Nordic Hydrology, 25, 1994, 53-64

Long-Term Records of Snow Cover Water Equivalent in the Swiss Alps

1. Analysis

Paper presented at EGS XVII General Assembly
(Edinburgh, GB – April 1992)

M. B. Rohrer, L. N. Braun and H. Lang
Swiss Federal Institute of Technology, ETH,
CH-8057 Zürich, Switzerland

The snow-water equivalent (*SWE*) of the seasonal snow cover is an important component of the water cycle in the Swiss Alps. It is used for predicting seasonal discharge, for short-range discharge forecasts and also for assessing water quality aspects. The *SWE* has been measured every two weeks at about 50 stations located between 860 and 2,540 m a.s.l. for more than 30 years. In addition there are special investigation areas with stations located between 600 m and 2,900 m a.s.l. where *SWE* is measured once per winter. The main characteristics of temporal and spatial *SWE* distributions are analyzed. The variations of *SWE* values depend in ranking order on elevation, on the year-to-year variations, on the region and on the exposition. The standardized *SWE*-values depend mostly on the year-to-year variations and on the region.

Introduction

The important role of the temporary storage of water in the form of snow in the Swiss Alps has long been recognized in the literature. In respect to discharge, earliest contributions were made by Lütschg (1945), Hoeck (1951), and Church (1957), among others. The main processes acting in the snow cover were described first by Bader *et al.* (1939), and the melting process received due attention in the early contributions of Zingg (1951) and Hoeck (1952). As a result, snow cover measurements were not only performed by the Swiss Meteorological Institute and the Swiss Federal Institute of Snow and Avalanche Research (SLF) on a routine basis, but also by various hydro-electric power companies and research institutions.

A coordinated effort to measure the snow-water equivalent (*SWE*) was initiated in 1943/44 by E. Hoeck. Details on this measurement network are presented below. These data acquired are being used operationally for the prediction of streamflow (Lang *et al.* 1993) and were published in part in the Annals of the SLF (Winterberichte). A comprehensive analysis of the long-term series of measured snow-water equivalent is presented by Rohrer (1992), and this paper summarizes the first part of it. The second part concerning the simulation of the SWE is given in the companion paper by Rohrer and Braun (1993).

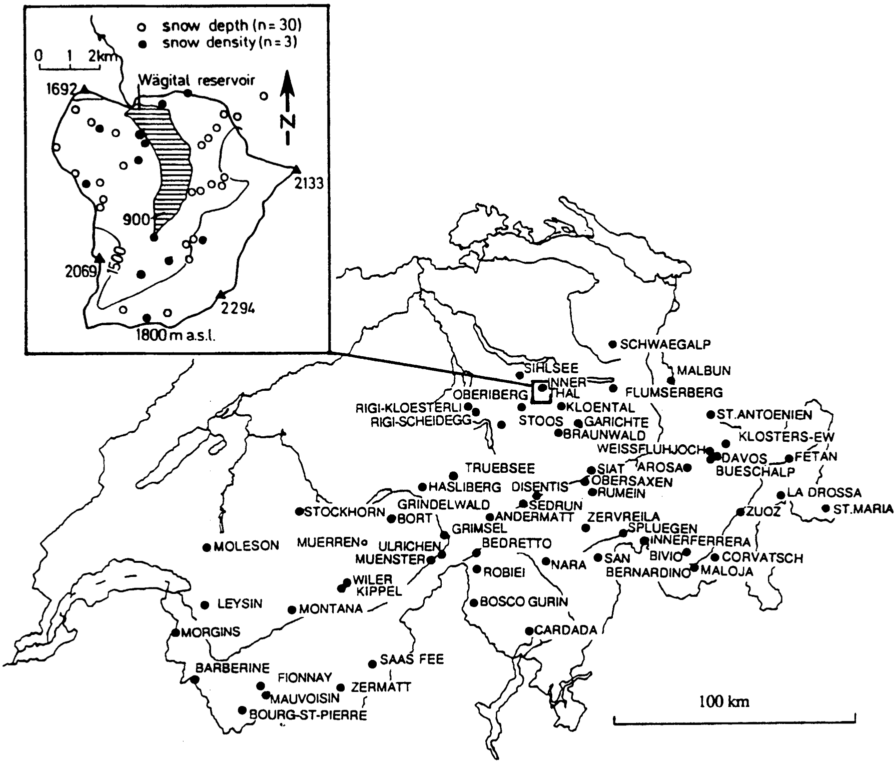

Fig. 1. Measurement network of the snow-water equivalent stations operated by the Swiss Fed. Inst. of Tech. (ETHZ) and the Swiss Fed. Inst. for Snow and Avalanche Res. (SLF). Insert map of the Wägital basin snow network, n=number of measurements at each location

Measurement Network ETHZ/SLF of the Snow-Water Equivalent

In 1943/44, a network to measure the snow-water equivalent in the Swiss alpine and lower alpine regions was initiated at the Swiss Federal Institute of Technology in Zurich (ETHZ), Hydrology section, which until 1983 was part of the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). At a pole, snow depth readings are

Table 1 – List of stations including elevation and period of observations of the snow-water equivalent network operated by ETHZ/SLF; only stations still in use or with record lengths of more than 10 years are given.

