Nordic Hydrology, 33 (1), 2002, 1-14

Experimental Hydrological Analyses in the Dischma based on Daily and Seasonal Evaporation

Selected paper from EGS General Assembly, Nice,
April-2000 (Symposium OA 36)

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The Dischma is a typical high mountain valley in the alpine source area of the River Rhine. A knowledge of the daily and seasonal water balance is important for understanding and predicting the effects of climatic fluctuations on river discharge. Traditional methods of analysing the water cycle usually involve deriving evaporation from precipitation and discharge. However, in mountain regions single station precipitation and discharge data cannot simply be extrapolated to represent regional evaporation characteristics. Measurements of precipitation in mountains are both limited in accuracy and spatial representativeness in contrast to well-defined discharge data. Field measurements of evaporation in the Dischma valley recorded over five summers give a fairly accurate picture of this component over space and time. New results on the characteristics of evaporation, transpiration and condensation are obtained from automated evaporation pans, lysimeters and climatological stations. The water cycle can be defined with greater precision by measuring discharge and evaporation and deriving precipitation than the more traditional technique of deriving evaporation.

Introduction

Analyses of the daily and seasonal water balance in high mountain regions such as the Dischma are important with respect to the role that they play as an alpine source area of the river Rhine. A knowledge of the weighting of the different hydrological

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components, such as evaporation, precipitation and discharge is of significance when solving the water cycle. In addition, a precise knowledge of the dynamics of the different components of the water balance is required in order to understand possible variations due to the impact of climatic change.

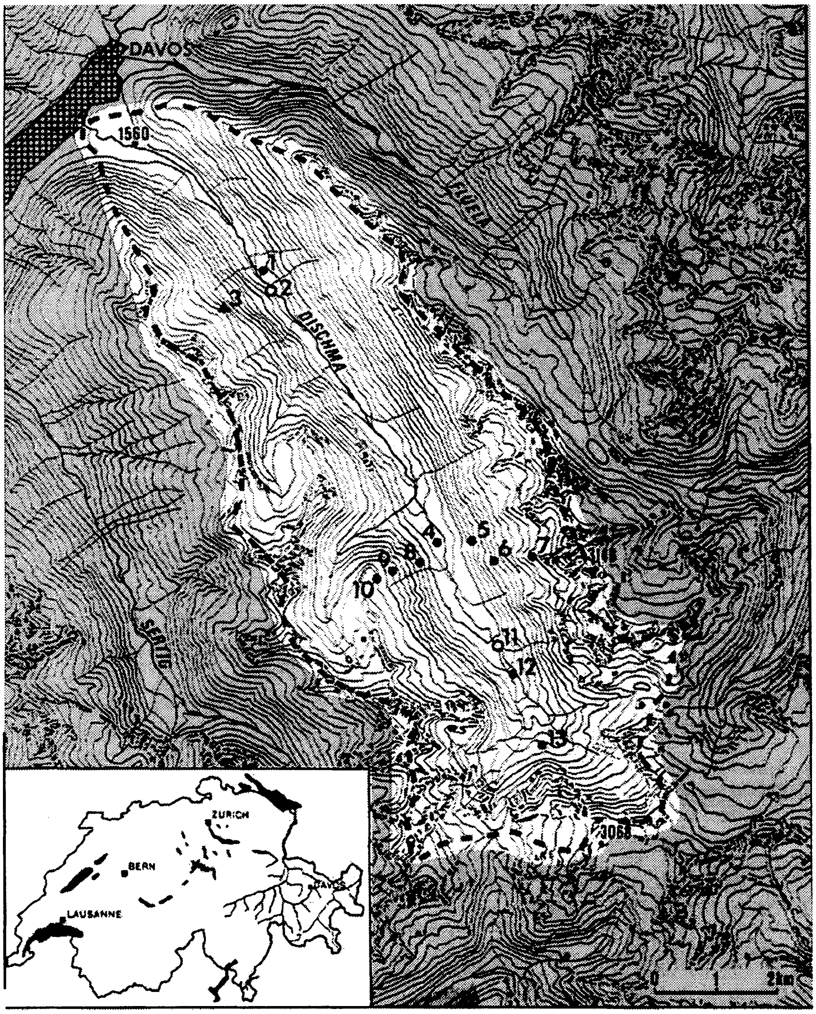
The solution of the water balance equation is mostly based on measured precipitation and discharge data (Wahrenberger *et al.* 1997). Evaporation, an equally important component of the water cycle, is usually derived from the water balance equation or from calculations based on meteorological data. This is mainly due to difficulties in measurement techniques concerning evaporation and transpiration, and the logistical difficulties involved in obtaining a precise picture of the regional character of evaporation. Above 2,000 m, evaporation is usually estimated (Spreafico *et al.* 1999; Baumgartner *et al.* 1983). Very few data exist on measured evaporation in high altitudes, especially above 1,600 m. Those that are available use Wild'sche scales or evaporation pans (Brändli 1996; de Jong and Ergenzinger 1996).

