

## MULTISENSOR SNOW COVER MAPPING AND SNOWMELT RUNOFF SIMULATIONS

Michael F. Baumgartner<sup>1</sup> and Klaus Seidel<sup>2</sup>

- 1) USDA/ARS, Hydrology Laboratory, Beltsville, Maryland
- 2) Institute for Communication Technology, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

### 1. INTRODUCTION

In Switzerland, 60% of the electricity is produced by hydropower. Therefore, runoff forecasting represents an essential tool for the utilization of water power in the Alps. Usually, reservoirs are designed for limited capacity and for mean peak flows. For optimum reservoir operation, the time and the amount of the expected meltwater have to be known precisely. Inefficient reservoir manipulation means wasting a part of the available water and causing economical losses. Precise snowmelt runoff forecasting can help prevent such situations and are therefore of special economic meaning.

#### 1.1 Remote Sensing Data

Seasonal variations of snow cover directly influence the meltwater production and the subsequent runoff. Successful forecasting of the meltwater runoff requires fairly constant information about the gradually decreasing snow cover. Remote sensing provides a means for periodical snow cover mapping over large areas. Remotely sensed snow cover data must be available with an adequate time resolution.

Data from the NOAA/AVHRR system are available twice a day. Nevertheless, only one to two images per week can be used, three to four under good meteorological conditions. Night-time observations cannot be used for snow cover mapping in alpine terrain since the evaluations should be carried out using only visible and near infrared bands (ROTT, 1978; BARNES and BOWLEY, 1980). In the remaining day-time coverages, the basin is periodically far off nadir due to orbit parameters. This results in heavy panoramic distortions which makes snow cover mapping impossible.

Landsat-MSS data allow a precise determination of the snow coverage (e.g., HAEFNER, 1980). Due to the long repetition cycle of Landsat (16 days for Landsat 4 and 5) the period between two satellite recordings is too long to precisely determine the snow cover variations. Heavy cloud coverage often prevents a recording of the earth's surface which additionally reduces the number of useful images.

Based on Landsat-MSS data only, operational runoff forecasting on a day-to-day basis cannot be guaranteed. Digital remote sensing information from both AVHRR and MSS data has to be integrated into the snow cover mapping scheme. Therefore, the number of available images can be increased, i.e., a precise recording of the snow cover variations is possible.

#### 1.2 Snowmelt Runoff Modeling

Efficient snow cover monitoring became available only recently. Therefore, most snowmelt runoff models do not use remote sensing information. In a recent international comparison (WMO, 1986) only the Martinec-Rango (SRM) snowmelt runoff model (MARTINEC et al., 1983) used the snow-covered areas derived from aircraft or satellites as daily input. Most of the models are designed and tested in selected basins with qualitatively good hydrological data. In large and remote basins where snowmelt runoff forecasting is of major importance, such conditions can seldom be found. Therefore, it is hardly possible to run complex models requiring data such as soil moisture, evaporation, radiation balance, and wind conditions. Simpler models have a better chance to be used for operational forecasting.

Using the SRM model, the difficult topographic conditions and the different spatial sensor resolution represented the main difficulties in simulating the meltwater runoff. The simulations were carried out for various numbers of elevations zones to estimate the influence of these factors on the results. The validation of these simulations can be derived by comparing simulated and measured runoff data.

The snow cover evaluations and the runoff simulations were carried out for the ablation periods 1982 and 1985 in a large alpine basin (Rhein-Felsberg/Switzerland; 3272 km<sup>2</sup>, 571-3614m a.s.l.). The years showed significant differences in precipitation and temperature patterns. The winter 1981/82 can be considered as a snow-rich year whereas 1984/85 showed a low snow coverage and an unusual temporal distribution of snow falls even in early summer.

## 2. SNOW COVER MAPPING

For the ablation periods 1982 and 1985, all available AVHRR and MSS data were used for snow cover mapping. The data were processed based on methods from digital image processing and pattern recognition (DUDA and HART, 1973; HARALICK, 1976).

### 2.1 Satellite Image Analysis

As a first step, satellite data have to be preprocessed. Landsat-MSS data were corrected for line drop-outs. These destroyed lines were replaced by multiplying the lines above and below. Additionally, for each date, MSS data had to be digitally mosaicked since the basin was located in the overlap zone of two frames.

