SEASONAL RUNOFF FORECASTS FOR HYDROPOWER
BASED ON REMOTE SENSING

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ABSTRACT

In this study, the target of seasonal runoff forecasts for April through September is the inflow into the reservoir of the Swiss hydroelectric station at Sedrun and the river flow for the run-of-the-river station at Tavanasa. The catchments are situated in the Swiss Alps at 1300-3200 m a.s.l. so that snow is an important runoff factor. Snow reserves on 1 April can be reconstituted from satellite snow cover monitoring during the snowmelt period. In real time, point measurements of the snow water equivalent on 31 March serve as indices to select a snow cover of a past year evaluated from monitoring. Based on snow reserves and expected precipitation, monthly runoff volumes are forecasted on 31 March and updated after satellite overflights. Errors in 1993 and 1994 resulted from unusually warm temperatures and heavy rainfalls at the end of the snow melt season in September. More reliable forecasts improve hydropower generation and help to achieve better prices on the electricity market.

INTRODUCTION

Winter accumulation of snow in mountain basins facilitates seasonal forecasts of runoff volumes usually for the period from April to September. Two main sources of forecast errors are: 1. Difficulties of the evaluation of snow reserves on 1 April from point measurements, and 2. Unpredictable precipitation in the summer half year. It has been recognized for decades that the areal extent of snow can improve the assessment of the seasonal snow cover. Panoramic terrestrial photographs (Potts, 1937), ground observations (Garstka et al., 1958) and air photographs (Martinec, 1973) were used to this effect. However, only the advent of satellite remote sensing made possible an efficient periodical snow cover mapping (Rango and Itten, 1976). Based on this information, examples of real-time seasonal runoff forecasts for two hydroelectric stations in the Swiss Alps are presented. This study was conducted in association with a research project "Operational monitoring and forecast of snowmelt runoff with the aid of satellite images" at the Swiss Federal Institute of Technology in Zurich.

HYDROELECTRIC STATIONS AND THEIR CATCHMENT AREAS

The power plants Sedrun and Tavanasa are situated in the Swiss Alps in the upper Rhine basin. Altitude conditions are described in Table 1.

At these altitudes, snow fortunately in some years is a more important runoff factor than the less predictable rain. Sedrun is an accumulation power plant with three artificial reservoirs totaling $152\cdot10^6$ m^3 of storage capacity and with an installed output of 150 MW.

Tavanasa is a run-of-the river power plant situated downstream with a compensating reservoir of $0.4\cdot10^6 m^3$ volume. It uses the outflow from the Sedrun station and additional runoff from the catchment area. The installed capacity is 180 MW.

RESERVOIR OPERATION

In Central Europe, the electricity consumption is higher in the winter than in the summer. The runoff in mountainous basins, however, is distributed in the opposite way because of snowmelt. In order to reduce this discrepancy, the hydroelectric station Sedrun accumulates water in the summer and adds to

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Table 1

Elevation zones of the catchment areas of the stations Sedrun and Tavanasa

Sedrun				Tavanasa			
Zone	Area km^2	Elev. Range m a.s.l.	Mean Elev. m a.s.l.	Zone	Area km^2	Elev. Range m a.s.l.	Mean Elev. m a.s.l.
				B	19.8	1277-1600	1490
C	14	1840-2100	2000	C	77.9	1600-2100	1877
D	63.2	2100-2600	2380	D	85.9	2100-2600	2323
E	30.3	2600-3210	2726	E	31.8	2600-3210	2750
	107.5	1840-3210			215.4	1277-3210	

runoff in the winter by emptying the reservoirs. These general operating rules are illustrated by a typical curve of reservoir filling in Figure 1 (Seidel et al., 1990). In stage 1, the reservoir should be filled as late as possible. At the same time, water releases through the spillway should be avoided which may occur when the inflow into a full reservoir exceeds the capacity of turbines. In stage 2, high electricity demands are met by emptying the reservoir and supplementing the flow to the turbines. In stage 3, the minimum water level in the reservoir is attained, but a necessary reserve must be maintained until the snowmelt season sets in. In stage 4, runoff increases thanks to snowmelt so that the excessive water can be stored and the reservoir gradually filled. The natural runoff regime is known from historical data. However, the snow accumulation varies from year to year and different runoff volumes are forecasted accordingly.