The aims of this paper are to disseminate the results and experiences of five years of hydrological measurements, with special emphasis on evaporation measurements in the high alpine zone of the Dischma. The main questions to be answered over the seasonal to daily scale are firstly: what are the regional differences of the components of the water cycle, secondly what are the main interactions of the components of the water cycle and thirdly, how does evaporation behave?

Study Area

The Dischma valley is located south of Davos in the Eastern Swiss Alps (Fig. 1). It has a catchment area of 51 km^2 and is drained by the Dischmabach. The geology consists mainly of gneiss with a few bands of amphibolites. The subsurface is not very permeable, so that the rain and snow water that is not freed through evapotranspiration accumulates as surface runoff and the groundwater component is locally variable (Lütschg-Loetscher 1944). The Dischma valley can be classified vertically into four hydromorphological types. Below 2,000 m.a.s.l. there is a forested zone that contains a fodder meadow zone on the valley floor between 1,600-2,000 m a.s.l.. This is followed by a dwarf shrub and mats zone between 2,000-2,400 m.s.l. consisting mainly of alpen-rose, blueberries, grasses and lichens. Between 2,400-2,700 m.a.s.l. is an alpine grassland zone covered with short alpine grass and lichens. The uppermost zone consists of pure rock surfaces and scree slopes between 2,700-3,100m a.s.l. The valley has been extensively glaciated and a small glacier still exists in the upper reaches of the valley. Above 2,550 m there is a zone of rock glaciers and screes which often remain snow-covered in summer. Numerous small streams, several lakes and moors are distributed across the valley.

The sites of evaporation, transpiration and precipitation measurement were chosen in order to represent all the main zones mentioned above the tree-line. Representative sites were chosen along a vertical and long-valley axis. As there are very



1 = Inner Hof
2 = Kriegsmatte
3 = Stillberg
4 = Jenatsch
5 = Schürli Alpenrosen
6 = Schürli Bowen Ratio
7 = Schwarzhorn

8 = Hüreli Alpenrosen
9 = Hüreli Bowen Ratio
10 = Hüreli Peak
11 = Dürrboden
12 = Gletschboden
13 = Oberer Schönbühl

○ = discharge station
● = pan/lysimeter

▲ = meteorological station

Fig. 1. Study area in the Dischma valley. Sites are marked with respect to where evaporation, discharge or meteorological data were collected.

few south-facing slopes in the valley, all sites were located on slopes in sectors facing west (NW-SW), east (NE-SE) or north (NW-NE). Discharge was measured at Dürrboden below the glacier (Fig. 1, Station 11), and at a permanent flow gauging site of the Swiss National Hydrological and Geological Survey at Kriegsmatte in the lower parts of the valley (Fig. 1, Station 2). Dürrboden and Kriegsmatte have a catchment area of 12 and 43 km^2 respectively. Additional meteorological data were obtained from a permanent station installed at Stillberg (Fig. 1 Station 3).

Methodology

Field data on precipitation, discharge and evaporation were collected over a period of five summers by applying new and modified techniques, which were supported by permanent stations.

Precipitation data were obtained at 10-minute intervals from a permanently installed Hellmann rain gauge at the Stillberg site (2,085 m a.s.l., Fig. 1, Station 3), from automatically recording rain-o-matic tipping spoons as well as from automated evaporation pans at the individual sites in 1998 and 1999. Between 1995-1997, the non-permanent stations measured at daily intervals.

A permanent discharge station, measuring at hourly intervals, has been installed at Kriegsmatte since the 1970's. In addition, discharge was measured with a stage gauge installed below the bridge at Dürrboden in 1995 and 1999.

Meteorological data have been obtained at 10-minute intervals at the permanent Stillberg site since the 1970's and were measured with the help of non-permanent climatological stations and Bowen Ratio stations during the study period. The main variables measured included radiation, air and ground temperature, humidity, wind speed and wind direction.