MSS and AVHRR data had to be geocoded using the ground control point approach, an affine backward transformation (image to map transform), and a nearest neighbor resampling onto a 100m x 100m grid for MSS data and onto a 500m x 500m grid for AVHRR data. Thereby, the spatial location of each pixel is exactly defined, enabling a superimposition of the satellite images with other data as digital terrain model (DTM), masks, etc., onto a multivariate data set. Additionally, AVHRR had to be corrected for panoramic distortion (FREI; 1984) caused by the large scan angle of 110.8 degrees.

MSS sensors do not allow a spectral separation between snow and clouds. Therefore, with an interactive image processing system, all clouds and the according shadows have been delineated in a false-color representation using a cursor. These areas have been stored in the multivariate data set as digital cloud masks. The snow coverage for these areas had to be reconstructed in a separate procedure (Chapter 2.2). Additionally, from the topographical maps, the basin boundary has been digitized and stored in the data base.

From a digital elevation model (DEM), aspect and slope have been calculated and added to the data base. The DTM is a basic need for the following snow cover evaluations in several elevation zones and for the reconstruction of the snow coverage under cloud-covered image parts.

Following the preprocessing procedures, the digital satellite imagery has been classified based on supervised classification techniques using MSS bands 5 and 7, and AVHRR bands 1 and 2. For supervised classification, training areas had to be selected for a set of categories (BAUMGARTNER et al., 1986a). Special attention had to be paid to the category "transition zone", a region between "aper" (snow free) and "snow covered". It is assumed that all pixels belonging to this zone are snow covered by 50%. Tests have shown (BAUMGARTNER et al., 1987) that with the MSS resolution, such details can be detected. With the AVHRR sensors, a subdivision into the transition zone is pointless since the sensors measure a signal, influenced by the percentage of snow coverage, topography, and solar illumination. The tests have also shown that in alpine terrain, a minimum basin size of 600-1000km<sup>2</sup> is necessary to allow accurate snow cover mapping with AVHRR data. In another test (BAUMGARTNER et al., 1987) several simulated resolution cells were compared with the DEM. It was found that the optimum spatial sensor resolution of about 200m x 200m would be adequate.

The results of the multispectral analyses are thematic maps and statistical reports representing the extent and the variations of the snow coverage within the basin. These data are the basis for deriving the snow cover depletion curves, separately for several elevation zones.

### 2.2 Cloud Cover Extrapolation

Before the depletion curves can be derived, the snow cover for the cloud-covered image parts had to be reconstructed (BAUMGARTNER et al., 1986b) using: (a) an extrapolation method based on the DTM; or (b) a substitution method for replacing the missing image parts with the corresponding parts of other images.

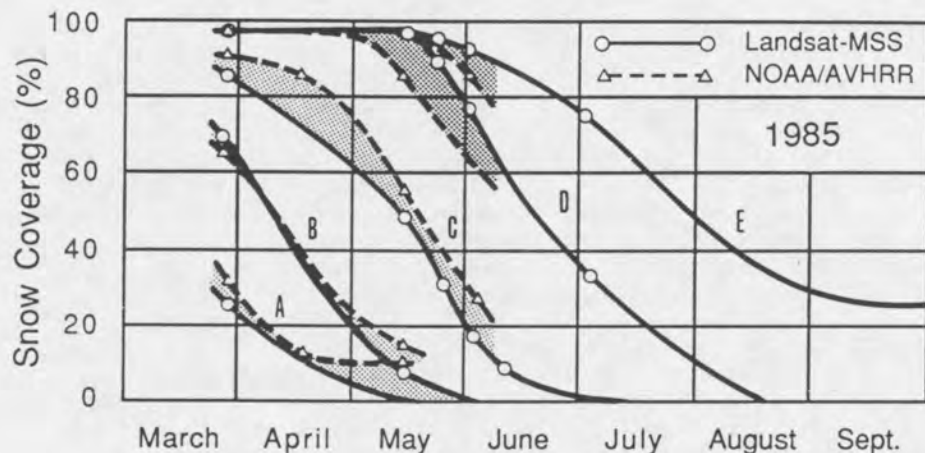


Figure 1. Depletion curves for the snowmelt period 1985 based on Landsat-MSS and NOAA/AVHRR snow cover evaluations; Rhein-Felsberg (Switzerland)