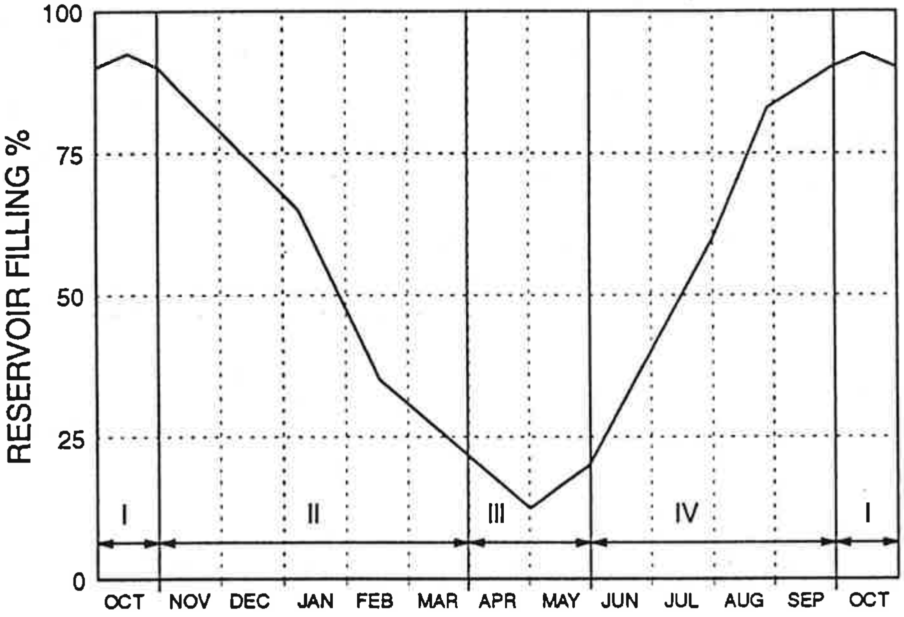

Figure 1. Typical stages of reservoir filling in a hydrological year.

As has been pointed out elsewhere (Yeh et al., 1982), timely water releases for power production based on runoff forecasts provide storage space to contain the potential spills. If the actual runoff exceeds the forecast, some spill may still occur. If the actual runoff is less than the forecast, it becomes more difficult to fill the reservoir and to maintain the minimum storage in March and April, which is necessary for avoiding a breakdown of the electricity supply.

The run-of-the river station Tavanasa cannot influence the inflow seasonally. It is, therefore, more difficult to avoid overflows of unused water over the weir. Short term runoff forecasts are carried out experimentally (Seidel et al., 1994) with the aim of reducing these losses.

Apart from improving reservoir operations, seasonal runoff forecasts provide advanced information on the future electricity production. With this knowledge, demands on the base and peak electricity supply in the national grid can be satisfied while achieving favorable prices on the international electricity market. The stations Sedrun and Tavanasa produce about $300 \cdot 10^6$kWh in the summer (Seidel et al., 1990). If $50 \cdot 10^6$kWh of the excessive summer energy can be sold for a price higher by just \$0.005/kWh, a gain of \$250,000 per year results considering just these two stations.

SNOW RESERVES FROM SNOW COVER MAPPING

Figure 2 shows an example of depletion curves of snow coverage for the Tavanasa catchment area obtained from periodical snow cover mapping by Landsat. The curves refer to the elevation zones listed in Table 1. Glaciers are responsible for the residual snow (or ice) covered area in zones D and E at the end of September.

