Large-Area Deterministic Simulation of Natural Runoff from Snowmelt Based on Landsat MSS Data

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Abstract—This work presents a method of periodic evaluation of snow-covered areas by digital processing of Landsat data. Since the snow cover was mapped for the first time in a large and morphologically complex alpine basin, it was necessary to develop procedures to determine the snow coverage for partly clouded regions or for incomplete satellite scenes.

The changing areal extent of the seasonal snow cover is an important variable for deterministic snowmelt runoff models. By using the SRM model, the natural runoff in the Rhein–Felsberg basin (3249 km², 571–3614 m a.s.l.) was simulated although the measured river flows are significantly influenced by artificial reservoir operation. Such simulation would not be possible by calibration models that optimize the model parameters by the measured discharge.

Keywords—Classification, digital terrain model, extrapolation, hydrology, Landsat-MSS, simulation, snow cover, snowmelt runoff, SRM.

I. INTRODUCTION

In view of the importance of river flow forecasts for hydropower generation and water supply, numerous snowmelt runoff models have been developed. For deterministic models, such as the Martinec–Rango model (SRM), the changing areal extent of the seasonal snow cover is the basic information for day-to-day discharge computations. So far the SRM has been tested in over 20 basins in about 10 different countries [1]–[5]. For operational runoff forecasts, the data must be evaluated within a few days; therefore, remote-sensing techniques represent a useful way of obtaining the calibration data [6]–[8]. In this work the snow cover has been determined using digital Landsat MSS data.

Special attention had to be given to the difficult and variable topographic and climatic conditions in the Swiss Alps. Serious problems are the frequently occurring clouds and missing data, which complicate the determination of the snow cover. Even rather unsuitable images have to be considered in order to get enough remote-sensing information to monitor the varying snow cover during a melting period. The areas with missing data have to be estimated using an extrapolation technique, based on a digital terrain model.

The different climatological conditions in the basin and the frequent changes of rainfall and snowfall during the melting period complicate the application of the SRM and have to be considered for the discharge simulation. A solution is presented to overcome these obstacles for a rather large catchment area in the Alps and simulation results are presented.

II. STUDY SITE

The basin Rhein–Felsberg is located in the eastern part of the Swiss Alps (Fig. 1) and includes the four Rhein tributaries Vorderhein, Hinterhein, Landwasser, and Albula. Its size is 3249 km², and the elevation ranges from 571 to 3614 m a.s.l. The ice-covered area (glaciers) adds up to 3 percent at the end of the hydrological year (September 30).

The basin can be divided into three different climatological regions. The western part (Vorderhein) has a significantly higher amount of precipitation than the eastern region (Landwasser and Albula). The southern part (Hinterhein) is influenced by the climate of the South Alps, i.e., very high precipitation in a very short time at the end of the melting period, compared to the seasonally more evenly distributed precipitation in the northern part of the Alps. These varying conditions can be explained by the interactions of differently oriented mountain chains and the prevailing westerly winds. The water regime in spring and summer depends mainly on snowmelt, in summer and autumn on rainfall.

As in many other alpine valleys the runoff is controlled by reservoirs for hydropower power generation. This presents serious problems in comparing the measured and the simulated runoff on a daily basis. The recorded (actual) daily minima and maxima and
the weekly variations reflect the needs for electricity and not the natural runoff.

III. SNOW COVER DETERMINATION BY REMOTELY SENSED SATELLITE DATA

For the determination of the changing snow cover within the test site, MSS data from Landsat have been used. With the repetition rate (18 days for Landsat-3, 16 days for Landsat-4 and -5) a sufficient number of images is seldom available during a snowmelt period. Heavy cloud cover often obscures the images. For the basin under study, we could use MSS data for the dates listed in Table I.

For the following processing of the satellite data we aimed at a virtually operational procedure using digital image processing techniques [9].

An extrapolation method for evaluating scenes partly covered by clouds or not available frame segments, preprocessing, and snow cover classification had to be applied. Finally, all geometrically corrected Landsat images were assembled together with a digital terrain model (DTM) into a multivariate data set. This facilitates a quantitative comparison and a combined interpretation of the picture elements [10].

A. Digital Terrain Model and Basin Perimeter

For the test site Rhein–Felsberg the DTM was interpolated from a 250 m x 250 m grid into a raster size of 100 m x 100 m applying the Akima method [12]. Simultaneous with the elevation, the surface normal (aspect and slope) was calculated.

