REMOTE SENSING OF SNOW COVER FOR OPERATIONAL FORECASTS*

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ABSTRACT

The areal extent of the seasonal snow cover is an important input variable for operational snowmelt runoff forecasts. It can be monitored by satellites and used by the SRM Snowmelt Runoff Model. An example is presented of simulated day-to-day runoff forecasts for a hydroelectric station Sedrun (108 km^2, 1840-3210 m a.s.l.). For realtime runoff forecasts it will be necessary to evaluate the satellite data within several days after each overflight.

1 INTRODUCTION

When the remote sensing technology became available for earth sciences some 20 years ago, it was first necessary to explore possibilities in potential fields of application and to devise appropriate sensors. Since then, spectacular results have been achieved, to be admired at wall calendars, but not very frequently as direct benefits in terms of money. The operation of earth observing satellites has been put to a commercial base, emphasizing further the need for operational applications with a favourable cost-benefit relation.

Monitoring of the seasonal snow cover in the visible range was from the start considered as a promising target. The snow accumulation in the mountains during each winter is an important source of renewable energy. The Institute of Communication Techniques at the Zurich Institute of Technology advocates the multidisciplinary approach. In the stage of snowmelt runoff simulations from historical data, it consisted in cooperation with hydrologists, who were wiling to use satellite data. For operational applications, that is to say for real time forecasts of the river flow power plants, it was further necessary to awake interest of hydroelectric companies.

A cooperative project envisages operational forecasts for 7 days of daily flows as well as of seasonal runoff volume for the Electric Company of North-East Switzerland. To this effect, Landsat, NOAA and SPOT data must be obtained as quickly as possible after each relevant overflight and without logistic delays. The Snowmelt Runoff Model (SRM), which uses satellite data as input variable, will also require short-term temperature forecasts and at least estimates of expected precipitation amounts. Thanks to these runoff forecasts, a higher electricity production can be achieved by avoiding overflow of unused water and generally a better position of the Electric Company can be assured on the electricity market.

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2 SNOW COVER MONITORING BY SATELLITE REMOTE SENSING

In mountain areas, snow accumulates in winter and becomes an important runoff factor in the subsequent months. During the snowmelt period, the areal extent of the seasonal snow cover gradually decreases. The daily meltwater volume is directly affected by the snow covered area as is evident from the following simple relation:

$$V_M = M \cdot S \cdot A$$

where

- V_M meltwater volume [$m^3 10^4$]
- M snowmelt depth computed by temperature (degree-day method) or by a more refined energy balance [cm]
- S snow covered area relative to total area
- A total area [km^2]

An efficient monitoring of the seasonal snow cover is possible only by satellite remote sensing. While the microwave methods are still in the experimental stage, snow cover mapping by sensors in the visible range is carried out already for some time in many parts of the world. If a limited accuracy and spatial resolution are acceptable, it could be even considered as operational (Schneider, 1980), that is to say serving decisions regarding the water management in real time. Table 1 lists the capabilities of various satellites which are presently in orbit.

Table 1 Characteristics of satellites for snow cover mapping

Satellite	Channels	Spectral Resolution	Repetition Rate	Track/Frame	Country
NOAA-AVHRR	5	1km x 1km	~24 h	3000 km	USA
Landsat-MSS	4	59m x 79m	16 d	185 km x 185 km	USA
Landsat-TM	7	30m x 30m	16 d	185 km x 185 km	USA
SPOT-XS	3	20m x 20m	26 d	60 km x 60 km	France
SPOT-Pan	1	10m x 10m	26 d	60 km x 60 km	France
MOS-MESSR	4	50m x 50m	17 d	100 km x 100 km	Japan
IRS-LISS	4	50m x 50m	22 d	100 km x 100 km	India

By way of example, Figure 1 shows periodical snow cover mapping in the Rhine-Felsberg basin (3250 km^2, 560-3614 m a.s.l.) and the gradual decrease of the snow covered area. In Figure 2, depletion curves of the snow coverage are derived separately for the elevation zones A (560 - 1100 m), B (1100 - 1600 m), C (1600 - 2100 m), D (2100 - 2600 m) and E (2600 - 3614 m), as required for snowmelt runoff computations. The curve for the zone E does not reach zero because of glaciers.

For operational snow cover mapping, it is necessary to replace satellites when their life time expires or to ensure an adequate alternative. Continuity is thus essential for financial exploits. At the same time, there are still problems to be solved by further research, in particular the interference of clouds. Another requirement for operational snow cover mapping is a speedy transmission and evaluation of satellite data. Runoff forecasts need snow covered areas to be determined within several days after each satellite overflight and data acquisition.