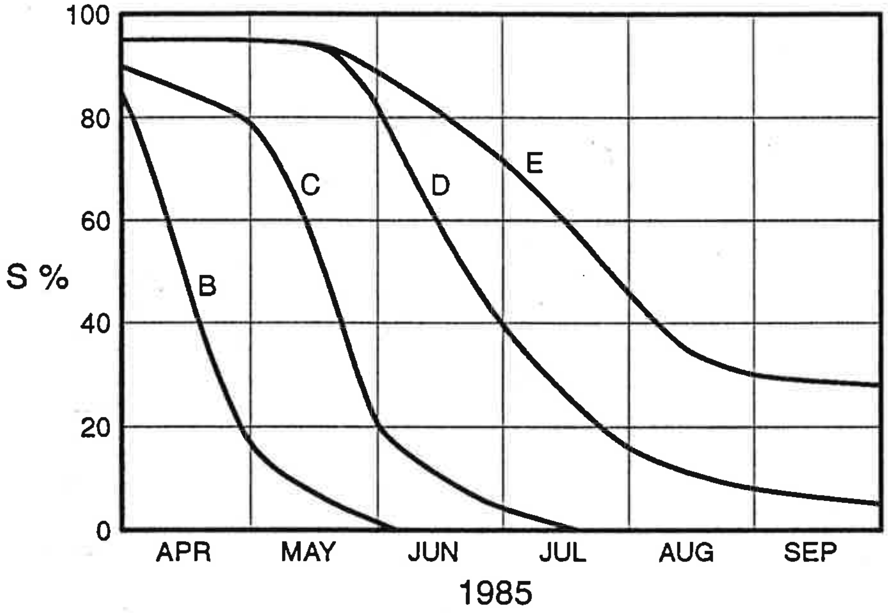

Figure 2. Depletion curves of snow coverage in the catchment area of the hydroelectric station Tavanasa for elevation zones B,C,D,E. Snow cover mapping from Landsat by the Swiss Federal Institute of Technology in Zurich.

The snow covered area S is a main input variable for the SRM snowmelt runoff model, as is evident from the following formula for a single-zone basin:

$$Q_{n+1} = (c_{Sn} \cdot a_n \cdot T_n \cdot S_n + c_{Rn} \cdot P_n) \frac{A \cdot 10000}{86400} (1 - k_{n+1}) + Q_n \cdot k_{n+1} \qquad (1)$$

where Q = computed daily discharge on n-th day [$m^3 s^{-1}$]
c = runoff coefficient expressing the losses with c_S referring to snowmelt and c_R to rain
a = degree-day factor [cm °C^{-1} d^{-1}]
T = number of degree-days [°C d] at the average hypsometric elevation of the zone
S = ratio of the snow covered area to the total area
A = area of the zone [km^2]
k = recession coefficient
$\frac{10000}{86400}$ = conversion from cm km^2 d^{-1} to $m^3 s^{-1}$
n = sequence of days

A detailed description is given in the SRM User's Manual (Martinec et al., 1994).

By substituting snow covered areas in the respective elevation zones (Figure 2) plus measured temperatures and precipitation into the SRM model, runoff can be simulated as shown in Figure 3. Incidentally, a SRM runoff simulation from a past year was used in Japan as a forecast in real time for optimizing the water level in a reservoir (Kawata and Kusaka, 1988). The computed runoff volume from April through September is only about 3% higher than the actual value. Of course, a comparable accuracy cannot be expected for real-time runoff forecasts. Instead of a complete set of measured input variables, only forecasted or estimated temperatures and precipitation are then available. Snow covered areas have to be projected according to temperature forecasts and updated after each satellite overflight.