### 2.3 Depletion Curves

To reach comparable accuracy by using MSS and AVHRR data for snow cover mapping, the evaluations had to be carried out for a certain number of elevation zones based on the DTM. MSS based evaluations in five elevation zones proved to result in precise snow-covered areas. For AVHRR data, three elevation zones gave adequate results. By using AVHRR and MSS snow cover data in a combined approach, the evaluations for the basin under investigation must be carried out for three elevation zones. From these data, the snow cover depletion curves have been derived representing the daily snow cover variations. The depletion curves are compared for independent evaluations with MSS and AVHRR data (Fig. 1). Some systematic deviations can be detected. At the beginning of the season (March/April) the derived snow coverages from NOAA/AVHRR data in the highest elevation zone are overestimated. Obviously due to the coarser spatial resolution of the AVHRR sensors and the brightness of the snow covered pixels, the aper (snow free) pixels cannot be detected. In heavily rugged terrain as in the "Rhein-Felsberg" basin, a snow coverage of 100 percent can never be reached. It means that steep rock faces and areas of previous avalanches even in higher elevations are not snow covered. In the lower elevation zones (A', B') the AVHRR derived snow coverage is underestimated due to the rugged terrain and the sun angle causing that pixels often are assigned to be aper (lower brightness than in reality). During the maximum snowmelt period (May, June) the conditions change; AVHRR snow coverages are overestimated in the lower elevation zones (A', B') because mixed pixels are mainly classified as snow covered. In the highest elevation zone (C') albedo values are decreasing caused by aging and soiling of snow which resulted in an underestimation.

### 3. SNOWMELT RUNOFF SIMULATIONS

The SRM requires three input variables for runoff simulations: air-temperature, precipitation, and the areal extent of snow cover for several elevation zones. All these values are required for each day of the runoff season in order to simulate the runoff values on a day-to-day basis. For the basin "Rhein-Felsberg" temperature and precipitation have been taken as weighted means (synthetic station) from seven different base stations which are routinely recorded. The SRM input parameters required to describe the topographical and physical conditions of the basin are the same for the simulations for 1982 and 1985 (BAUMGARTNER et al., 1986b). One should realize that the SRM does not need any updating during the simulation process, i.e., at no time the measured discharge was used to correct any deviations.

As a measure of the simulation accuracy, two values have been calculated: (a) overall accuracy as the seasonal runoff volume difference between measured and simulated runoff; (b) Nash-Sutcliffe  $R^2$  which indicates, to what extent the daily deviations from the average discharge have been simulated (MARTINEC et al., 1983). A direct comparison of the computed runoff with the measured runoff is complicated due to reservoir operations for electricity production, i.e., the measured discharge does not represent a natural one. The reconstruction of the natural runoff is difficult and not always faultless.

### 3.1 Snowmelt Runoff Simulations 1982

The simulation for the snowmelt period 1982 was based only on Landsat-MSS snow cover data, evaluated for five elevation zones. Figure 2 shows this simulation compared with the natural, reconstructed runoff. The reason for the relatively low  $R^2$  (Table 1) were two heavy thunderstorms, typical for the season (August, September). The model did not react sufficiently caused probably by the synthetic meteorological station. If we concentrate on the real snowmelt period (April-August), the results (Table 1) are significantly better, confirming that the deviations were mainly caused by these two rainfalls.

### 3.2 Snowmelt Runoff Simulations 1985

In Table 2, the results for the simulations in 1985 are summarized. Runoff values based on 5, 3, 2, and 1 elevation zone(s) are compared. Based on snow cover data from MSS recordings, evaluated for five elevation zones, a precise extrapolation of the air-temperature was possible resulting in a highly accurate simulation. Again, simulated and natural, reconstructed runoff were compared (Figure 3). At first glance, a good conformity with the overall accuracy can be seen (Table 2). However, a more detailed inspection shows some systematic deviations on each Tuesday during the entire season. The not-quite-correctly reconstructed natural runoff causes the constantly bad Nash-Sutcliffe value of about 0.65, i.e., this  $R^2$  is not representative for the effective simulation accuracy. Unfortunately we have not been able to correct for this strange effect.