Station	Elevation (m a.s.l.)	Period of observation
above 2500 m		
Weissfluhjoch	2536	1947-
2500 - 2001 m		
Corvatsch	2270	1973-
Nara II	2065	1976-1988
2000 - 1501 m		
Arosa	1818	1981-
Barberine	1820	1946-1973
Bivio	1770	1960-
Bourg-St. Pierre	1650	1952-
Büschalp	1980	1947-
Cardada	1660	1973-
Davos	1560	1950-
Fetan	1710	1973-
Garichte/Mettmen	1610	1944-
Grimsel	1981	1950-
Grindelwald-Bort	1570	1949-
Hasliberg	1850	1960-
La Drossa	1710	1968-
Malbun	1600	1972-1988
Maloja	1800	1953-
Mauvoisin	1841	1960-
Mürren	1650	1950-
Rigi-Scheidegg	1620	1974-
Robiei	1890	1975-
Saas-Fee	1780	1953-1972
San Bernardino	1630	1973-
Sasso della Boggia	1900	1984-
Stockhorn	1650	1972-
Trübsee	1800	1949-
Zermatt	1620	1947-
Zervreila	1740	1965-
Zuoz	1710	1951-
1500-1001 m		
Andermatt	1440	1948-
Bedretto	1400	1951-1982
Bosco Gurin	1490	1963-1984
Braunwald	1340	1960-
Disentis	1170	1960-
Fionnay	1500	1972-
Flumserberg	1310	1972-
Innerferrera	1480	1960-
Kippel	1370	1969-1983
Klosters-EW	1200	1948-
Leysin	1250	1953-
Moléson	1500	1967-
Montana	1500	1952-
Morgins	1380	1962-
Münster	1360	1952-1986
Nante	1420	1984-
Nara I	1450	1976-1988
Oberiberg	1100	1954-
Obersaxen	1300	1947-1961
Rigi-Klösterli	1410	1960-1971
Rumein	1200	1966-
Schwägalp	1290	1966-
Sedrun	1420	1968-
Siat	1250	1960-
Splügen	1460	1960-
St. Antönien	1480	1947-
St. Maria	1400	1968-
Stoos	1290	1954-
Ulrichen	1345	1951-
Wiler	1405	1985-
1000-501 m		
Brandhaltli	950	1944-1986
Güntlenau	860	1968-
Innerthal (Stock)	910	1943-
Klöntal	860	1943-
Sihlsee	895	1943-

taken every morning, the density of new snow is measured in the morning if new snow depth exceeds 10 cm, and the density of the total snow cover is assessed in a snow pit nearby at the beginning and the middle of each month. The gravimetric method is employed, and the snow samples are taken using an aluminium cylinder having a cross-sectional area of 70 cm^2 and a length of 55 cm. The mass of the snow sample is measured either by a spring balance or by melting and using a graduated measurement cylinder. At present, this network of some 50 stations is further maintained by the Department of Geography at ETH and the Swiss Federal Institute of Snow and Avalanche Research (SLF). Fig. 1 shows the location of the stations, and Table 1 gives further details concerning elevation and length of observation of each station.

In addition, some results of the Wägital Hydroelectric Power Company measurements of the snow water equivalent are taken along snow courses around 1 April each year, which generally represents the maximum snow accumulation for this basin.