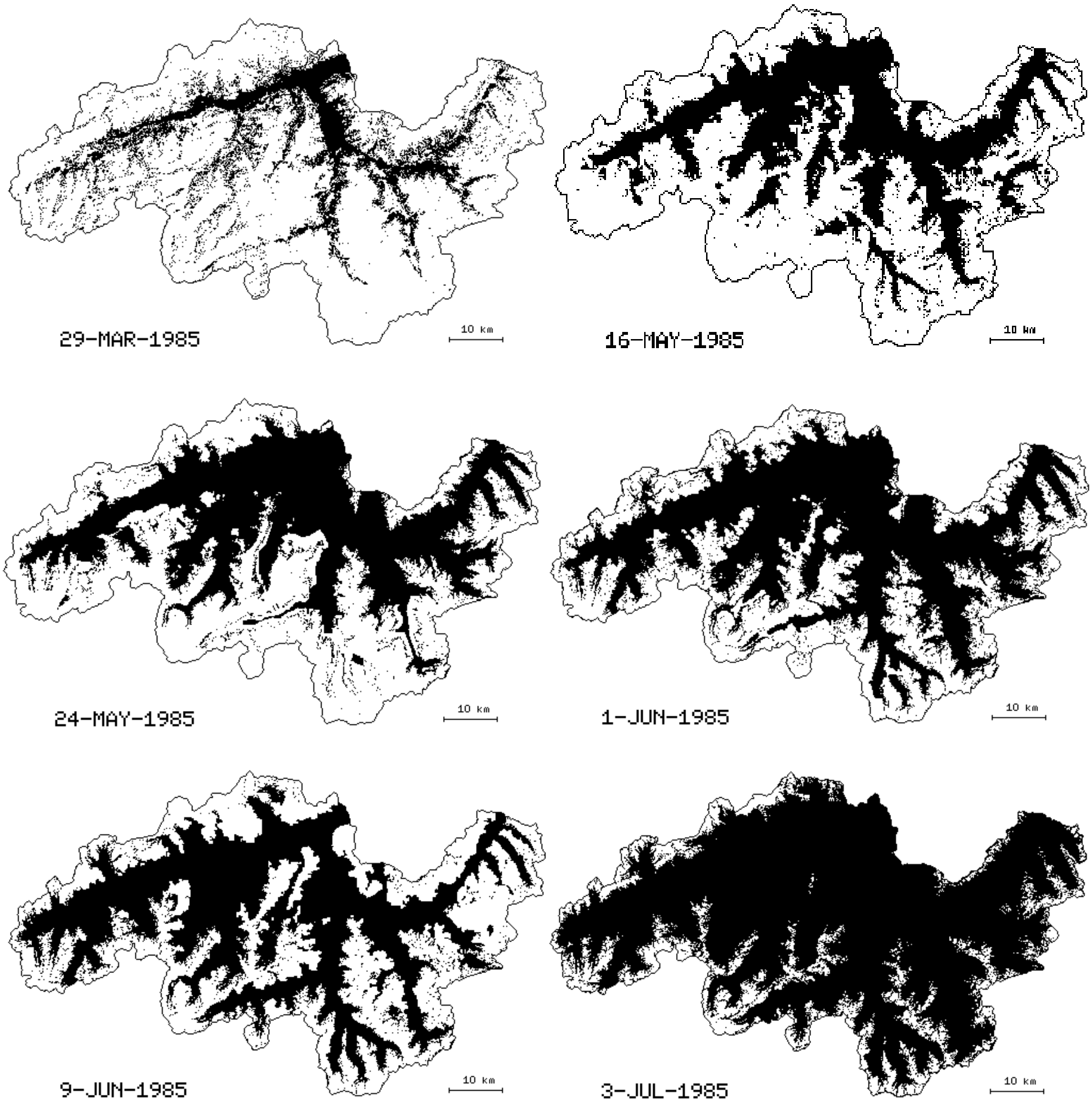

Figure 1 Gradual decrease of snow covered area in the Rhine-Felsberg basin (3250 km^2, 560-3614 m a.s.l.) for the season 1985 derived from Landsat-MSS data.