Again using MSS snow cover data, but reducing the number of elevation zones, it is evident that the accuracy of the air-temperature extrapolation from base station to mean hypsographic zone elevation decreased resulting in a lower simulation accuracy.

Table 1. Results of Snowmelt Runoff Simulations Based on Landsat-MSS Snow Cover Evaluations; Rhein-Felsberg, Switzerland, 1982

Period	Runoff volume [m <sup>3</sup> ]		Volume difference [%]	$R^2$
April-Sept. 1982	natural	3162.10 <sup>6</sup>		
	simulated	2960.10 <sup>6</sup>	-6.4	0.64
April-August 1982	natural	2605.10 <sup>6</sup>		
	simulated	2592.10 <sup>6</sup>	-0.5	0.87

Table 2. Results of Snowmelt Runoff Simulations Based on Landsat-MSS and NOAA/AVHRR Snow Cover Evaluations for a Different Number of Elevations Zones; Rhein-Felsberg, Switzerland, 1985

Period	Runoff volume [m <sup>3</sup> ]	Volume diff. [%]	$R^2$	Number of elevation zones	Sensor	
April-Sept. 1985	natural	2815.10 <sup>6</sup>				
April-Sept. 1985	simulated	2789.10 <sup>6</sup>	0.9	0.66	5	MSS
April-Sept. 1985	simulated	2867.10 <sup>6</sup>	-1.6	0.67	3	MSS
April-Sept. 1985	simulated	3027.10 <sup>6</sup>	-7.5	0.65	3	AVHRR
April-Sept. 1985	simulated	3134.10 <sup>6</sup>	-11.3	0.66	2	MSS
April-Sept. 1985	simulated	3230.10 <sup>6</sup>	-14.8	0.60	2	AVHRR
April-Sept. 1985	simulated	4216.10 <sup>6</sup>	-49.8	0.26	1	MSS/AVHRR



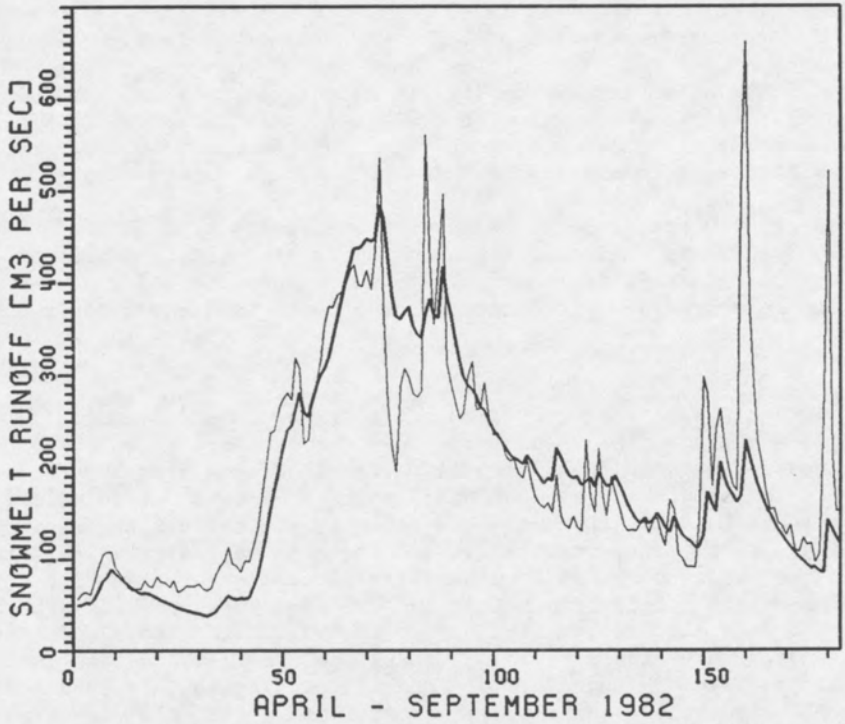


Figure 2. Snowmelt runoff simulation 1982 (bold) compared with the natural, reconstructed runoff (light); Rhein-Felsberg (Switzerland)