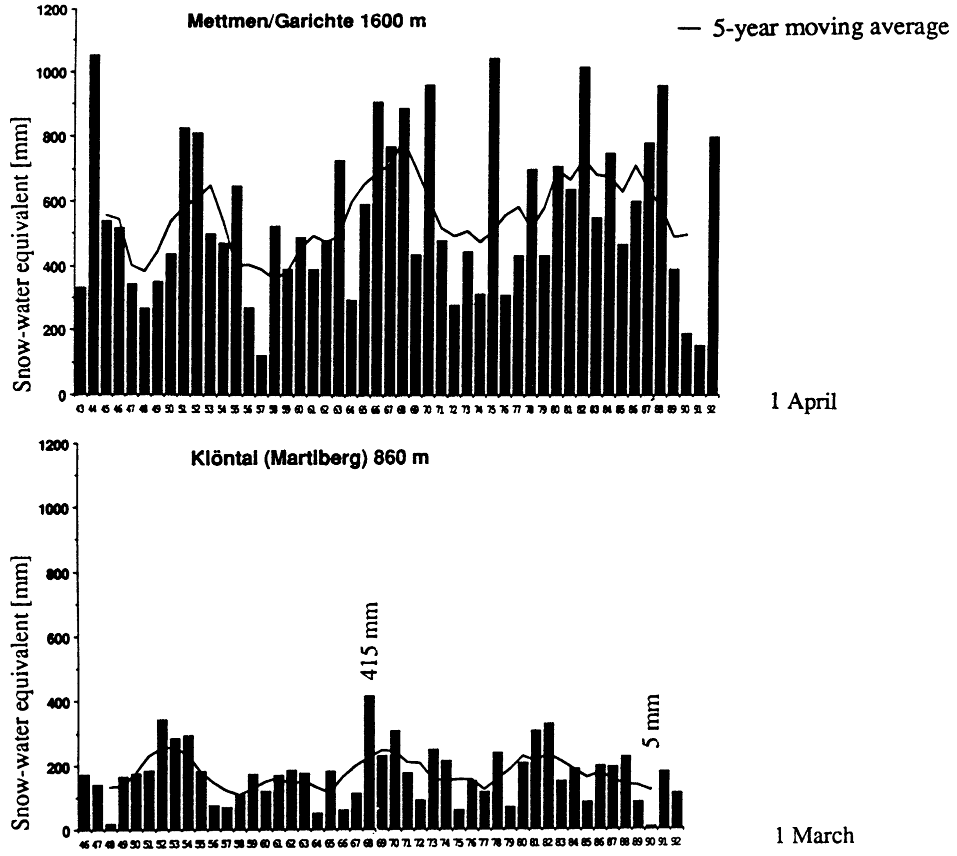

Fig. 2. Long-term variation and moving 5-year average of the snow-water equivalent at appr. time of maximum accumulation measured at index points: a) Mettmen/Garichte, 1,600 m a.s.l., as of 1 April, 1943-1992; b) Klöntal, 860 m a.s.l., as of 1 March, 1946-1992.

Variation of the Maximum Snow Accumulation from Year to Year

Long-Term Variation of the Snow-Water Equivalent at Index Points

Fig. 2. shows the long-term variation of the snow-water equivalent of the two stations Mettmen/Garichte (as of 1 April) and of Klöntal (as of 1 March). It can be seen that this annual maximum snow storage varies from year to year to a great extent at both stations. While there is a slight increase in the snow-water equivalent

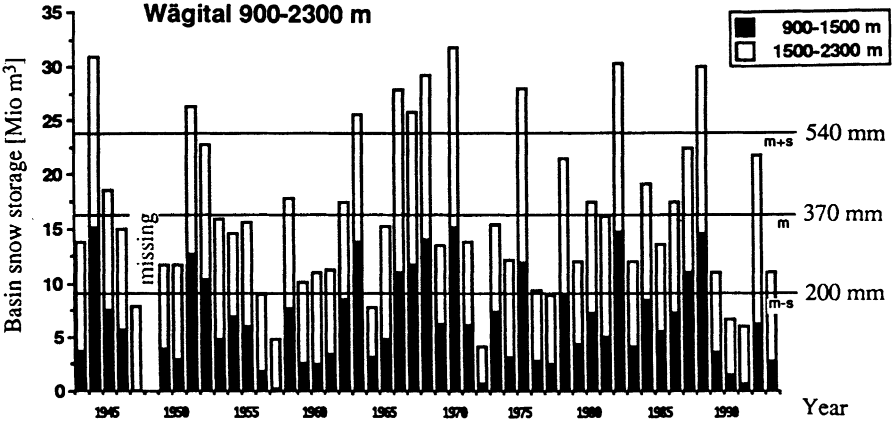

Fig. 3. Long-term variation of basin snow storage (in mio m^3) in the Wägital catchment for elevation zones 900-1,500 and 1,500-2,300 m a.s.l (see also Fig. 1). The mean value m of abt. 16.3 mio m^3 corresponds to appr. 370 mm for the whole basin, the standard deviation s corresponds to 170 mm. Figure based on Lepori (1993).

over the past 50 years at the Mettmen/Garichte station, no such trend can be seen for the Klöntal station. Such lengthy time-series of snow storage at index points are very valuable in today's discussion concerning the influence of a changed climate on snow cover. As an example, Bultot *et al.* (1992) predicted a reduction in the snow-water equivalent of up to 50 % in the elevation zone 1,200 to 1,500 m a.s.l. due to a doubling of CO_2 in the atmosphere. It is evident that a continued effort to monitor the snow cover at these index points is essential in the future, so that such predictions can be tested against observations.