Legend: black snowfree
white snow covered
gray cloud covered

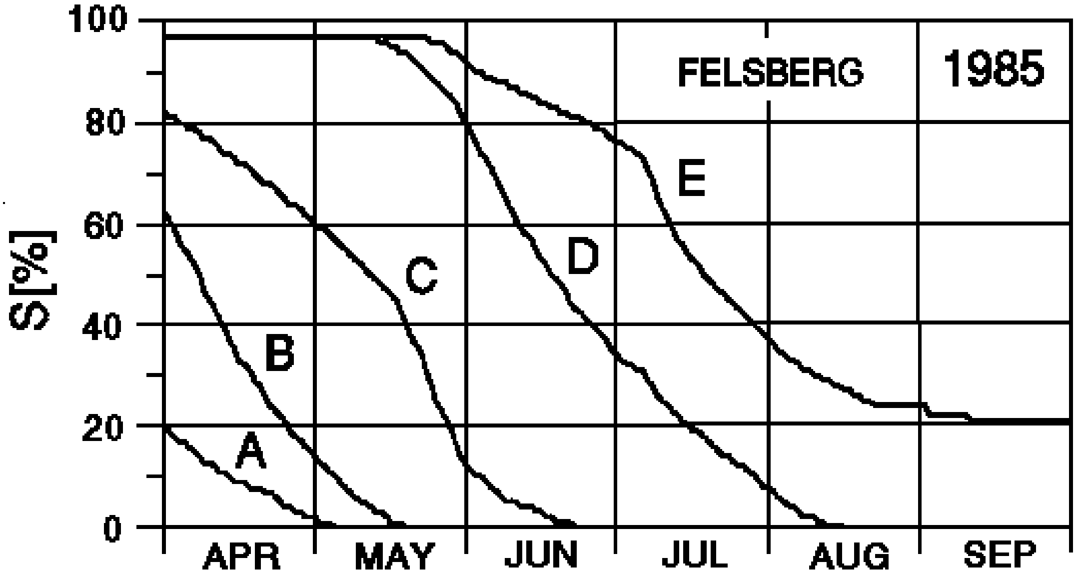

Figure 2 Depletion curves of the snow coverage S for the elevation zones A, B, C, D, and E derived from the snow cover mapping in Figure 1.

In 1979 - 1983, the World Meteorological Organisation conducted tests of snowmelt runoff models (WMO, 1985). Out of 10 participating models, only one (the SRM model) was designed to use the snow covered area as a measured input variable. This proved to be a decisive advantage in basins with available remote sensing data, but disadvantage in basins without such data.

This disadvantage is diminishing thanks to the expansion of snow cover mapping in new areas, including developing countries. The advantage (a better model accuracy) should be extended from the stage of runoff simulations using historical data to real time runoff forecasts by "operationalizing the remote sensing".

3 RUNOFF SIMULATIONS USING SNOW COVER MAPPING

The role of snow cover mapping in the SRM model is illustrated by Figure 3. For day-to-day runoff computations, the snow covered area is read off the depletion curves such as those shown in Figure 2. The other variables are the air temperature and precipitation. The SRM formula and the parameters have been described on earlier occasions (for example Martinec and Rango, 1986).

The Electric Company of North-East Switzerland (NOK) requires runoff forecasts for improved operation of two hydroelectric stations in the Felsberg basin. As an example of model test runs, Figure 4 shows a runoff simulation for the catchment area of the station Tavanasa (215 km^2, 1277 - 3210 m a.s.l.) (Seidel et al., 1989). The daily snow covered areas were obtained from the depletion curves which were derived from satellite snow cover mapping similarly as the curves in Figure 2. Temperatures and precipitation amounts were measured at the station Disentis (1170 m a.s.l.). In line with deterministic character of the SRM model, the values of the parameters (runoff coefficients for rain and snow, degree-day factor, temperature lapse rate, critical temperature for distinguishing between rain and snow, time lag and recession coefficient) were predetermined by