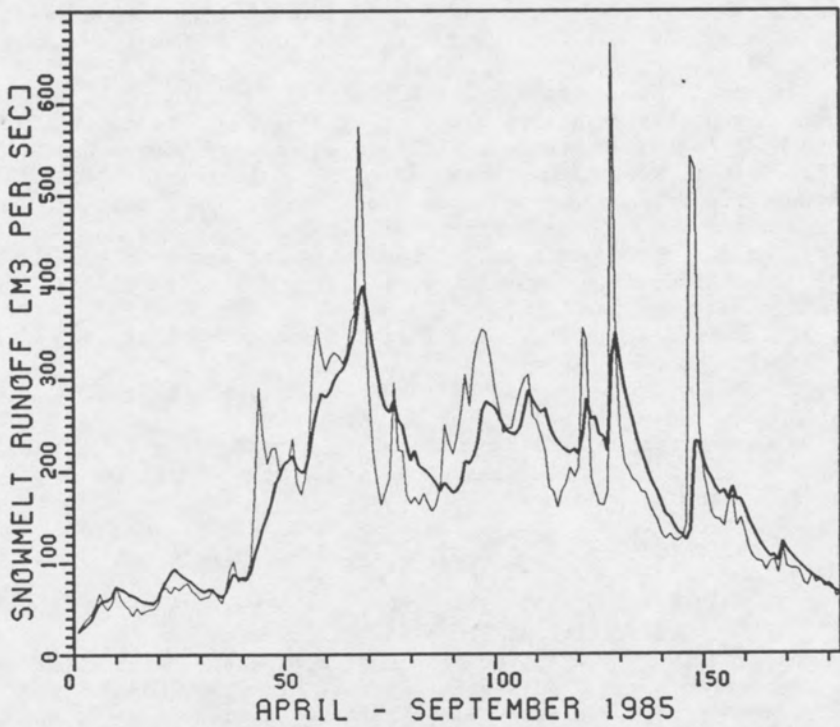


Figure 3. Snowmelt runoff simulation 1985 (bold) compared with the natural, reconstructed runoff (light); Rhein-Felsberg (Switzerland)

Similar simulations have been carried out using NOAA/AVHRR data (Table 2). The missing parts of the depletion curves have been completed using the corresponding values from the Landsat-MSS curves. The coarser resolution of the AVHRR sensors obviously resulted in a lower simulation accuracy compared to simulations based on MSS snow cover data. By decreasing the number of elevation zones, the difference between MSS and AVHRR based simulations decreased. If only one elevation zone was used, simulations with MSS and AVHRR snow cover data showed the same results. Although precise snow cover evaluations could be carried out, large deviations in runoff resulted due to inaccurate temperature extrapolation.

Due to these facts, we can state that snow cover measurements from NOAA/AVHRR and Landsat-MSS data can be used interchangeably by choosing an appropriate number of elevation zones. In the very beginning and at the very end of the season, depletion curves based solely on NOAA data are less precise. At least in these cases Landsat-MSS data should be used for calibration.

#### 4. CONCLUSIONS

Snowmelt runoff simulations have been carried out with the SRM using digital satellite imagery from NOAA/AVHRR and Landsat-MSS sensor systems in a combined approach. The derived areal extent of the snow coverage in function of time is one of the most important input variables for the SRM. The snow cover evaluations have been carried out for different elevation zones using a digital terrain model. In order to reconstruct the snow coverage under cloud-covered image parts, an extrapolation method based on a digital terrain model has been applied. It has been shown that by increasing the number of elevation zones, the overall accuracies of snowmelt runoff simulations improve as long as precise snow cover data are available. MSS data allowed precise snow cover evaluations and simulations based on 5 elevation zones. Only three zones could be established using AVHRR data, still giving acceptable simulation results. MSS and AVHRR data can interchangeably be used for snow cover mapping and runoff simulation. An improved operational utilization seems to be possible if AVHRR data are used in combination with MSS, SPOT and MOS data.

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