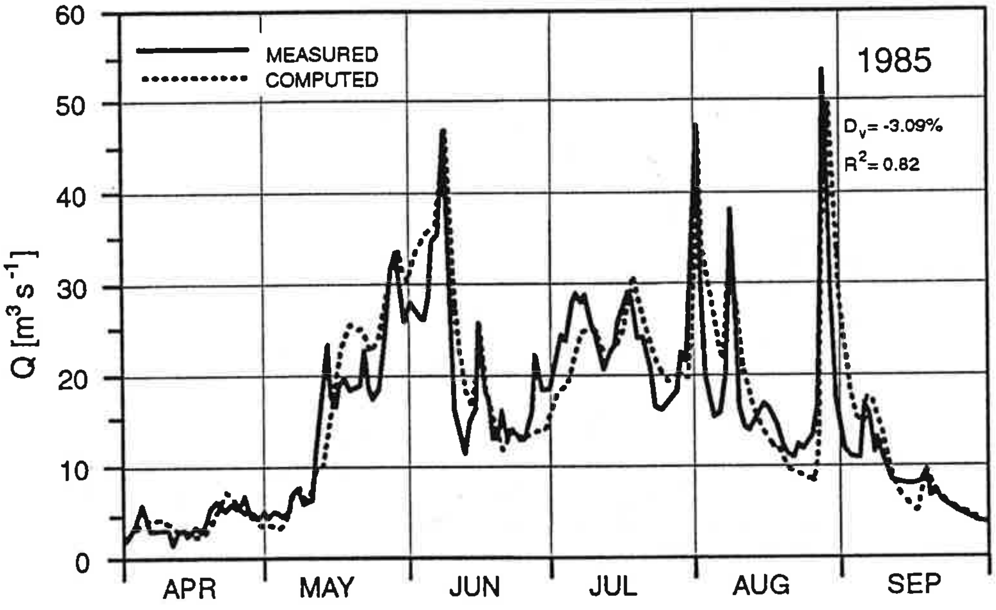

Figure 3. Example of a runoff simulation for the hydroelectric station Tavanasa by the SRM model using snow covered areas in Figure 2 (Seidel et al., 1989).

At the same time, a high coefficient of determination (R^2=0.82) confirms that the preselected model parameters agree with hydrological conditions in the given basin. Some of the parameters (a, c_S,c_R) can then be used with more confidence for real-time runoff forecasts.

As a first step, conventional depletion curves (CDC) shown in Figure 2 can be converted to so called modified depletion curves (MDC) by replacing the time scale with cumulative snowmelt depths (Martinec and Rango, 1987). Figure 4 shows a modified depletion curve derived from the CDC for zone C in Figure 2. Snowmelt depths are computed as the product of model degree-day factors and degree-days measured each day. Degree-days necessary to melt new snow falling during the snowmelt season are excluded from the total melt. For example, a total snowmelt depth ΣM = 75 cm is computed by 29 May, including 3 cm melt depth of new snow. Then $\Sigma M - \Sigma M_{NEW}$ = 72 cm and the corresponding snow coverage from CDC (Figure 2) S = 20%. In this way, all points are automatically plotted by the SRM computer program. MDC_{EXCL} indicates which total snowmelt depth is necessary to decrease the areal extent of the snow cover which existed on 1 April to a given percentage. The area below the curve corresponds to the average areal water equivalent (HW) of the seasonal snow cover on 1 April. The rectangle in Figure 4 indicates HW = 8 cm and the curve indicates HW = 40.8 cm. The water volume stored in the snow cover on 1 April is 77.9 km² x 0.408 m = 31.78 · 10^6 m³. Because the snowmelt depths are computed from the measured degree-days, the accuracy of these results depends on a good assessment of degree-day ratios. Deviations from actual melt depths which may occur on single days are cancelled out in a longer computation period. Also, a good model performance in the simulation mode (Figure 3) confirms that reasonable degree-day ratios have been used.

Similarly as with the runoff simulation, this result is obtained only after the end of the snowmelt season so that it cannot be directly used for real-time runoff forecasts. However, together with results from other years, it can improve the evaluation of snow reserves in a current year.

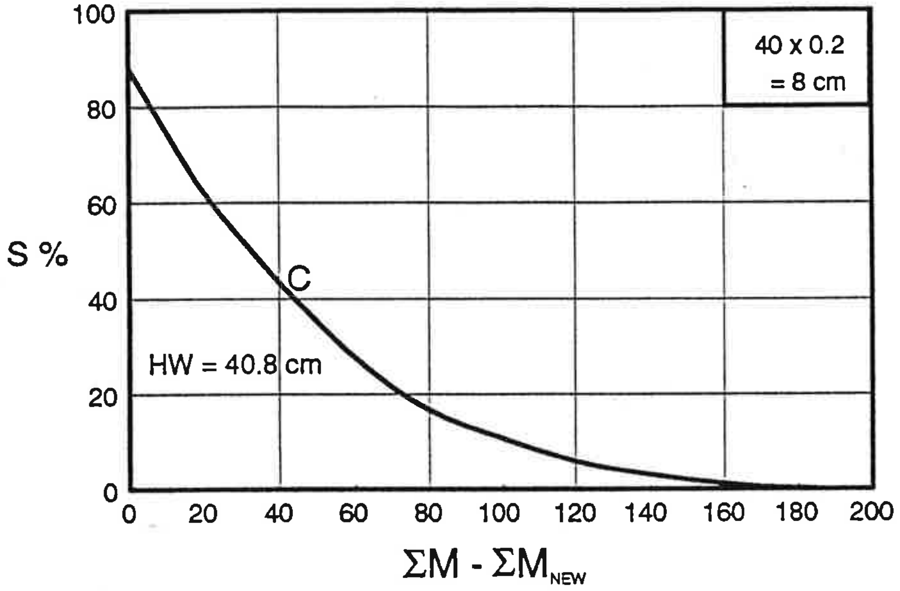

Figure 4. Modified depletion curve for the elevation zone C, Tavanasa, derived from the conventional depletion curve C in Figure 2. The curve indicates the areal average water equivalent of the snow cover on 1 April 1985.