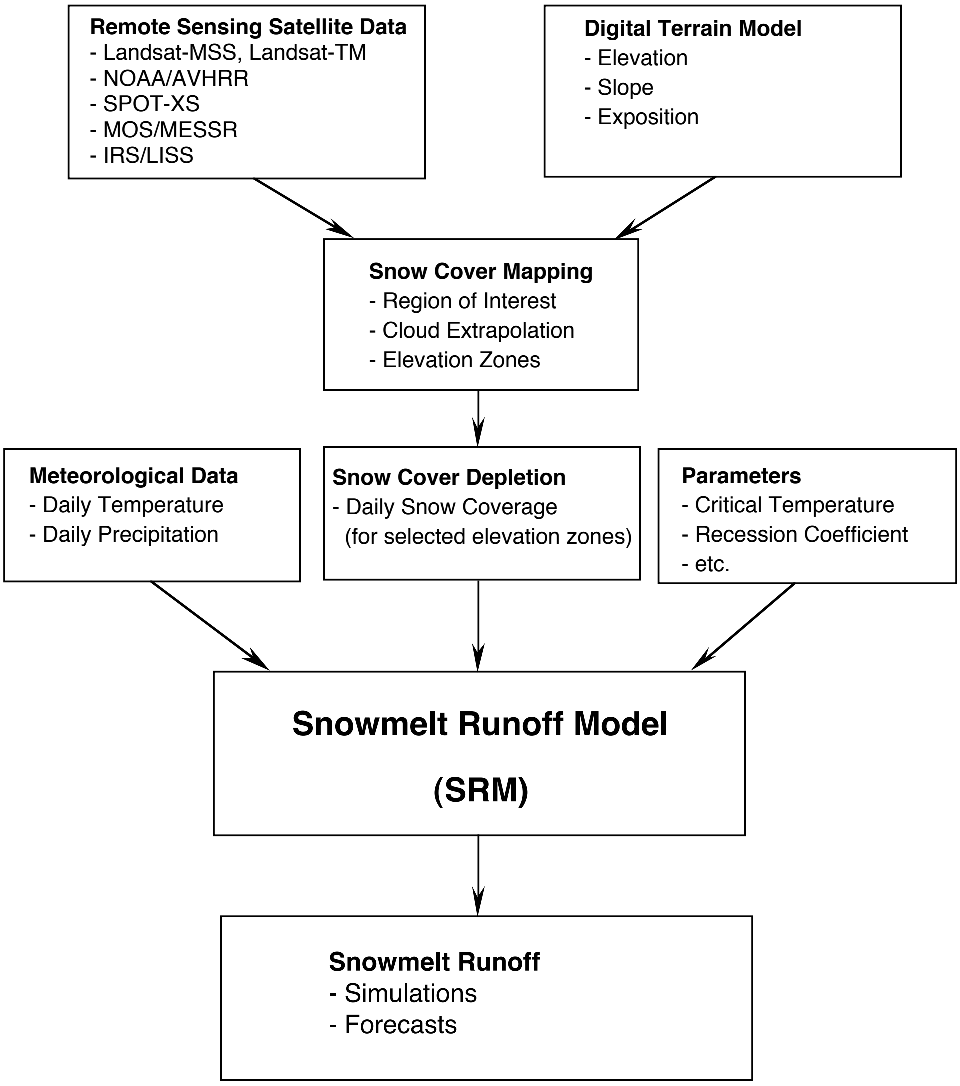

Figure 3 Flow chart for Snowmelt Runoff Modelling

hydrological judgement as explained elsewhere (Martinec and Rango, 1986), taking into account the characteristics of the basin. A visual inspection of the measured and computed hydrographs in Figure 4 reveals a good agreement. Two statistical criteria of accuracy, D_V and R^2, have been evaluated:

$$D_V \; [\%] = \frac{V - V'}{V} * 100$$

where D_V is the volume deviation
V is the measured runoff volume
V' is the computed runoff volume

