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LARGE AREA SNOWMELT RUNOFF SIMULATIONS
BASED ON LANDSAT-MSS DATA

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Abstract

The purpose of this paper is to show a feasible method for processing satellite images and a runoff simulation by the SRM model based on these data. Two problems had to be dealt with:

1. the morphological and the climatological complexity of basins in the Swiss Alps,
2. the requirement of at least 4 snow cover evaluations during the snowmelt period, which necessitates the use of incomplete satellite scenes.

The changing areal extent of seasonal snow cover is a very important variable for the Snowmelt-Runoff Model (SRM). The runoff simulation for the snowmelt season 1982 was carried out in the alpine basin Rhine-Felsberg (3249 km², 571-3614 m a.s.l.).

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 a basic information for day-to-day discharge computations. So far, the SRM was tested in over 20 basins in about 10 different countries [1]-[5]. In this paper, the snow cover is determined by satellite techniques using Landsat MSS data [6]-[8]. For operational runoff forecasts, the data must be evaluated within several days after each satellite overflight.
Study Site

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

The basin can be divided in three different climatological regions. The western part ('Vorderrhein') has a significant higher amount of precipitation than the eastern part ('Landwasser' and 'Albula'). The southern part ('Hinterrhein') is influenced by the climate of the South Alps, i.e. very high precipitations in a very short time at the end of the melt period, compared to the more evenly distributed precipitation in the northern part of the Alps. 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 generation. Therefore it is impossible to compare the measured and the simulated runoff on a daily basis. The recorded daily minimum and maximum and weekly variations reflect the needs for electricity and not the natural runoff.

![Fig. 1: Location of the 'Felsberg' Basin area CH totally 41'293 km² 'Felsberg' (shaded area) 3'249 km²](image)

Snow Cover Determination by Remotely Sensed Data from Satellites

For the determination of the changing snow cover within the test site MSS recordings of the earth resources and
technology satellites LANDSAT have been used. With the repetition rate of LANDSAT (18 days for LANDSAT-3, 16 days for LANDSAT-4 and -5), a sufficient number of images is very seldom available during a snowmelt season. Heavy cloud coverage is often obscuring the images.

For the basin under study in 1982 we could use MSS dates as listed in Tab. 1. A method was developed for evaluating scenes partly covered by "clouds" or "not available" frame segments.

Tab. 1: LANDSAT MSS Scenes used (3-209-27/3-209-28)

<table>
<thead>
<tr>
<th>Date</th>
<th>Clouds (%)</th>
<th>Not Available (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-MAR82</td>
<td>1.4%</td>
<td>18.8%</td>
</tr>
<tr>
<td>18-MAY82</td>
<td>15.1%</td>
<td>13.1%</td>
</tr>
<tr>
<td>5-JUN82</td>
<td>20.9%</td>
<td>2.1%</td>
</tr>
<tr>
<td>11-JUL82</td>
<td>0.9%</td>
<td>3.4%</td>
</tr>
<tr>
<td>29-JUL82</td>
<td>0.2%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

*) corrected for missing lines and channel misregistration

We aimed at a virtually operational procedure using digital image processing techniques [9]. Preprocessing, snow cover classification and an extrapolation for missing data had to be applied. Finally all geometrically corrected LANDSAT images were assembled together with the Digital Terrain Model (DTM) into a multivariate data set. This facilitates a quantitative comparison and a combined interpretation of the picture elements [10].

- Digital Terrain Model and Basin Perimeter

The mentioned method is based on a Digital Terrain Model (DTM). For the test site 'Felsberg' it was interpolated from the 250 m by 250 m grid into a raster size of (100 * 100) m² applying the Akima method [11]. Simultaneously with the elevation the surface normal (aspect and slope) was calculated.

For the snow cover determination in invisible or obscured areas we used an extrapolation method mentioned earlier [12]. We partitioned the continuum of elevation-aspect-slope values 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)
- 5 slope classes (<0-15, 16-22, 23-28, 29-36, 37-90°)
- 1 class for flat terrain

The basin boundary has been digitized from the National Topographic Maps using the scale M = 1:50000.
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: 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*100) m² grid was introduced.

For the supervised classification procedure a detailed set of categories was introduced. The classification accuracy increases significantly if e.g. the 'snow free' category is subdivided into: 'water', 'forest', 'crop fields', 'meadow', 'pasture', and 'wet grassland'. With the same argument 'snow covered' has been characterized by training samples for 'snow in sun', 'snow in shadow' and 'dark snow', i.e. less reflecting snow due to soiling or debris. Since the different scenes under investigation are recorded at different illumination and atmospheric conditions the classification approach had to be adapted individually. We used simple Parallelepiped Discrimination (PPD) as well as more sophisticated Maximum Likelihood algorithms. The classification results are represented by snow cover maps. Certain regions are marked as 'cloud covered/not available' subregions. They will be considered especially during the following extrapolation process.