SEASONAL RUNOFF FORECASTS

The first experimental forecast of the runoff volume to be expected from April through September 1993 was given to the Electric Company of North-East Switzerland on 1 April 1993. There is no snow gauging station in the catchment areas of Sedrun and Tavanasa. The nearest station, Sedrun, is at a low elevation (1420 m a.s.l.) and reported on 1 April a snow depth of 20 cm, with no measurement of the water equivalent. The only station at an adequate altitude, Weissfluhjoch, 2540 m a.s.l. situated about 85 km eastwards, reported on 31 March 1993 a snow water equivalent HW = 72.5 cm. This indicated a similar snow accumulation (with a greater altitude gradient) as in 1985, for which year the areal water equivalents in the respective elevation zones had been evaluated from MDC curves (Martinec et al., 1991). The values are listed in Table 2.

Table 2

Areal water equivalents HW of snow cover on 1 April 1993

Elev. zone	From satellite snow cover mapping 1985 Tavanasa + Sedrun cm	Estimate on 1 April 1993 Sedrun cm	Estimate on 1 April 1993 Tavanasa cm
B	29.5	--	20
C	40.8	50	40
D	93.0	95	90
E	127.6	135	135
Total Area	80.9	100.4	72.1

Slightly higher water equivalents in Sedrun than in Tavanasa were assumed because of the higher Sedrun mean hypsometric elevations in the zones C and D.

In the absence of long-term precipitation forecasts, average amounts were assumed (comparable with the year 1985) from stations Weissfluhjoch (2540 m a.s.l) and Tavanasa (800 m a.s.l.), taking into account the altitude gradient.

The runoff volume in April - September is obtained as follows:

$$R = (HW \cdot c_S + P \cdot c_R) \cdot A \qquad (2)$$

where R is the forecasted runoff volume $[m^3 \cdot 10^6]$
HW is the average areal water equivalent on 1 April [m]
P is the expected precipitation in April-September [m]
A is the catchment area $[km^2]$
c_S, c_R are runoff coefficients for snow and rain expressing the losses.

The runoff coefficients ($c_S = 0.9$, $c_R = 0.75$ for Tavanasa and $c_R = 0.8$ for Sedrun) were taken over as seasonal average values from SRM runoff simulations. With P = 75 cm for Tavanasa and P = 80 cm for Sedrun, the forecasted runoff volumes are listed in Tables 3 and 4. Monthly runoff volumes (originally not communicated) are evaluated from the forecasted totals by long term average proportions in percent.

Table 3

Runoff volumes forecasted for Tavanasa on
1 April 1993 $[m^3 \cdot 10^6]$

	Measured			Forecasted	
	Month	Total	%	Month	Total
April	12.78	12.78	5	13.06	13.06
May	42.66	55.44	7	44.4	57.46
June	61.55	116.99	25	65.3	122.76
July	46.24	163.23	25	65.3	188.06
August	36.09	199.32	17	44.4	232.46
September	46.94	246.26	11	28.73	261.19

Table 4

Runoff volumes forecasted for Sedrun on
1 April 1993 $[m^3 \cdot 10^6]$

	Measured			Forecasted	
	Month	Total	%	Month	Total
April	4.40	4.40	2.5	4.15	4.15
May	28.29	32.69	13.5	22.40	26.55
June	48.21	80.9	29	48.12	74.67
July	28.27	109.17	28	46.46	121.13
August	17.67	126.84	16	26.55	147.68
September	40.10	166.94	11	18.26	165.94

After Landsat and SPOT overflights in June, the snow cover was mapped and the MDC curve, provisionally used for the evaluation of snow reserves, was updated. It appeared that the areal snow water equivalents (see Table 2) had been overestimated by using the Weissfluhjoch measurement as an index. The forecasted runoff volume was, therefore, reduced by 20% for Tavanasa to $208 \cdot 10^6 m^3$ and by 17% for Sedrun to $137.5 \cdot 10^6 m^3$.