Long-Term Variation in Basin Snow Storage

Fig. 3 shows the variation of basin snow storage of the Wägital catchment on 1 April over the last 50 years, based on the measurements at locations indicated in Fig. 1. The mean value lies at 16.3 Mio m^3 corresponding to 370 mm. The year-to-year variation is remarkable: the maximum of 726 mm in 1970 is 8 times higher than the minimum of 92 mm observed in 1972. More details concerning the remaining parts of the water balance of this basin are given by Lepori (1993).

Principal Component Analysis of the Snow-Water Equivalent of Selected stations

The water equivalent measurements taken 1 April and 1 May between 1975 and 1989 at 9 high elevation stations were analyzed using principal component analysis as described in Kendall and Stuart (1966) and Fahrmeier and Hammerle (1974) for example. The first principal component explains some 60 % and 50 % of the variation of all stations for 1 April and 1 May, respectively, which can be interpreted as the year-to-year variation of snow storage. The second principal component explains some 26 % of the snow storage variation at both dates, and two groups can be distinguished: northern and southern alpine stations. The results pertaining to 1 April confirm previous findings by Jensen (1979) who investigated a larger number of stations and another reference period. It is interesting to note that the station Zervreila cannot be clearly characterized as the northern or southern alpine type, and that the station Mauvoisin (1,810 m, Val de Bagnes in the Valais) is clearly northern alpine. This may be related to the particular topographical situation of this station being open to the north-westerly winds (for more details see Lang and Rohrer 1987).

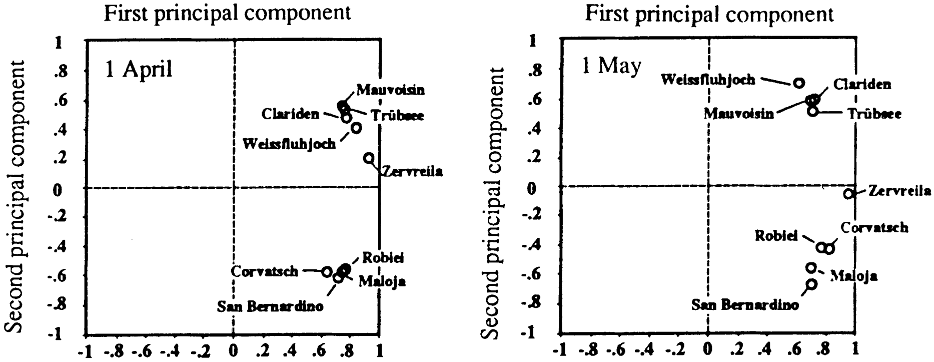

Fig. 4. Principal component analysis of snow-water equivalent of 9 stations situated at high elevations (1,740-2,536 m a.s.l) for 1 April and 1 May, 1975-1989.

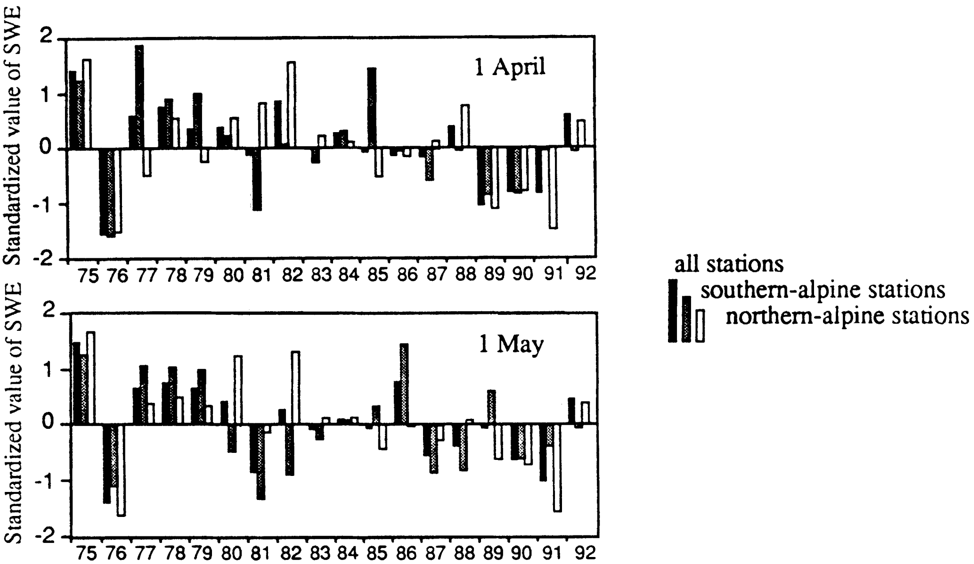

Fig. 5. Standardized snow-water equivalent values of all stations as shown in Fig. 1 on 1 April and 1 May, as well as for the southern and northern alpine station groups, 1975-1992.