The classified scenes and the DTM have been assembled into a multivariate data set. As mentioned above by means of the DTM the test site can be subdivided into
Fig. 2: Depletion curves for 5 elevation zones A to E

Fig. 3: Measured (N) and simulated (C) snowmelt runoff \( m^3s^{-1} \)

Total runoff volume:

\[ \text{N: } 2778 \times 10^6 \text{ m}^3 \]
\[ \text{C: } 2937 \times 10^6 \text{ m}^3 \]

205 classes, 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 detected for the same class in the cloud free portion. Finally, the snow coverage has been totalised for each elevation separately, as demanded by the SRM. The contribution of the transition zone has been weighted with 50%. From these values the depletion curves have been constructed (Fig. 2). The curves are representing the relative snow coverage for each elevation zone during the snowmelt period 1982.

Runoff Simulation by SRM-Model

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

The SRM equation reads:

\[
Q_{n+1} = Q_n k_{n+1} + \sum_{i=1}^{N} \left[ c_{n,i} \left( a_{n,i} (T_n + \Delta T_{n,i}) S_{n,i} + P_{n,i} \right) \right]
\]
Q = average daily discharge
C = runoff coefficient expressing the losses as a ratio (runoff/precipitation)
a = degree-day factor indicating the snowmelt depth resulting from 1 degree-day
T = number of degree-days
ΔT = 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 = ratio of snow covered area to total area
P = precipitation contributing to the runoff. A preselected threshold temperature determines whether this contribution is rainfall and immediate
A = area of a zone
k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall:
\[ k = \frac{Q_{m+1}}{Q_m} \]
(m, m+1 are the sequence of days during a true recession flow period)
n = 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 hours. As a result, the number of degree-days correspond to the discharge on the day n+1.
N = number of elevation zones

In view of the great elevation range, the Rhine-Felsberg basin was divided into \( N = 5 \) elevation zones. In order to arrive representative precipitation and temperature data for this relative large basin, a synthetic station was created as the arithmetic means of stations Alveneu 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., Hinterrhein 1619 m a.s.l. and Neisfluhjoch 2667 m a.s.l.
The recession coefficient depends on the current discharge and is obtained each day as
\[ k_{n+1} = x \frac{Q^n}{Q_{n-1}} \]
where \( Q \) is the last computed discharge, \( x, y \) are constants which must be determined for the given basin.

Since the discharge at Felsberg is influenced by reservoir operation, \( x \) and \( y \) have to be derived indirectly from the Dischma basin [14]. The resulting simulated discharge is shown in Fig. 3 and compared with the measured discharge.
One should realize that the SRM used does not need any "updating" during the simulation process. That is to say at no time the measured discharge was used to correct the deviation.

It should be noted that the discharge in the Rhine at Felsberg is influenced by reservoir operation 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 the summer, in line with hydroelectricity demands. In spite of those fluctuations, the total runoff volume was simulated with a reasonable accuracy. The rainfall peaks are insufficiently simulated and would require detailed rainfall data, possibly also a modification of the model.

- 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 subbasins for separate runoff simulations (Fig. 4). Unfortunately there are no runoff measurement available in these subbasins. In Fig. 5 the simulated runoff values are compared: curve C represents the result based on a synthetic base station and curve S gives the summarised values from the simulations in the subbasins.

![Fig. 4: Simulated runoff (m³ s⁻¹) for different subbasins](image1)

V: subbasin 'Vorderhein'  
H: subbasin 'Hinterhein'  
L: subbasin 'Landwasser'  
S: summarised runoff

![Fig. 5: Simulated runoff (m³ s⁻¹)](image2)

S: summarised from runoff of subbasins (curve S from Fig. 4)  
C: based on "synthetic base station" (curve C from Fig. 3)
Conclusions

Even in a relative large alpine basin, it appears possible to determine periodically snow covered areas from Landsat MSS data and to simulate daily river flows by a snowmelt runoff model. Methods are available to evaluate the snow cover in areas obscured by clouds. In years with especially frequent cloud interference, an improved frequency of Landsat overflights would be desirable. Another possibility is to complement the data by imagery from NOAA-AVHRR.

Acknowledgement

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References


