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Mapping of snow cover and glaciers with high resolution remote sensing data for improved runoff modelling

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Abstract

The study presents investigations of the runoff from snow and ice, carried out in the high alpine basin of the Rhône river at Sion (3371 km ^{2} , 491 -- 4634 m a.s.l.). Using satellite remote sensing data, features like the snow coverage in the whole basin, the gradually decreasing snow coverage on glaciers and the area of exposed ice have been mapped. The periodical monitoring of the basin is based on Landsat-TM data enabling snow and ice areas to be distinguished. The satellite imagery has been geocoded with high accuracy and interpreted using supervised classificationtechniques. The satellite derived snow and ice coverages were supplied to the snowmeltrunoff model SRM+G allowing to compare the different runoff input components: seasonal snow cover, new snow, rain and glacier-ice. Due to the high part of glaciers in the basin (17% glaciered) special attention has been paid to the melt conditions of ice in comparison with the melt conditions of snow. Conditions for a norm year in terms of normalized daily values de-rived for the time period 1961 to 1990 for snow cover depletion, temperature and precipitation have been established. Based on norm year conditions the effect of climate change was evalu-ated for the scenarios 2030 and 2100, which are characterized by increasing temperatures during winter and summer and increased precipitation during winter. The results show the influence of increased summer icemelt in the basin Rhône-Sion.

INTRODUCTION

Snowmelt runoff modelling in high mountain areas based on periodical snow cover mapping derived from earth observation satellites has been regularily reported in the last decades (Mar-tinec 1973, Baumgartner et al., 1985, Kumar et al., 1991, Martinec et al, 1991, Seidel and Mar-tinec, 1992, Rango and Martinec, 1999). Advanced methods of satellite data processing make it possible to account for specific features of glacier melt if high resolution iamges are available (Ehrler et al., 1997, Schaper et al., 1999, Schaper et al., 2000a, Schaper et al., 2000b). Apart from the improvement of runoff modelling, the independent computation of glacier melt is an important step towards evaluations of glacier behaviour with regard to global warming.

BASIN RHÔNE-SION

The selected test basin of the river Rhône at Sion has an area of 3371 km ^{2} and ranges from 488 to 4634 m a.s.l.. The total area of glaciers (among them the large Aletsch Glacier) amounts to 580 km ^{2} or 17%. The situation of the basin in the Swiss Alps is shown in Fig. 1. For the pur-pose of runoff modelling, the basin has been divided into 7 elevation zones with respective data listed in Table 1.

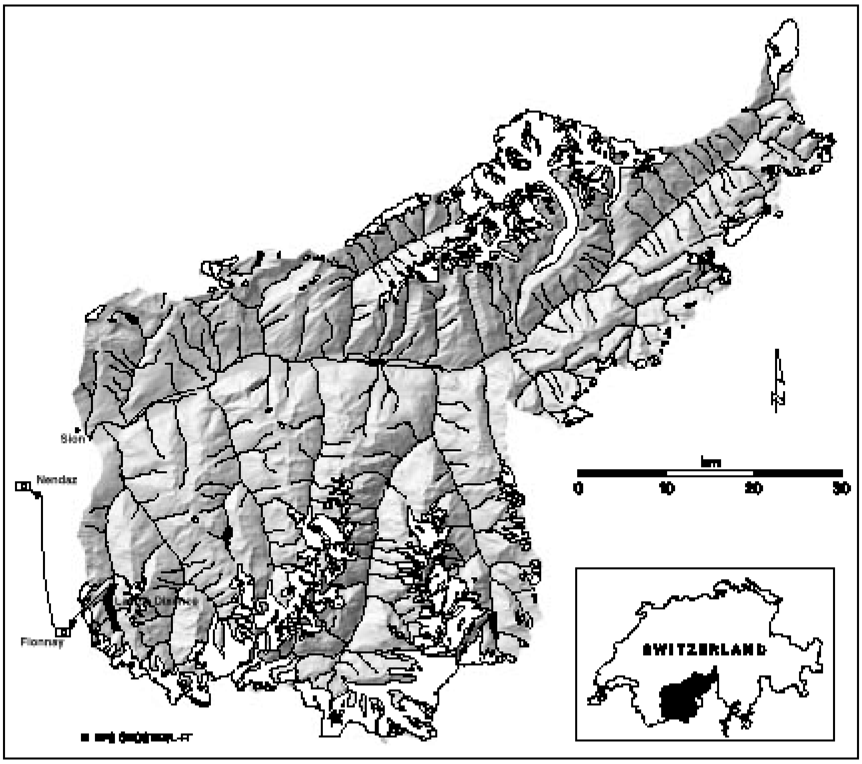

Figure 1. Basin-Sion with runoff diversion to hydroelectric plants. Gray appears the shaded relief, white areas indicate the glaciers and black areas indicate the water bodies.