Evaporation and transpiration was measured manually between 1995 and 1997 from evaporation pans and lysimeters lowered into the ground (Fig. 2). From 1998-1999 data were registered automatically at 10-minute intervals from scales based on the same principal. Evaporation was determined from water-filled evaporation pans with a surface area of 0.066 m^2, a depth of 0.10 m and a maximum weight of 5 kg. The automatic measuring scales were equipped with a RS232 exit into a storage module and had a resolution of 1g and an accuracy of ± 0.3%. A calibration experiment between the evaporation pans and a normal class-a pan carried out over a period of 3 months in 1995 produced a good correlation ($r^2 = 0.97$).

Transpiration data were obtained from lysimeters, which were weighed on the same type of measuring scales as the evaporation pans. Lysimeters were constructed in three different dimensions, accommodating as many different root systems as possible. The surface area varied between 0.040-0.066 m^2 and the lysimeter depths varied between 0.10-0.25 m. Each lysimeter was perforated and surrounded by a collecting container. Care was taken to relocate each lysimeter as exactly as possible into its original vegetation niche.

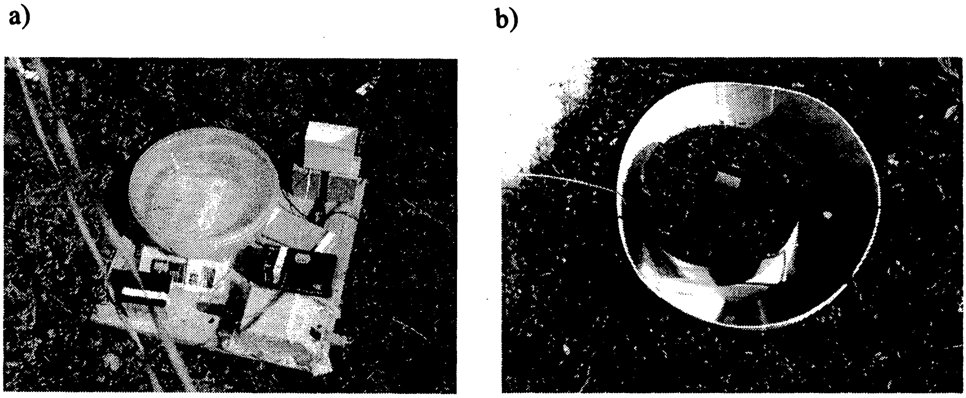


Fig. 2. Instrumental set-up of a) evaporation pan and b) lysimeter, placed ontop of automatic weighing scales inside a protective cylinder inserted level with the ground. A tipping-spoon raingauge is installed next to the evaporation pan. The data are transferred at 10-minute intervals to a storage module.

Results and Discussion

Seasonal Water Balance

Seasonal water balance analyses were restricted to the mid-summers, from 1. June to 15. September, between 1995-1999 *i.e.* during the snow-free period dominated by rainfall events. The solution of water balance equation (Eq.(1)) was based on data from the permanent discharge and precipitation stations at Kriegsmatte and Stillberg as well as from evaporation pan data at the Jenatsch site.

$$P = Q + ET + S \tag{1}$$

where P – precipitation
Q – discharge
ET – evapotranspiration
S – storage

The average mid-summer sum of evaporation, 246 mm, measured at a height of 1,960 m at Jenatsch, compares well with the sum for Davos, 267 mm, measured at 1,590 m a.s.l. (Brändli 1996). Precipitation ranges from 440 to 636 mm for all four test years. For all test years, the seasonal data reflect a major imbalance in the water cycle equation, caused mainly by an underestimation of rainfall (Table 1). Even without the evaporation component, discharge exceeds precipitation. The imbalance of the measured rainfall in comparison to the calculated rainfall varies by a factor of between 1.7-2.4. This can be explained in two ways. The first reason could be that

Table 1 – Seasonal balance of components of the water cycle: precipitation (*P*), measured at Stillberg, calculated precipitation (*P* catchment) and the ratio of the calculated precipitation to measured precipitation(*P* calculated / *P* measured).

Year	*P* (measured)	*P* catchment (calculated)	*P* (calculated)/ *P* (measured)
		(mm)	mm
1995	450	> 1019	2.2
1997	440	> 1063	2.4
1998	507	>964	1.9
1999	636	>1068	1.7

the Stillberg site is located in a rain shadow and that it is not representative for the regional precipitation of the Dischma valley. The second reason could be that the discharge is augmented by the melting of permafrost and snow during the summer months.

From Fig. 3 it is clear that precipitation is exceeded by discharge during the whole study period. In 1998, the ratio of calculated precipitation to measured precipitation was relatively low. This is due to the fact that the month of August can steer the summer evaporation and discharge. Thus during years with a very dry August as in 1998, evaporation is high and discharge low. During the remaining season however, a relatively high overall precipitation is maintained.