Standardized Values of the Snow-Water Equivalent: Regional Characteristics

Based on the principal component analysis as described above standardized values of the snow-water equivalent were calculated for the northern and southern alpine station groups, and also for all 9 stations as a whole. Fig. 5 shows the results for 1 April and 1 May: in 10 cases the deviation from the mean is in the same sense for both northern and southern stations, and in 7 cases it is in the opposite direction. It is noted that quite drastic changes in the snow accumulation situation can occur between 1 April and 1 May, particularly for the southern stations (see years 1977, 1986 and 1989), where warm Mediterranean air masses can cause heavy snow falls.

Seasonal and Altitudinal Dependence of the Snow Cover

Seasonal Variation of the Snow-Water Equivalent at Index Points

The seasonal variation (November till June) of the snow-water equivalent was investigated for all 50 stations of the ETHZ/SLF network, and presented in the Hydrological Atlas of Switzerland (1992). As an example, the results for Andermatt (1,440 m, period 1947/47 to 1987/88) are shown in Fig. 6. Generally snow storage is at its maximum in mid-March, in the extreme case of 1977 it occurred in mid-April at this elevation.

Seasonal and Altitudinal Dependence of the Snow-Water Equivalent in Various Regions of the Alps

For the various regions of the Swiss Alps the altitudinal dependence of SWE during the course of the winter season was determined (Rohrer 1992), and the results for the north-eastern slope of the Alps and the inner-alpine regions are given in Fig. 7. There is a striking difference between the two regions: while on the north-eastern slope of the Alps the accumulation gradient increases progressively with the sea-

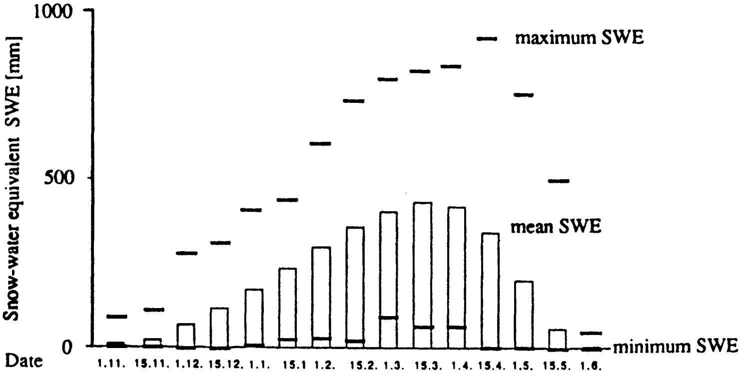

Fig. 6. Seasonal variation of minimum, mean and maximum snow-water equivalent at Andermatt, 1,440 m a.s.l., 1946/47-1987/88 (42 years).

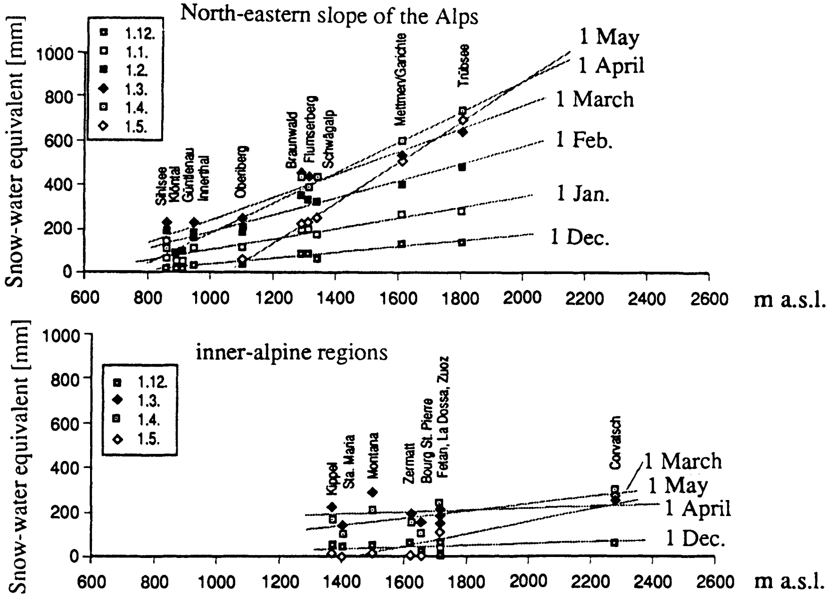

Fig. 7. Mean altitude dependence of snow-water equivalent in course of winter season from 1960/71 to 1984/85 for a) the north-eastern slope of the Alps; b) inner-alpine regions.

