometeorological information to study hydrological processes variability in time and space. The assumption of significant difference for evapotranspiration processes due to sub-catchment exposition could be accurately examined in the future. On the other

hand it should be recognized that such network are not common for hydrological studies. Thus, even if the structure from an area under investigation is well known, there still remains the definition of the system inputs and outputs patterns in time and space. Data regionalization in mountainous environment is effected by uncertainties comparing to lowlands which must be taken into account when interpreting the results of scenario simulations from distributed physically based rainfall runoff models.

Summary

Catchment distributed physically based models enable to calculate discharge values all along the river channel. This makes such models very useful for water resources management purposes. Nevertheless, hydrometeorological data scarcity implies that the reliability of these models depends entirely on hydrologists' ability to describe data variability in time and space. The present work focuses on the temporal and spatial dynamic of the main water balance components (rainfall, discharge and loss term) at the research catchment Pöllauer Safen (about 60 km^2). Its dense hydrometeorological network constitutes the basis for the present analyses although the measured time series display many lacks. The results clearly evidence the high variability in time and space for all water balance terms. This limits the reliability of hydrometeorological data regionalization in mountainous areas comparing to lowlands which must be taken into account when interpreting the results of scenario simulations from distributed physically based rainfall runoff models.

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Zusammenfassung

Physikalische flächendetaillierte Modelle des Wasserkreislaufes ermöglichen es, den Abfluss an beliebigen Standorten entlang eines Bachbettes zu berechnen, was solche Modelle für Wasserressourcenstudien sehr attraktiv macht. Da aber in der Regel sehr wenige hydrometeorologische Daten in Untersuchungsgebieten zur Verfügung stehen, beruht die Zuverlässigkeit dieser Modelle vollständig auf der Fähigkeit des Hydrologen, die Datenvariabilität in Zeit und Raum zu beschreiben. Der Schwerpunkt dieser Arbeit liegt deshalb in der Studie der Variabilität der Hauptwasserbilanzkomponenten (Niederschlag, Abfluss und der „Verlustkomponente“ am Beispiel des Einzugsgebietes Pöllauer Safen – ca. 60 km^2). Basis dieser Studie sind die Daten seines dichten hydrometeorologischen Messnetzes, obwohl die Zeitreihen viele Lücken aufweisen. Die Ergebnisse zeigen sowohl in Zeit als auch in Raum eindeutig die hohe Variabilität aller Komponenten, was die Zuverlässigkeit regionalisierter Daten des Wasserkreislaufes in gebirgigen Regionen im Vergleich zum Flachland begrenzt. Die Fehlergrenzen müssen bei der Interpretation von Szenariosimulationen auf Basis von physikalischen flächendetaillierten Modellen beachtet werden.

Keywords: Pöllauer Safen, mountainous region, water balance, hydrological processes, variability in time and space

Schlüsselwörter: Pöllauer Safen, gebirgige Region, Wasserbilanz, hydrologische Prozesse, zeitliche und räumliche Variabilität