The high rates of evaporation during the dominant month of August can be explained by its favourable meteorological conditions, including low precipitation, low relative humidity, high temperatures and high wind speeds. On the other hand, discharge is low due to a lack of rainfall and the lack of meltable sources such as snow fields after prolonged dry periods. For very wet years, such as 1999, the ratio between calculated precipitation and measured precipitation is also relatively low. During such summers, evaporation is low, precipitation high and discharge high for the opposite reasons. For normal years, however, the imbalance between the components is much higher. What is also intriguing is that, for the summer months, evaporation varies between 34-68% of the precipitation input. For one month in August 1998, the evaporation actually exceeded precipitation by 10%.

In the Dischma, the response of discharge to temperature and rainfall variations is an important aspect of the seasonal water balance. Discharge can be divided into two main components, that of glacial meltwater, which is typified by the Dürrboden discharge station at 2,000 m a.s.l., and that of the entire Dischma valley, which is captured by the Kriegsmatte station at 1,710 m a.s.l. (Fig. 4). At both sites, discharge can be measured precisely. Whereas the Dürrboden site indicates a lower discharge and fewer variations, the Kriegsmatte site measures about double the amount of discharge and shows distinct peaks caused by secondary floods from the smaller side

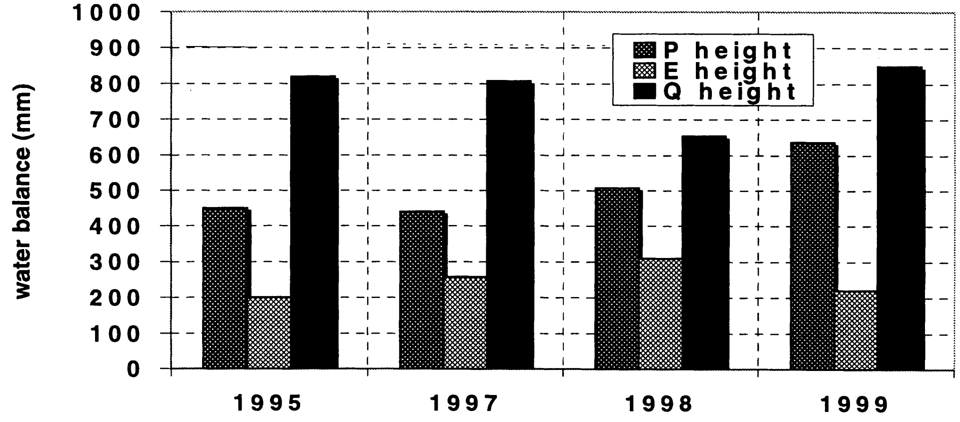


Fig. 3. Water balance components *P* (precipitation height in mm), *E* (evaporation height in mm), measured at Jenatsch, and *Q* (discharge height in mm), measured at Kriegsmatte, for the summer months (1 June-15 Sept.).

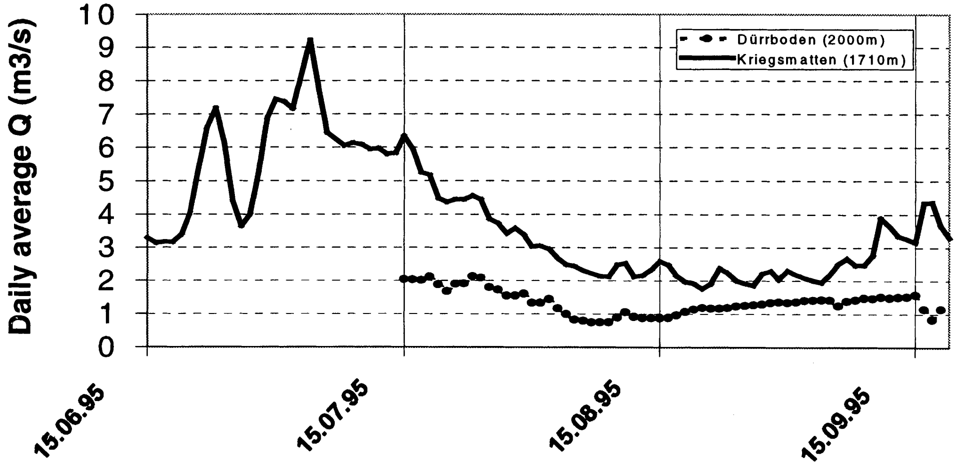


Fig. 4. Discharge measured between 15 July 95-15 Sept. 95 at Dürrboden (near glacier) and Kriegsmatte (in the lower valley).

valleys of Riner and Rüedisch. Since glacial melt is steered by summer temperatures and basin runoff is steered mainly by rainfall and snowmelt, the interaction between both discharge components causes considerable seasonal variations.