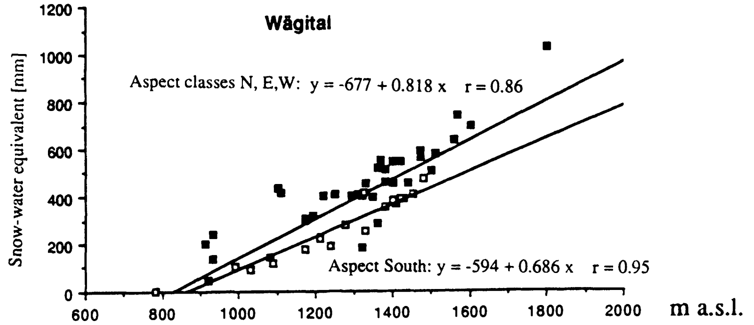

Fig. 8. Long-term mean of altitude dependence of snow storage in the Wägital basin for 1 April, 1942/43-1988/89. Open squares: southern aspect. Filled squares: units oriented towards N,E,W.

son, no such dependency can be seen in the inner-alpine regions. There, precipitation events are less frequent, and when snowfall occurs and is observed over all elevation zones, no obvious increase in snow storage is observed with elevation. On the alpine slope oriented towards the westerly winds, however, frequent advection of warm humid air causes stronger snow accumulation at higher elevations. Similar results are reported by Witmer (1986) for snow depth data.

In a lower northern-alpine basin (Alptal) at elevations between 1,140 and 1,450 m a.s.l. Keller *et al.* (1984) found a mean snow accumulation gradient of about 100 mm/100 m elevation change for open and 50 mm/100 m for forested areas. At considerably higher elevations (1,900 m till 2,800 m a.s.l.) in the Linth-Limmern area Steinegger (1990) found a mean increase of SWE with elevation of 51 mm/100 m based on measurements taken 1 May during the period 1965 till 1985. The gradient varied greatly from year to year, with a minimum value of 22 mm/100 m in 1983 and a maximum of 97 mm/100 m in 1984.

Fig. 8 shows the mean altitudinal dependence of the SWE as measured 1 April in the Wägital catchment (900 till 1,800 m a.s.l.), based on the period 1942/43 till 1988/89, given separately for southern exposed units (gradient = 69 mm/100 m) and the units oriented towards N, E and W (gradient = 82 mm/100 m).

Seasonal and Altitudinal Variation of the Density of New Snow and Total Snow Cover

For the stations of Sihlsee (895 m) and Weissfluhjoch (2,536) the mean densities of new snow are given in Table 2 for the months November to April. It is remarkable that the new snow densities are quite constant through the winter season. Only in May and July does Weissfluhjoch experience higher densities (139.1 and 180 kg/m^3, respectively, n = 443 and 277). The dependency of new snow density on air temperature and wind speed has more thoroughly been investigated by Meister (1986).

Fig. 9 summarizes the statistical distribution of snow densities at four stations between 855 m and 1,835 m a.s.l. for the total winter period. It can be seen that there is no apparent dependency between snow density and elevation, and a mean value of 99.2 kg/m^3 is based on 48 measurement locations (n = 22'166). Therefore, an approximate value of 100 kg/m^3 can well be used for modelling purposes.

Fig. 10 shows snow density as a function of season at three locations of different elevations. It can be shown that there is a steady increase of snow density with progressing season within a band width of about 150 to 220 kg/m^3 at high elevations (2,535 m a.s.l.), while in lower elevations this trend is less pronounced and the band width is much larger. It is obvious from these temporal variations that snow depth alone is a rather poor measure of total snow cover storage, in particular in the lower regions.

Table 2 – Seasonal variation of new snow density at the Sihlsee Station (895 m a.s.l.) and Weissfluhjoch (2,536 m).

	Nov.	Dec.	Jan.	Feb.	March	April
Sihlsee						
Mean [kg/m^3]	95.2	101.8	96.7	94.8	96.7	105.0
n	54	85	117	95	76	55
Weissfluhjoch						
Mean [kg/m^3]	102.2	101.2	96.3	98.2	96.3	99.1
n	428	492	540	458	535	535