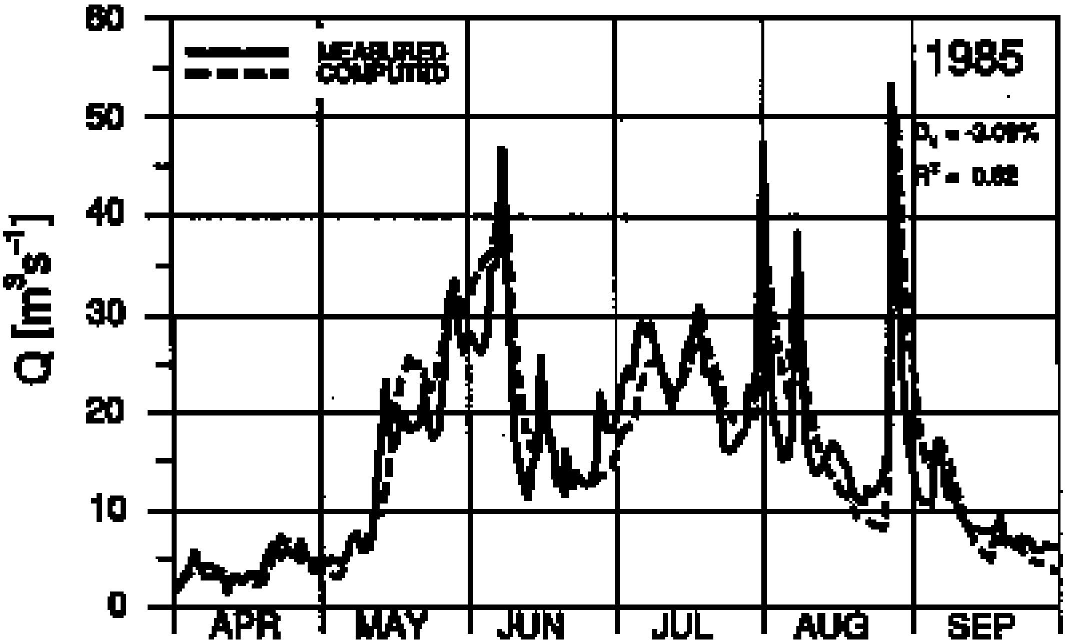

Figure 4 Computed and measured discharge from the catchment area of the hydroelectric station Tavanasa. D_V = difference of the total runoff volume, R^2 = coefficient of determination.

In the given example, D_V = -3,09% which means that the total runoff in the summer half year has been slightly overestimated. It would be possible to achieve an even better agreement by optimising the model parameters. This is not done because it would mean to give up the advantages of the deterministic approach of the SRM model. These advantages consist for example in the capability to compute runoff in basins without long histories of measurements encountered in developing countries:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2}$$

where R^2 is a measure of model efficiency
Q_i is the measured daily discharge
Q'_i is the computed daily discharge
$\overline{Q}$ is the average measured discharge
n is the number of daily discharge values (n = 183 in the given case)

The resulting $R^2 = 0,82$ means that 82% of the daily runoff fluctuations were simulated by the model.

This example, as well as hundreds of other applications by various SRM users, indicate that it is possible to simulate daily runoff fluctuations as well as the seasonal runoff volume by using periodical snow cover mapping, without direct ground measurements of the snow water equivalent. A further step is a transition from simulations using historical data towards operational runoff forecasts.

4 OPERATIONALIZATION OF SNOWMELT RUNOFF SIMULATIONS

Electric Companies require runoff forecasts for the operation of reservoirs as well as for run-of-river power plants.

4.1 Seasonal forecasts of the runoff volume

Snow reserves accumulated in winter in mountain basins contribute by a major proportion to the runoff during snowmelt season. Terrestrial point measurements of the snow water equivalent are however not sufficient to evaluate the water storage in the snow cover. Areal average water equivalents of the seasonal snow cover can be determined from the so called modified depletion curves of the snow coverage (Martinec 1985, Hall and Martinec 1985). These curves are derived from the conventional depletion curves, which are shown in Figure 2, as follows: while the conventional curves indicate the decrease of the snow covered area in time, the modified curves are obtained by plotting the snow covered area against the cumulative snowmelt depths computed each day from the measured degree-days. An example of these curves is shown in Figure 5.

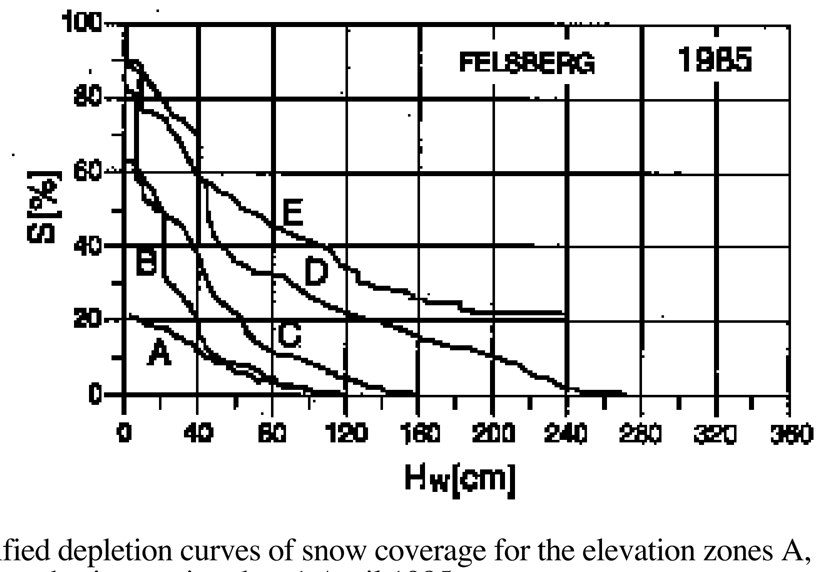

Figure 5 Modified depletion curves of snow coverage for the elevation zones A, B, C, D, E of the Felsberg basin, starting date 1 April 1985.