Precipitation is more difficult to determine since it varies considerably with height, topography and measurement technique. High altitude sites such as Brämbüel (2,560 m) can capture between 10 to 130 mm more precipitation than the Stillberg site at 2,130 m (Urfer-Henneberger 1970). In general, precipitation increases with height but wind-induced errors and wetting loss from measurements may underestimate the results significantly (Sevruk 1997). However, the variation of precipitation is large for extreme events. For example on the 25th July 1995 rainfall varied by a factor of 3 over only 400 m of height.

Evaporation does not vary as much with altitude as precipitation nor does it produce great variations when summed over the season. It can therefore be determined far more precisely than precipitation. In contrast to precipitation, most evaporation occurs during snowmelt and snow-free periods between June and September. Maximum evapotranspiration is constrained by the type of vegetated surface. Unlike precipitation and discharge, this sets an upper limit to the evapotranspiration height.

From these investigations it is suggested that precise measurements of evaporation and discharge should suffice to determine a correct minimal precipitation by solving the water balance equation in a high mountain valley such as the Dischma.

Monthly Water Balance

Dry August 1998 – A typical dry month was chosen in order to demonstrate how variable rainfall can be in comparison to evaporation at the Jenatsch station (Fig. 5a). While average rainfall only amounted to 2.97 mm, the average daily evaporation amounted to 4.22 mm, compared to a relatively high average discharge of 4.14 mm. The sum of rainfall, evaporation and discharge over 24 days amounted to 74 mm, 102 mm and 98 mm respectively, so that evaporation actually exceeded discharge. Whereas evaporation was high during the rain free period at the beginning of August, most rainfall and least evaporation and discharge occurred during the end of the month.

Wet August 1999 – The month of August at Jenatsch in 1999 was exceptionally wet (Fig. 5b). Taking into account that there were no data recorded for altogether 6 days, between the 16-20th of August and 27-28th of August, rainfall exceeded evaporation by 93.81 mm over the 22 days recorded.

The missing values of rainfall were obtained from a correlation between the measurement site and the permanent station at Stillberg. While average rainfall amounted to 4.58 mm, average evaporation only amounted to 1.39 mm but average discharge amounted to 4.95 mm. The monthly sum of precipitation, 132.81 mm, was much higher than in 1998. As expected, the monthly sum of evaporation, which amounted to 39 mm, was lower than in 1998 and the sum of discharge, 143.3 mm, was higher than in 1998. In neither year was daily evaporation as variable as rainfall. Also, there was a slightly inverse trend in evaporation as compared to discharge.

Rainfall events usually persisted only over a few hours. Considerable evaporation on days with precipitation (*e.g.* 25 Aug.1999 or 23 Aug.1998 in the preceding year) occurred as a result of high interception evaporation proceeding immediately after a rainfall event, in addition to normal evaporation before and after.