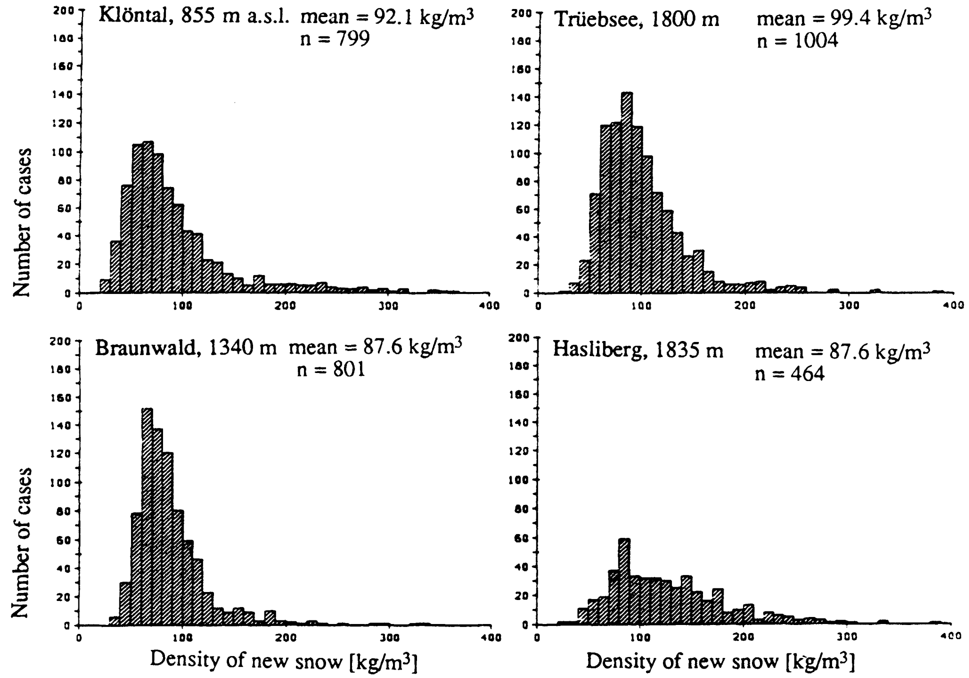

Fig. 9. Distribution of density of new snow as measured at 4 stations. a) Klöntal, 855 m a.s.l 1967/68-1984/85; b) Braunwald, 1,340 m a.s.l. 1960/61-1984/85; c) Trübsee, 1,800 m a.s.l. 1956/57-1984/85; d) Hasliberg, 1,835 m a.s.l. 1960/61-1984/85.

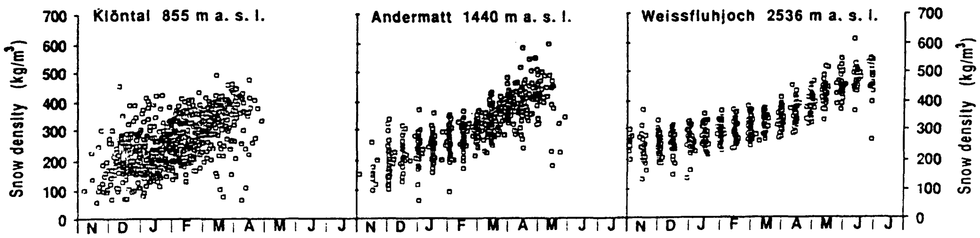

Fig. 10. Seasonal variation of measured snow density at 3 index points: a) Klöntal, 855 m a.s.l. 1945/46-1984/85; b) Andermatt, 1,550 m a.s.l. 1946/47-1987/88; c) Weissfluhjoch, 2,536 m a.s.l. 1947/48-1984/85.

Summary and Conclusions

Based on direct measurements of the snow-water equivalent taken twice a month at some 50 stations, some of which have made recordings since the early 1940s, the variations of the maximum snow accumulation from year to year were analyzed for the Swiss Alps. Maximum snow storage varies greatly from year to year, and no obvious trend can be detected. A principal component analysis at 9 stations at high elevations indicates that over 50 % of the variation can be attributed to the year-to-year variation, and that a northern and a southern alpine station group can be distinguished, explaining another 25 % of the variation. It can be shown that the snow accumulation situation can change drastically between 1 April and 1 May, particularly for the southern stations. Some examples of the seasonal variation of snow storage (water equivalent and snow density) are given, and the altitudinal dependence of snow storage is analyzed for the northern-alpine and inner-alpine region. The mean density of new snow is 99.2 kg/m^3 based on over 22,000 individual measurements, and it does not vary greatly with season.

The data of this measurement network form a valuable basis for the assessment of the current snow accumulation situation, and hence for the prediction of streamflow. They serve as a means to validate snow models, which, in their turn, use the standard meteorological observations. A great effort should be undertaken to continue these measurements.

Acknowledgements

The results presented here were achieved as part of the Ph. D. thesis of the first author, and the contributions of Prof. A. Ohmura, Dr. H. Keller, H. Jensen, as well as those of numerous other colleagues are gratefully acknowledged. The authors would like to thank especially those who performed, supervised and made available the results of the snow and meteorological measurements, in particular H. Siegenthaler of the Swiss Federal Institute of Technology, and the personnel of the Swiss Federal Institute for Snow and Avalanche Research and the Swiss Meteorological Institute.

References

Bader, H., Haefeli, R., Bucher, E., Neher, J., Eckel, O., and Thams, C. (1939) Der Schnee und seine Metamorphose. *Beiträge zur Geologie der Schweiz, Geotechnische Serie*, Hydrologie, Lieferung 3. Kümmerly und Frey AG, Bern, 340 p.