Snowfalls during the snowmelt season are eliminated, that is to say the degree-days necessary to melt each new snow are excluded in computations of the cumulative snowmelt depth.

Consequently, the water storage in snow on 1 April, which was selected as starting date, is directly proportional to the area below each curve. This result is available at the end of the snowmelt season, which is of course too late for real time forecasts. For this purpose, a set of modified depletion curves must be derived such as shown in Figure 6. The points refer to the cumulative snowmelt depth (new snow excluded) one month after the starting date, which was in this case 1 May, and to the corresponding snow covered areas. If, in a forecast year, the cumulative snowmelt depth reaches for example 30 cm and the snow coverage at the same time decreases to 50%, the modified depletion curve which indicates the initial water equivalent of 35 cm can be identified for that year. In 1970, the total water equivalent of melted new snow slightly exceeded the total melt depth of the snow cover of 1 May so that a negative x-coordinate results. In such a year it is difficult to identify the proper depletion curve within a few weeks. However, a correlation can be derived between the areal water equivalents from snow cover mapping and point measurements from a reliable station. The point measurements can be used as an index to accelerate the decision. For example, stationWeissfluhjoch (2540m a.s.l.) measured 1192 mm of water equivalent on 1 May 1970 and only 621 mm on 1 May 1971, which would have helped at once to select the proper modified depletion curve.

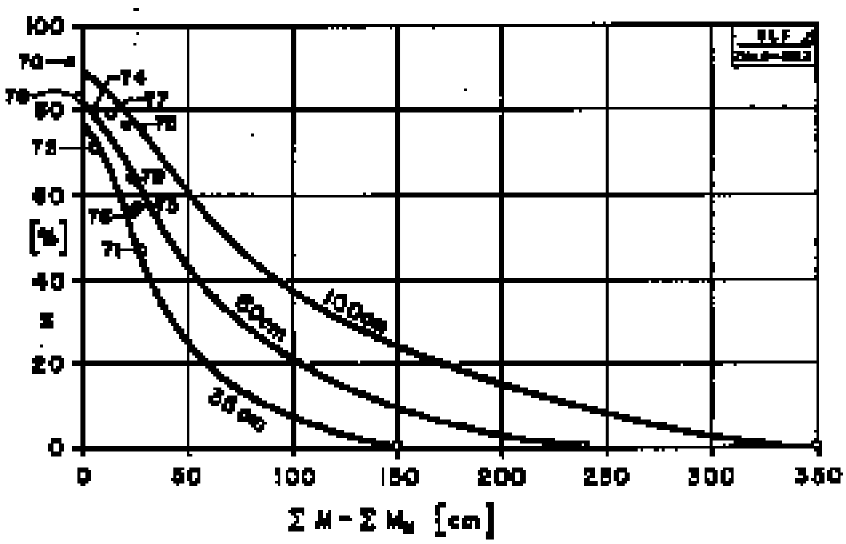

Figure 6 Nomograph of modified depletion curves for the elevation zone 2100-2600 m a.s.l., 24.5 km^2, of the Dischma basin in the Swiss Alps. The curves are labelled with the average areal water equivalent of snow on the starting date 1 May. the position of points for the respective years indicate different snow reserves on 1 May.

In the cooperative project with the Electric Company of North-East Switzerland, it will be necessary to derive sets of modified depletion curves for the catchment areas of the hydroelectric stations in order to forecast the seasonal runoff volume in the early stages of the snowmelt season.