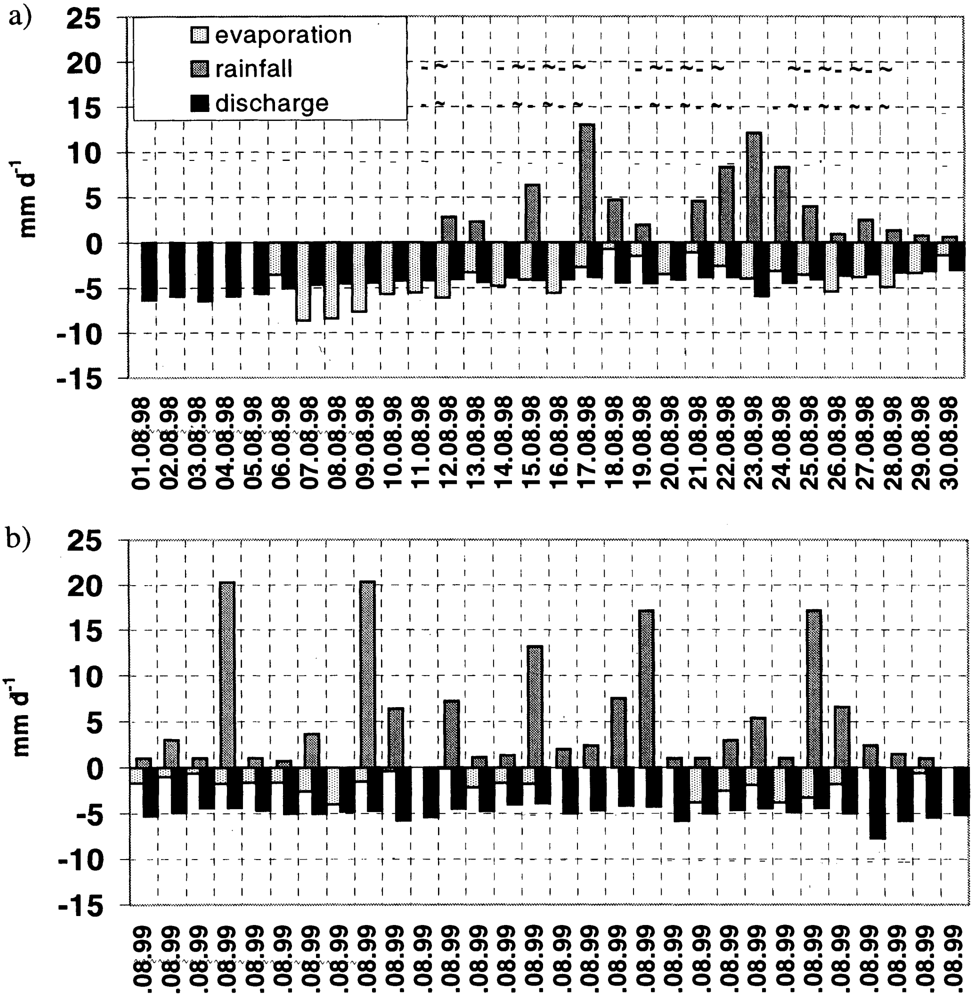


Fig. 5. Daily (24-hour) sums of evaporation and rainfall at the Jenatsch site (1960 m) for the month of August in a) 1998 and b) 1999. In 1999 there were no evaporation data recorded during the heavy rainfall period of 16-20th August and 27-28th of August.

Altogether, the dynamics of evaporation associated with short rainfall periods of approximately 2 hours duration were steered according to whether rain fell by day or night (Fig. 6). If rain fell by night, this had nearly no impact on the daily evaporation. On the other hand, if rain fell by day, the onset of evaporation was delayed but high rates of interception evaporation (> 1,2 mm h^{-1}) followed over a time interval of 30-40 minutes after the event.

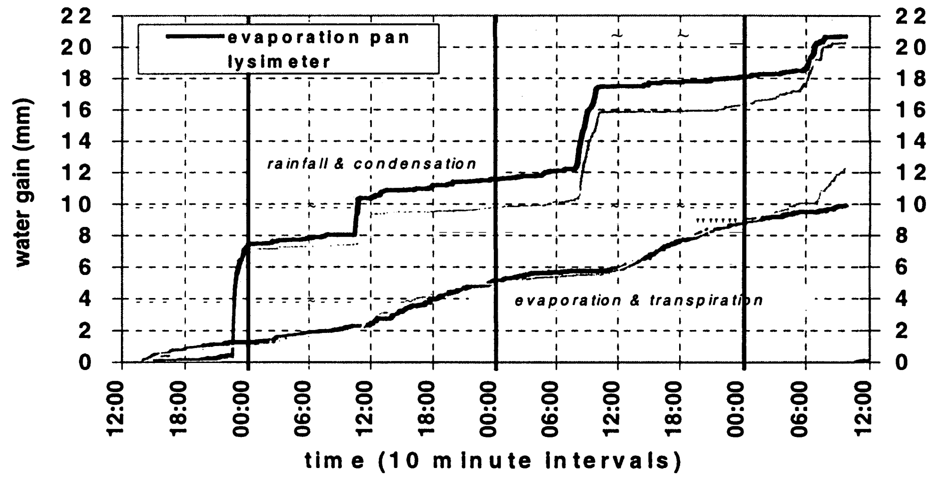


Fig. 6. Cumulative sums of evaporation and transpiration (water loss) and rainfall and condensation (water gain) in mm measured at 10-minute intervals over a 3-day period at Gletschboden in 1999. Rainfall events are marked by sudden water level increases in the lysimeter and evaporation pan whereas condensation is marked by a more gradual increase. During the day time transpiration exceeds evaporation.

Daily Water Balance

The daily hydrological analyses of the 5th of August 1999 reveal two previously unknown facts: firstly that condensation controls the beginning of evaporation and transpiration until the late morning hours, and secondly that evaporation and transpiration continues through at least part of the night until condensation takes over (Fig. 7).