The DTM has been used in two ways. First, for the snow cover determination in different elevation zones as required by the snowmelt runoff model. Second, for the snow cover determination in obscured areas using an extrapolation method developed by Seidel et al. [11]. For the extrapolation, the continuum of elevation-aspect-slope values has been partitioned into 205 classes:

5 elevation zones: 560–1100, 1100–1600, 1600–2100, 2100–2600, 2600–3600 m a.s.l.;
8 aspect classes: N, NE, E, SE, S, SW, W, NW, N;
1 class for flat terrain.

The basin boundary has been digitized from the National Topographic Maps using the scale $M = 1:50$ 000.

B. Preprocessing: Restauration, Cloud Masking, Geocoding

The determination of the relative snow coverage is based on the evaluation of the digital Landsat-MSS data. For the interpretation method used, different preprocessing steps had to be applied:

It was necessary to compensate in image 1 (see Table I) for missing lines by doubling the neighbouring lines and in 3 for misregis-

tered lines and channels. The frames (209/27) of scenes 4 and 5 covered only a part of the basin. They were digitally mosaiced with the southward adjacent frames (209/28). The cloud coverage on the image of July 29 has been reduced by a pixelwise comparison with the record of July 11, i.e., in each doubtful case the picture element in 5 has been assigned to the category of the corresponding element in 4. This procedure is not possible if new snowfall has changed the situation in the meantime.

The spectral responses for snow and clouds in the MSS recordings are very similar and cannot be used for an automated separation process. In the false color representation using an interactive image display system, the clouds have been detected by visual inspection. For these areas (and the parts without remote-sensing data) digital masks were produced. These image parts have to be reconstructed using an extrapolation method, explained in more detail in Section III-D.

The MSS input data had to be geocoded according to the coordinate system of the National Topographic Maps. With the standard reference point approach Landsat image and map were registered by an affine backward transformation [13]. At the same time a nearest neighbor resampling into a common 100 m x 100 m grid was introduced.

During a supervised classification process the data of each scene under investigation have been assigned to the categories "aper" (snow free), "transition zone," or "snow covered."

C. Supervised Classification Procedure

For the supervised classification procedure a detailed set of categories was introduced. The classification accuracy increases significantly if, e.g., the aper category is subdivided into water, forest, crop fields, meadow, pasture, and wet grassland. With the same argument, snow covered has been characterized by the categories snow in sun, snow in shadow, and dark snow, i.e., less reflecting snow due to soiling or debris.

1) Training Samples: For the supervised classification, training samples for each of these classes have been selected. Experience and familiarity with the terrain is necessary to delineate representative samples. Special attention is recommended during the time of maximum snowmelt. Carelessly selected training samples, in particular wet grassland (wet and long grass from the previous year, beneath the transition zone, watered by the melting snow) and transition zone can cause serious misclassifications. By using MSS data with 80 m by 80 m resolution, for an exact determination of the snow line, it became necessary to introduce a transition zone. It represents a region with scattered snow patches, positioned between snow covered and aper. This zone contains a snow coverage of 25–75 percent known as mixed pixels (mixels) in multispectral image classification. The contribution of this zone to the relative snow coverage is weighted with 50 percent.

2) Classification Results: Since the different scenes under investigation are recorded at different illumination and atmospheric conditions, the classification approach had to be adapted individually for each scene. We used simple parallelepiped discrimination (PPD) as well as more sophisticated maximum likelihood algo-

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**TABLE I**

**USED LANDSAT MSS SCENES**

(3-209-27/3-209-28)

<table>
<thead>
<tr>
<th>No.</th>
<th>Recording Date</th>
<th>Cloud Coverage</th>
<th>Part of Basin not Covered by MSS-Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>25-MAR82</td>
<td>1.4% clouds</td>
<td>10.0% not available</td>
</tr>
<tr>
<td>(2)</td>
<td>18-MAY82</td>
<td>15.1% clouds</td>
<td>13.1% not available</td>
</tr>
<tr>
<td>(3)</td>
<td>5-JUNE82</td>
<td>28.9% clouds</td>
<td>2.1% not available</td>
</tr>
<tr>
<td>(4)</td>
<td>11-JUL82</td>
<td>8.9% clouds</td>
<td>3.4% not available</td>
</tr>
<tr>
<td>(5)</td>
<td>29-JUL82</td>
<td>10.8%/8.2% clouds</td>
<td>3.4% not available</td>
</tr>
</tbody>
</table>
Fig. 2. Depletion curves for five elevation zones: curve A: 560–1100 m a.s.l.; curve B: 1100–1600 m a.s.l.; curve C: 1600–2100 m a.s.l.; curve D: 2100–2600 m a.s.l.; and curve E: 2600–3600 m a.s.l.