4.2 Short-term runoff forecasts

Forecasts of daily flows always for the next 7 days are envisaged in the mentioned cooperative project. In contrast to runoff simulations, the input variables of the SRM model, snow covered

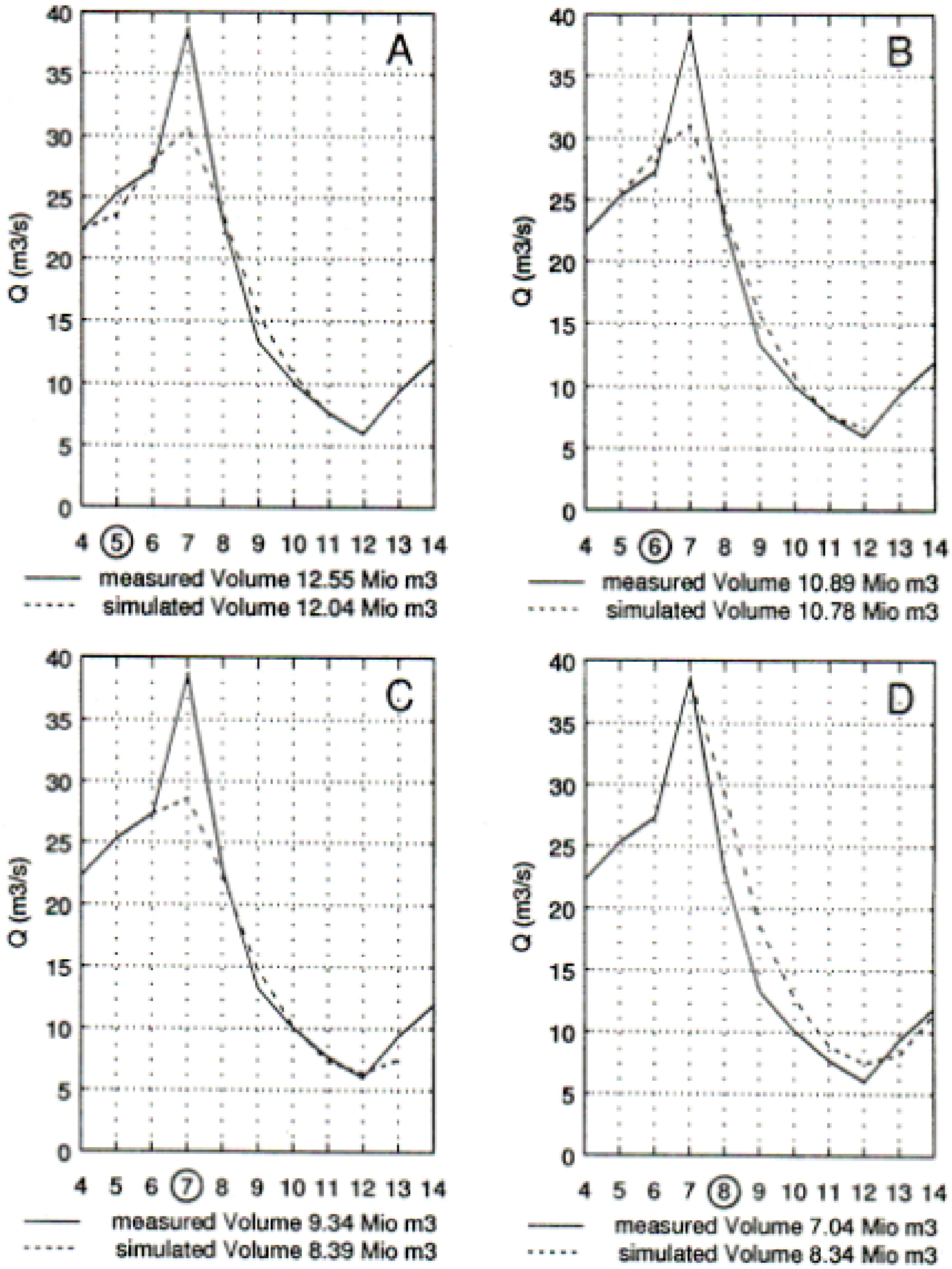

Figure 7 Simulated short term forecasts for the hydroelectric station Tavanasa.

area, temperature and precipitation, will not be available as historical data but must be forecasted as well.

The depletion curves of the snow coverage can be projected several days ahead by using temperature forecasts and modified depletion curves, as explained elsewhere (Martinec, 1985). Temperature forecasts will be provided by the Swiss Meteorological Office in Zurich. Quantitative precipitation forecasts are very difficult but it is hoped to obtain at least amounts in a certain range to be expected with a certain probability.

Figure 7 shows an example of simulated (because historical data are used) short-term runoff forecasts for the hydroelectric station Tavanasa. A period of sharp hydrograph fluctuations was selected. On 4 June 1985, the last known discharge of 3 June, the temperature, precipitation and snow covered area of 4 June are used to compute the runoff on 4, 5, 6, 7, 8, 9 and 10 June. On 5 June, the known discharge of 4 June is used together with temperature, precipitation and snow covered area of 5 June for the simulated 7 day forecast. In this way, the starting date is always moved one day ahead.