As illustrated in Figures 5 and 6, the original forecast actually agrees better with the total measured runoff than the revised forecast. This is, however, due to abnormally high precipitation (803 mm in Tavanasa instead of an average of 593 mm), particularly in September.

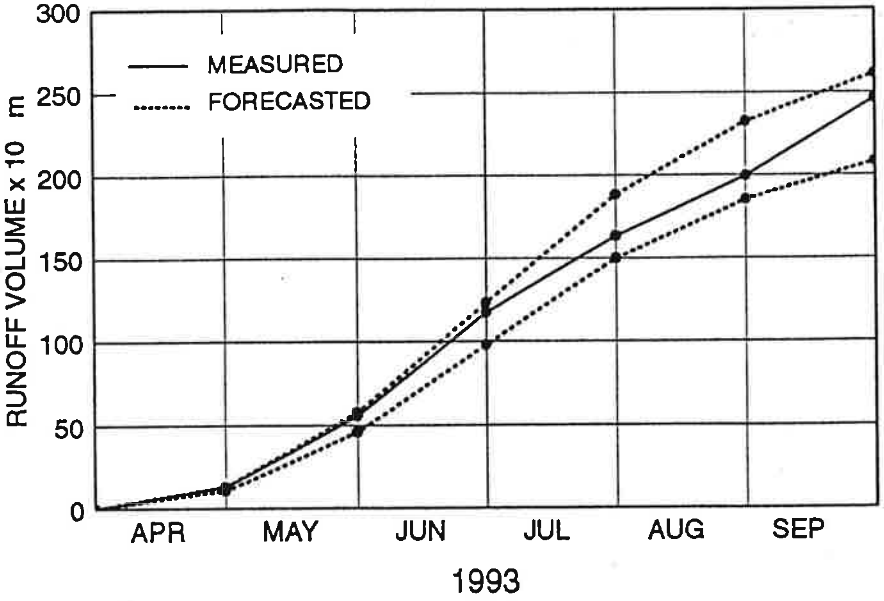

Figure 5. Initial (high) and updated (low) forecast of cumulative runoff volumes for the station Tavanasa compared with the measured runoff.

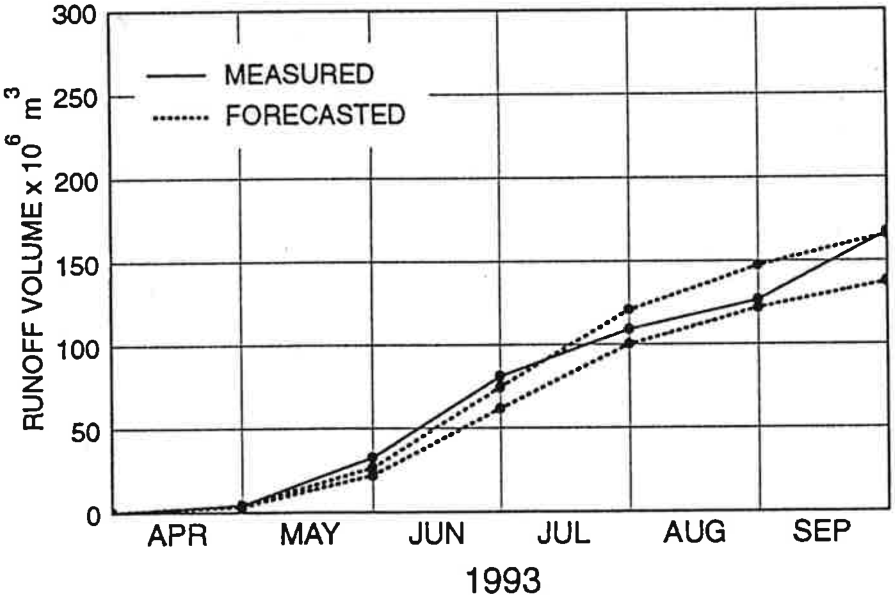

Figure 6. Initial (high) and updated (low) forecast of cumulative runoff volumes for the station Sedrun compared with the measured runoff.

The uncertainty caused by precipitation was taken into account in 1994 forecasts. According to the frequency analysis of precipitation totals from April through September measured at the station Weissfluhjoch, 86.5% of the normal value is assured with a probability $p = 0.9$ and 120.7% with a probability $p = 0.1$. Precipitation at Tavanasa may have a different range but in the absence of sufficient data, the result from Weissfluhjoch is used to illustrate the method. Concerning the snow component, a narrower margin of error was assumed amounting to ±10%.