Compared to a classification using three or even four MSS bands best results were obtained with two MSS channels (bands 5 and 7). In the resulting snow cover maps certain regions are marked as "cloud-covered/not available" subregions. They will be considered especially during the following extrapolation process.

9. Extrapolation for Cloud Covered or Not Available Subregions

The classified scenes, the masks (clouds and missing data) and the DTM have been assembled into a multivariate data set, a prerequisite for the following extrapolation procedure. As mentioned above, the test site can be subdivided into 205 classes by means of the DTM, whereby each class is characterized by certain ranges of elevation, aspect, and slope. Under the assumption that for each class a unique relative snow coverage is given, we assign to all cloud-covered picture elements the same relative snow coverage as extracted for the same class in the cloud-free portion.

Finally, the snow coverage has been totaled for each elevation separately as required by the SRM. From these values depletion curves have been constructed (Fig. 2). The curves represent the relative snow coverage for each elevation zone during the 1982 snowmelt period.

IV. Simulations with the Martiniec–Rango Snowmelt Runoff Model (SRM)

The SRM model [14] is designed to simulate or forecast the daily discharge in mountain basins, resulting mainly from snowmelt but so from precipitation. The necessary variables are air temperature, precipitation, and relative snow coverage (for each day).

The SRM equation is:

\[ Q_{n+1} = Q_n c_{n+1} + \sum_{i=1}^{N} \{ c_{n,i} (a_{n,i} (T_n + \Delta T_n, i) S_{n,i} + P_{n,i} A_{i}) \} - (Q_{n, i}) \]

where

- \( Q \) is the average daily discharge;
- \( c \) is the runoff coefficient expressing the losses as a ratio (runoff/precipitation);
- \( a \) is the degree-day factor indicating the snowmelt depth resulting from 1 degree-day;
- \( T \) is the number of degree-days;
- \( \Delta T \) is the adjustment by temperature lapse rate necessary because of the altitude difference between the temperature station and the average hypsometric elevation of a zone;
- \( S \) is the ratio of snow-covered area to total area;
- \( P \) is the precipitation contributing to the runoff (a preselected threshold temperature determines whether this contribution is rainfall or immediate);
- \( A \) is the area of a zone;
- \( k \) is the recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall

\[ k = Q_m^{-m+1} \]

(where \( m, m + 1 \) are the sequence of days during a true recession flow period);

\( n \) is the sequence of days during the discharge computation period (the equation is written for a time lag between the daily temperature cycle and the resulting discharge cycle of 18 h; as a result, the number of degree-days corresponds to the discharge on the day \( n + 1 \)); and

\( N \) is the number of elevation zones.

B. Runoff Simulation in the Rhein–Felsberg Basin

In view of the great elevation range, the Rhein–Felsberg basin was divided into \( N = 5 \) elevation zones. In order to arrive at representative elevation, precipitation and temperature data for this relatively large basin, a synthetic station was created as the arithmetic mean of stations:

- Alpavere 1175 m a.s.l.
- Arosa 1847 m a.s.l.
- Chur 586 m a.s.l.
- Davos 1590 m a.s.l.
- Disentis 1180 m a.s.l.
- Hinterhein 1619 m a.s.l.
- Weissfluhjoch 2667 m a.s.l.

All model parameters were predetermined as follows:

1) The runoff coefficient (losses) for snowmelt \( c_s \):

- zones A, B: April 1–April 30 \( c_s = 0.8 \)
- May 1–August 31 \( c_s = 0.7 \)
- zones C, D, E: April 1–May 15 \( c_s = 0.9 \)
- May 16–September 30 \( c_s = 0.8 \)

2) The runoff coefficient for rainfall \( c_r \):

- zones A, B: April 1–April 30 \( c_r = 0.9 \)
- May 1–September 30 \( c_r = 0.6 \)
- zones C, D, E: April 1–June 15 \( c_r = 0.9 \)
- June 16–September 30 \( c_r = 0.6 \)

3) The degree-day factor \( a \) (in centimeters per degrees Celsius per day) for computing snowmelt from temperature (Table II).

4) Temperature lapse rate for extrapolation from the elevation of the station to the average elevations of the respective zones:

- 0.65°C per 100-m altitude difference.