Fig. 7 shows that transpiration is higher than evaporation for the six different sites. On average, transpiration exceeds evaporation by 30%. The highest amount by

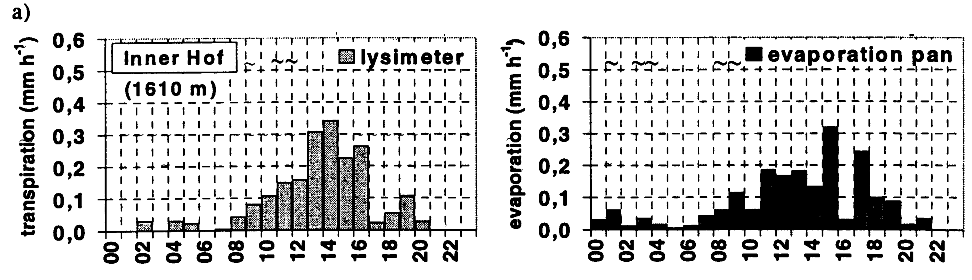


Fig. 7. Hourly sums of transpiration (left hand) and evaporation (right hand) for a) Inner Hof, b) Jenatsch, c) Gletschboden, d) Hüreli Alpenrosen, e) Schürli Alpenrosen, f) Oberer Schönbühl from 00:00-00:00, 5.-6. August, 1999. No data were recorded between 08:00-13:00 at Schürli Alpenrosen.