At the end of March 1994, the measured snow water equivalent at Weissfluhjoch, HW = 70 cm, indicated snow accumulation similar to 1985. However, snow cover mapping in late March revealed a decline of snow covered areas due to warm weather in the Tavanasa and Sedrun catchments. The MDC curve used for the evaluation of snow reserves in 1993 was decreased according to snowmelt depths before 1 April. Estimated snow water equivalents are listed in Table 5.

Table 5

Estimated areal water equivalents, HW, of snow cover on 1 April 1994

Elevation zone	Sedrun cm	Tavanasa cm
B	--	4
C	36	30
D	80	80
E	115	115
Total area	84	60

Expected precipitation for the Tavanasa and Sedrun catchments were evaluated from the average amount of the Tavanasa station with the respective coefficients reflecting the altitude gradient:

Tavanasa: 59.33 cm x 1.3 = 77.13 cm
Sedrun: 59.33 cm x 1.43 = 84.84 cm

Runoff volumes were computed by Eq. (2) with the same runoff coefficients as in 1993. With regard to the mentioned range of precipitation and of the snow water equivalent, three forecasts results:

Normal forecast Tavanasa: $R = 241.0 \cdot 10^6 m^3$
High forecast: $P \cdot 1.207, HW \cdot 1.1$: $R = 278.3 \cdot 10^6 m^3$
Low forecast: $P \cdot 0.865, HW \cdot 0.9$: $R = 212.4 \cdot 10^6 m^3$

Measured $R = 282 \cdot 10^6 m^3$

Normal forecast Sedrun: $R = 154.9 \cdot 10^6 m^3$
High forecast: $P \cdot 1.207, HW \cdot 1.1$: $R = 177.6 \cdot 10^6 m^3$
Low forecast: $P \cdot 0.865, HW \cdot 0.9$: $R = 136.4 \cdot 10^6 m^3$

Measured $R = 185.9 \cdot 10^6 m^3$

Cumulative runoff volumes according to measurements and forecasts are shown in Figures 7 and 8.

The forecasted monthly subtotals have been evaluated in the same way as in Tables 3 and 4. The average monthly distribution of runoff implies average temperatures. In 1994, however, temperatures in April through September were on the average by 1.6°C higher and therefore, since May, the measured runoff is ahead of forecasts.

The total seasonal runoff is higher than the forecasts for the following reasons:

1. Due to extremely high temperatures in July and August (+4.1°C and +2.7°C above the normal at the station Disentis) runoff from snowmelt and precipitation was increased by glacier melt.

2. Local precipitation of the catchment areas might have been higher than amounts extrapolated from the station Tavanasa. In September, the forecast was based on the average precipitation of 10.65 cm, extrapolated to 15.2 cm for the Sedrun catchment area. Actual measured amount was 16.6 cm, amounting to 23.7 cm by extrapolation. The measured runoff depth was even higher, 30.5 cm.