5) Critical temperature to decide whether a precipitation event was snowfall or rainfall:

- April–June 15 \( T_{c, 15} = +3.00°C \) April: rainfall runoff only from the snowfree area. May–Sept.: rainfall runoff from the total area.
- June 16–30 \( T_{c, 16} = -2.00°C \)
- July 1–Sept. \( T_{c, 17} = -0.75°C \)

6) Recession coefficient (ratio of two subsequent daily flows in a dry period) depends on the current discharge and is obtained each day as

\[ k_{n+1} = x \cdot Q_n' \]

where \( Q \) is the last computed discharge and \( x, y \) are constants that must be determined for the given basin. Since the discharge at Rhein–Felsberg is influenced by reservoir operation, \( x \) and \( y \) had to be derived indirectly from the Dischma basin [14]

\[ k = 1.07 \cdot Q^{-0.029} \]

7) Time lag (delay of runoff against snowmelt)

\( t = 18 \) h.

One should realize that the SRM procedure used does not need any updating during the simulation process. That is to say that at no time the measured discharge was used to correct any deviation.

The resulting simulated discharge is shown in Fig. 3 and compared with the measured discharge. It should be noted that the discharge in the Rhein at Felsberg is influenced by reservoir operations upstream. A complete agreement of measured and simulated
daily flows is therefore not to be expected. In April, the actual discharge is higher than the simulated values. In the remaining months, the simulated values are generally higher. This is caused by the artificial increase of discharge in the winter months and by water accumulation in summer, in line with hydroelectric demand. Also, there is a drop of the measured discharge each weekend as the electricity supply is adjusted to a smaller consumption. In spite of these fluctuations, the total runoff volume was simulated with a reasonable accuracy (Table III) according to the formula

$$D_r = \frac{R_{M} - R_{S}}{R_{M}} \times 100$$

where $D_r$ is the volume difference (in percent), $R_M$ is the measured runoff volume (in cubic meters), and $R_S$ is the simulated runoff volume (in cubic meters).

### C. Comparative Evaluations in Subbasins

In order to estimate the climatic influences on the snowmelt runoff of different regions within the basin, it was subdivided into three subbasins for separate runoff simulations. The summarized simulated streamflow of the three subbasins was found to be in good coincidence with the simulated curve in Fig. 3. We conclude that it is justified to represent the climatic conditions by the synthetic base station.

### D. Model Performance with Regard to Natural River Flow

The numerical simulation results are summarized in Table III. In addition, values for the model performance are given resulting from following formula (Nash-Sutcliffe $R^2$), which is evaluated on a daily basis:

$$R^2 = 1 - \frac{\sum (q_i - q_{av})^2}{\sum (q_i - \bar{q})^2}$$

where

- $R^2$ is a measure of model efficiency,
- $q_i$ is the measured daily discharge,
- $q_{av}$ is the simulated daily discharge,
- $q_i$ is the average daily discharge for the given period, and
- $n$ is the number of days (183 in the given case).

As indicated in Table III, the total simulated runoff volume exceeds the measured volume by 6.5 percent. This deviation could have been reduced by adjusting some of the predetermined parameters, for example, the runoff coefficient. However, such adjustments should be avoided except in extremely difficult conditions because they contradict the deterministic approach of the SRM model. Actually, it was probably correct to simulate a higher runoff volume since under Swiss conditions, water is usually stored in summer in order to cover the electricity demands in winter. Thus the measured runoff volume is artificially reduced.

This assumption was confirmed when the daily storage and release data were obtained from the hydroelectric stations. Fig. 4 shows the reconstituted natural river flows at Felsberg, compared with the same simulation as in Fig. 3; that is to say, with the unchanged original model parameters. Most of the daily deviations disappeared and the simulated runoff volume is now by 6.4 percent less than the measured uninfluenced volume.

Should the runoff coefficient be adjusted after all? The answer is again negative. The deficit occurs mainly after the end of the snowmelt season due to two rainfall peaks in September. Better precipitation data might have helped to improve the rainfall-runoff simulation. By restricting the simulation to the real snowmelt period of April-August, the criteria of accuracy assume, without artificial help, satisfactory results.

### V. Conclusions

The rugged terrain and complex morphology of alpine basins require adequate methods of satellite data evaluations for determining the areal extent of the seasonal snow cover as frequently as possible during the snowmelt season. It appears possible to use digital Landsat MSS data for basins even larger than 3000 km², to map the snow cover separately in respective elevation zones and to extrapolate for partly clouded or incomplete scenes. Envisaged is a complementation of data by NOAA/AVHRR imagery.

Remotely sensed snow cover data enable the snowmelt runoff models to use a deterministic approach so that natural river flows...
can be simulated even in large basins affected by operation of hydroelectric stations.

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REFERENCES