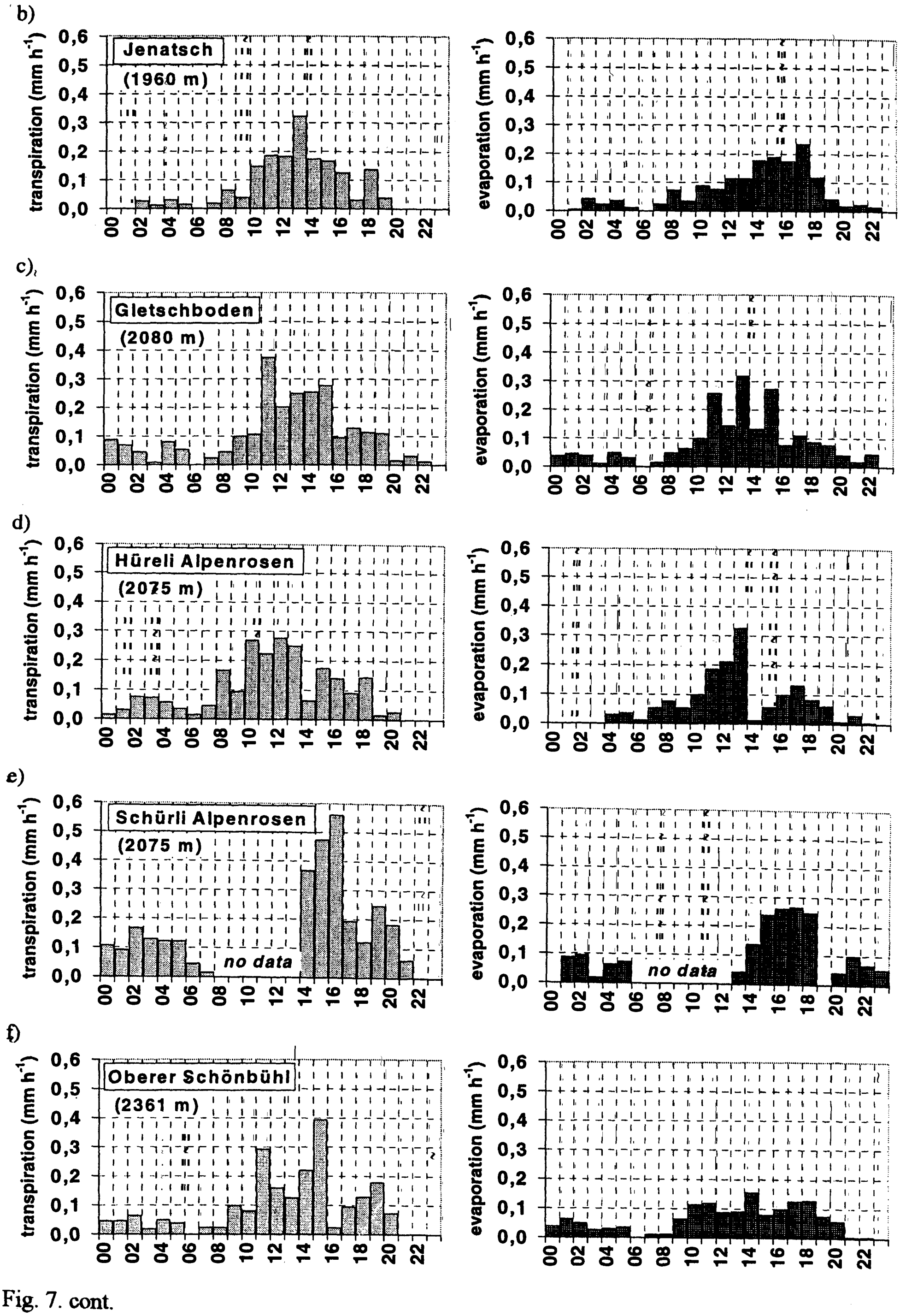

b)
Jenatsch
(1960 m)
c)
Gletschboden
(2080 m)
d)
Hüreli Alpenrosen
(2075 m)
e)
Schürli Alpenrosen
(2075 m)
no data
f)
Oberer Schönbühl
(2361 m)
transpiration (mm h^{-1})
evaporation (mm h^{-1})
0,0
0,1
0,2
0,3
0,4
0,5
0,6
00
02
04
06
08
10
12
14
16
18
20
22

Fig. 7. cont.

which transpiration exceeds evaporation, 68%, is found in the alpen-rose sites (Fig. 7 e) and the lowest amount, 1%, is found in the alpine meadow (Fig. 7 a). The highest hourly rate of transpiration, 0,54 mm h^{-1} was recorded at the Schürli Alpenrosen site (Fig. 7 e) within the alpen-rose on a southwest facing slope experiencing the longest evening sunshine. The lowest rate of transpiration, 0,29 mm h^{-1}, is found at Oberer Schönbühl (Fig. 7 f), in high altitude pasture on the cold and exposed head of the valley near the glacier. In the few studies that exist on the transpiration of alpen-rose and alpine grasses, much lower rates of transpiration are usually indicated (Larcher 1995). On the whole, the valley floor sites experience the lowest evapotranspiration whereas the valley slope sites in the alpen-rose experience the highest rates. All sites record nightly transpiration and evaporation. Whereas the valley sites record more nightly evaporation than transpiration, transpiration exceeds evaporation by up to three times the amount in all the other sites.

All sites have a bi- or trimodal distribution of transpiration and evaporation and transpiration reaches its peak earlier in the day than evaporation. There are three main peaks of transpiration, varying by plus or minus one hour depending on valley site, at 11:00, 15:00 and at 18:00 hours respectively and a nightly peak around 03:00 hours. For evaporation, the peaks mostly lie at 13:00, 15:00 and 17:00 hours with a nightly peak at 02:00 hours. The first peak corresponds with the onset of evaporation and transpiration as condensation stops and the surface starts warming up. The second peak corresponds with the increase in afternoon wind speed. The third, small but distinct peak, corresponds with the setting of the sun following a short but intensive period of condensation together with a change in wind direction. LeDrew (1975) also found a maximum in morning transpiration, followed by a minimum at 12:00 and a secondary maximum in the late afternoon in his investigations on Niwot Ridge in Colorado at 3,500 m height.

Conclusion

Contrary to previous studies, the seasonal water balance in the high mountain valley of the Dischma can be more precisely determined from evaporation and discharge than from discharge and precipitation. High resolution lysimeter and evaporation pan studies show that measured precipitation is underestimated by a factor of between 1.7-2.4. For extremely dry summer months, there may be a twofold excess of evaporation in relation to precipitation. In contrast, during very wet summers, there may be a threefold excess of precipitation in relation to evaporation. Average evaporation for dry summer days measured above the tree-line at 1960 m height reaches 4.2 mm, whereas only 1.2 mm are reached on wet summer days. On a daily basis, condensation controls the start of evaporation and transpiration. Transpiration usually exceeds potential evaporation and responds more sensitively to the impact of condensation and rainfall.

Acknowledgements

This project was supported by a Habilitation fellowship of the Deutsche Bundesstiftung Umwelt and a postdoctoral fellowship of the DFG (German Research Council). I would like to thank Peter Ergenzinger, Arne Köcher, Florian Goroncy and numerous students for their intensive help in the field, Mr. Weierganz for initial storage module programming and Mr. Knabe for construction work. I also obtained invaluable help from numerous staff and technical workers of the SLF and WSL. My warmest thanks go to the comments and support by Ruedi Häsler, WSL. My thanks also go to Arnold Streule of the WSL for provision of meteorological data, to Manfred Spreafico and Christian Koch of the Swiss National Hydrological and Geological Survey for the provision of discharge data and to Bertil Krüsi of the WSL for plant identification within the lysimeters. I am thankful to Andreas de Jong for correcting the English.

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Received: 30 September,2000
Revised: 12 April, 2001
Accepted: 30 April, 2001

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