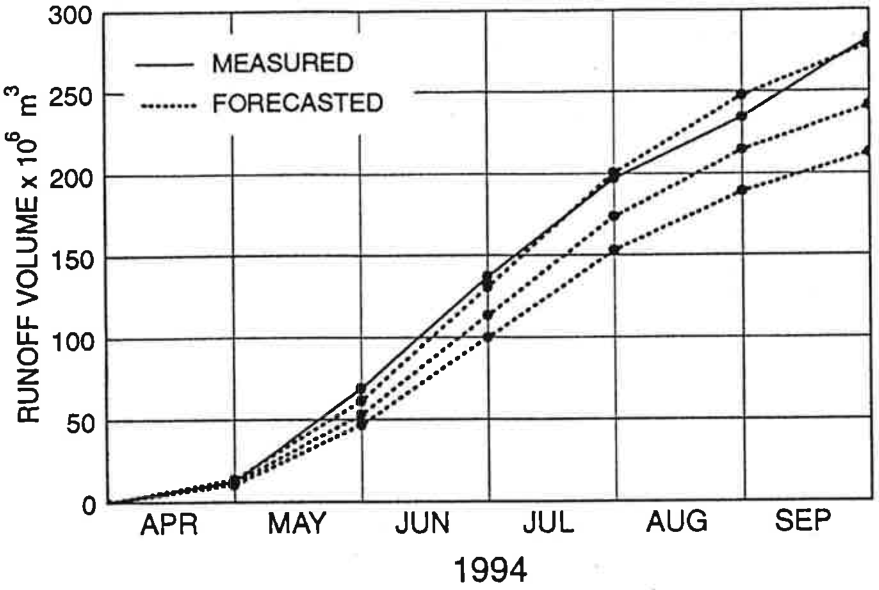

Figure 7. Medium, minimum, and maximum forecasts of cumulative runoff volumes for the station Tavanasa compared with the measured runoff.

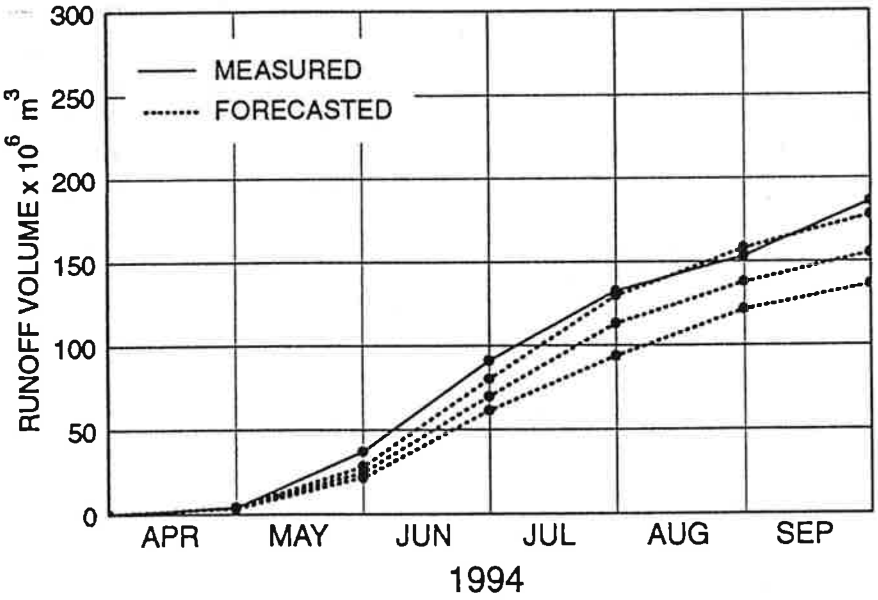

Figure 8. Medium, minimum, and maximum forecasts of cumulative runoff volumes for the station Sedrun compared with the measured runoff.

3. Snow reserves on 1 April 1994 may have been slightly underestimated.

Leaving aside the updating in 1993 and subsequent statistical alternatives in 1994, the deviations of forecasts issued at the beginning of the snowmelt season from the measured runoff volumes are as follows:

	Forecast of 1 April 1993	Forecast of 31 March 1994
Tavanasa	+6%	-14.5%
Sedrun	-0.6%	-16.7%

The initial overestimation of snow reserves in 1993 was compensated by heavy rainfalls while the results for 1994 were compromised by glacier melt due to high summer temperatures, as well as by heavy local rainfalls in September. Recalling Figure 1, the unexpected runoff in September should be taken into account by short term forecasts based on temperature and precipitation forecasts.

CONCLUSIONS

The scatter of seasonal runoff forecasts for hydropower in mountain basins can be narrowed by a proper assessment of the snow component, particularly in years with extremely high or low accumulation of snow.

In alpine catchment areas like those of the hydroelectric stations Sedrun and Tavanasa, remote sensing can improve a quantitative evaluation of snow reserves on 1 April which is not possible from the normal snow gauging network. Periodical snow cover mapping by satellites from past snowmelt seasons and updating from snow cover monitoring in the forecast year serves this purpose as demonstrated by experimental real-time forecasts in 1993 and 1994. Snowmelt runoff simulations improve the knowledge of parameters to be used for computing seasonal runoff volumes from areal snow water equivalents and precipitation.

The advantages of this approach could not be fully demonstrated in the years 1993 and 1994 because the snow accumulation was not far from normal, while rainfalls in certain months were heavy and the water balance in 1994 was influenced by glacier melt due to extremely high summer temperatures.

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