In the real case, possible errors in meteorological forecasts will affect the accuracy of runoff forecasts. On the other hand, revised forecasted values will be currently taken into account for up-dating of runoff forecasts.

4.3 Predictions of runoff regimes in a changed climate

Apart from runoff forecasts, snow cover mapping can be used for predictions (not forecasts, because the time is not specified) of changes in the runoff regime due to global warming. The SRM PC-program (Martinec et al., 1992) is now equipped with a climate change feature which enables the depletion curves of snow coverage to be shifted in time according to an assumed change of temperature and precipitation. With the climate-adjusted snow covered areas the redistribution of runoff during the snowmelt season can be computed. The redistribution of runoff between the winter and summer half year can be also evaluated which is of special importance to the hydropower industry. These assessments require no special speed of snow cover mapping because the runoff regime of the present times are remodelled by an assumed climate scenario to the expected snow cover conditions and runoff to be expected in the next century.

5 ECONOMICAL BENEFIT OF SNOWMELT RUNOFF FORECASTS

In order to prove an economical benefit, it is not sufficient to say that runoff forecasts are useful for electricity production, or that the damage from floods is great. Water power can be generated without runoff forecasts and such forecasts are even possible without remote sensing. The question is, how the forecasts can be improved by remote sensing data.

In an American study (Castruccio et al., 1980), a relative forecast improvement of 6% by operational satellite measurement of snow covered areas was used in computer benefit models. The benefit for hydroelectric production in the western United States, in basins with operational snow cover mapping, was evaluated at U.S.$ 10 millions per year, with the price of 3.8 cents per kWh.

The relative importance of hydropower is in some countries higher than in the United States: In Norway, it represents nearly 100% of the total electricity production and in Switzerland still 60%, in spite of the recent increase of the nuclear power. It is a renewable source of energy and it can cover peak demands at short notice, in contrast to conventional or nuclear power plants. Possibilities of building new hydroelectric plants are limited by environmental concerns. Efforts to increase the electricity production of the existing hydroelectric plants are therefore officially encouraged.

Reservoir operators in Switzerland have a difficult task to reconcile discrepancies between the seasonal changes in electricity consumption and available water: In the winter, the consumption is high and the runoff is low. In the summer, these conditions are reversed. Consequently, reservoirs are emptied to improve the low winter flows while the high flows during the snowmelt season are expected to refill them. Even so, there is generally an overproduction of electricity in the summer which must be exported. Seasonal runoff forecasts facilitate optimum use of water in winter months, thus reducing the necessary electricity import, and early decisions to sell electricity in the summer, thus achieving better prices on the spot market. If, for example, only 50 millions kWh of excessive summer electricity can be sold by 0.01 sFr/kWh higher, the economical benefit of forecasts amounts to sFr. 500'000 each year (Seidel et al., 1990). Runoff forecasts also facilitate the planning of revisions and repairs of machinery. If a turbine unit is revised, the intake capacity of the plant is reduced so that excessive runoff may overflow unused. This can be avoided by planning revisions when low flows and sufficient accumulation space are forecasted.

Short-term runoff forecasts also improve the operation of reservoirs but they are especially important for run-of-river power plants: Whenever a quick runoff peak exceeds the intake capacity of turbines, the excessive water overflows the weir and is lost. Such situations can be at least partially avoided thanks forecasts by timely decisions and cooperation with other power plants.

6 CONCLUSION

Periodical mapping of the seasonal snow cover during the snowmelt period appears to be the most promising contribution of remote sensing with regard to a favourable cost-benefit analysis. Monitoring of the areal extent of snow provides an essential input variable for snowmelt runoff models, notably the SRM model.

With these data, short-term forecasts of daily river flows as well as seasonal forecasts of runoff volumes are possible in mountain regions where snow is a major runoff factor. The economical benefit for hydroelectric companies can be summarised as follows:

a) Improved freedom of action on the electricity market in order to achieve higher prices for selling and lower prices for buying. This benefit is particularly important in the conditions of Switzerland.

b) Avoiding water losses by overflow and thus increasing the electricity production in kWh by existing hydroelectric stations.

Apart from hydropower, runoff forecasts are useful for flood control, river navigation, irrigation, municipal and industrial water supply. Although a quantitative evaluation of such benefits is hardly possible, these examples support continued and intensified efforts in the remote sensing in snow cover.

7 ACKNOWLEDGEMENT

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