Bultot, F., Gellens, D., Spreafico, M., and Schädler, B. (1992) Repercussions of a CO2 doubling on the water balance – a case study in Switzerland, *Journal of Hydrology, Vol. 137*, pp. 199-208.

Church, J. E. (1957) Forecasting the summer runoff the Rhine River, IAHS Publ. No. 46, pp. 97-123.

Fahrmeir, L., and Hammerle, A. (1984) *Multivariate statistische Verfahren,* De Gruyter, Berlin, 796 p.

Hoeck, E. (1951) La prévision du débit éstivale de quelques rivières suisses par la méthode de corrélation à plusieurs variables, IAHS Publ. No. 34/3, pp. 262-274.

Hoeck, E. (1952) Der Einfluss der Strahlung und der Temperatur auf den Schmelzprozess der Schneedecke. *Beiträge zur Geologie der Schweiz*, Geotechnische Serie, Hydrologie, Lieferung 8. Kümmerly und Frey AG, Bern, 36 p. and Tables.

Hydrological Atlas of Switzerland (1992) Editor: Swiss Hydrological and Geological Survey. Map 3.3: Water equivalent of the snow cover. Authors: Rohrer, M. and Lang, H. EDMZ Vertrieb, CH-3000 Bern, ISBN 3-9520262-0-4.

Jensen, H. (1979) Statistische Untersuchung der Beziehung zwischen den Schneereserven und dem Sommerabfluss alpiner Gebiete. Festschrift für Peter Kasser, Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der ETH Zürich VAW-Mitteilungen No. 41, pp. 123-144.

Keller, H. M., Strobel, Th., und Forster F. (1984) Die räumliche und zeitliche Variabilität der Schneedecke in einem schweizerischen Voralpental, DVWK-Mitteilungen Nr. 7 (Schneehydrologische Forschung in Mitteleuropa), Bonn, pp. 257-284.

Kendall, M. G., und Stuart, A. (1966) *The Advanced Theory of Statistics*, Vol. 3: Design and Analysis, and Time-Series, Griffin, London, 552 p.

Lang, H., und Rohrer, M. (1987) Temporal and spatial variations of the snow cover in the Swiss Alps, IAHS Publ. No. 166, pp. 79-92.

Lang, H., Jensen, H., Rohrer, M. B., Steinegger, U., and Vit, J. G. (1993) Vierzig Jahre Zuflussprognosen für die Elektrizitätswirtschaft: Stand der Forschung und Ausblick, Bulletin des Schweizerischen Elektrotechnischen Vereins SEV/VSE 16/93, ISSN 036-1321, pp. 11-16.

Lepori, M. (1993) Langjährige Halbjahres-Wasserbilanzen im Einzugsgebiet des Wägitals. Berichte und Skripten Nr. 50, Geographisches Institut ETH Zürich, 97 p.

Lütschg, O. (1945) Zum Wasserhaushalt des Schweizer Hochgebirges. I. Band, 1. Teil: Allgemeines. *Beiträge zur Geologie der Schweiz*, Geotechnische Serie, Hydrologie, Kümmerly und Frey AG, Bern, 171 p.

Meister, R. (1986) Density of new snow and its dependency on air temprature and wind. In: Correction of precipitation measurements. Workshop on correction of precipitation measurements, *Zürcher Geographische Schriften*, Eidgenössische Technische Hochschule, Zürich, *Heft 23*, pp. 73-80.

Rohrer, M. B. (1992) Die Schneedecke im Schweizer Alpenraum und ihre Modellierung, *Zürcher Geographische Schriften, Heft 49*, 178 p.

Rohrer, M. B., and Braun, L. (1994) Long-term records of the snow cover water equivalent in the Swiss Alps: 2. Simulation, *Nordic Hydrology, Vol. 25*, pp. 65-78.

Steinegger, U. (1990) Niederschlagsmessung im Hochgebirge: Informationsgehalt von Totalisatoren- und Schneedaten im Limmerngebiet. Diplomarbeit am Geogr. Institut der ETH Zürich, 133 p.

Winterberichte (various years) of the Swiss Federal Institute of Snow and Avalanche Research (SLF), Weissfluhjoch-Davos.

Witmer, U. (1986) Erfassung, Bearbeitung und Kartierung von Schneedaten in der Schweiz, *Geographica Bernensia*, Bern, Band G25, 215 p.

Zingg, Th. (1951) Beziehung zwischen Temperatur und Schmelzwasser und ihre Bedeutung für Abflussfragen, IAHS Publ. No. 32, pp. 266-269.

Received: August, 1993
Accepted: 1 October, 1993

Address:
Swiss Federal Institute of Technology ETH,
Winterthurerstr. 190,
CH-8057 Zürich, Switzerland.