As illustrated in Fig. 1, runoff from an area, including more than 35 glaciers, is collected by galleries and stored in the Grande Dixence reservoir with an storage volume of 400 x 10^6 m^3.

Table 1. Elevation zones and glacier areas of basin Rhône-Sion. For the purpose of runoff modelling each zone is divided into glacier and glacier-free areas.

Zone	Altitude Range (m a.s.l.)	Mean Altitude (m a.s.l.)		Area (km^2)		Glacier Area (%)
		Glacier	Glacier free	Glacier	Glacier free	
1	488-1100	-	796	0	277.0	-
2	1100-1600	-	1374	0	390.0	-
3	1600-2100	1961	1884	4.1	562.9	0.7
4	2100-2600	2410	2384	48.4	812.6	5.6
5	2600-3100	2854	2849	238.5	571.5	29.4
6	3100-3600	3349	3362	237.5	137.5	63.3
7	3600-4634	3836	3880	51.0	40.0	56.0
Total	488-4634			579.5	2791.5	17.2

From this reservoir, water is diverted outside the basin to the hydroelectric plants Chandoline, Fionnay and Nendaz. Also, there are other hydroelectric schemes in the basin which store runoff in the summer and release it in the winter. Over 80% of the hydroelectricity is produced in the winter in order to meet the demand in Switzerland. Both the runoff diversion and the reservoir operation must be taken into account in order to rectify the runoff measured at Sion to natural runoff which can be compared with the modelled runoff. The climatic conditions with regard to precipitation and temperature are assessed in earlier publications (Funk, 1985; Schüepp et al., 1978).

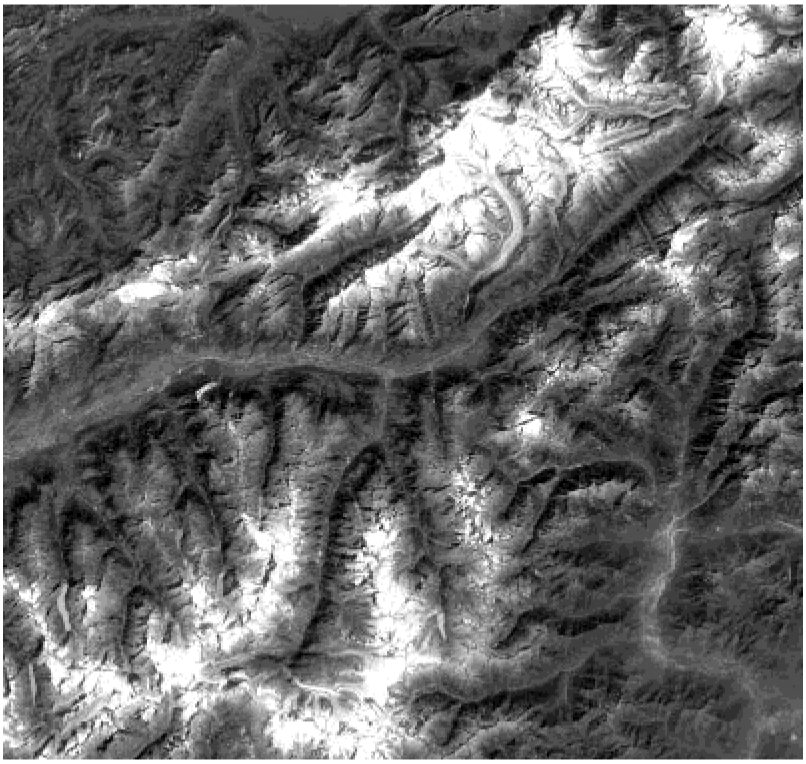

Figure 2. Detail from Landsat-TM image 195-28, Channel 1, from 12 September 1985 showing snow cover and glaciers of basin Rhône-Sion in bright colors.

SNOW AND ICE COVER MAPPING

For a deterministic approach of runoff modelling in high mountain basins, the changing areas of the seasonal snow cover and of the exposed glacier ice must be evaluated throughout the snowmelt season. In 1985, 10 subsequent Landsat-TM and Landsat-MSS images were available. An example from 12 September is shown in Fig. 2.

Thanks to the good spatial resolution of the Landsat sensors (80 m for MSS and 30 m for TM) and advanced methods of satellite data processing (Ehrler and Seidel, 1995), it was possible to distinguish between snow and ice and periodically determine the respective areas in each Fig. 2: Detail from Landsat-TM image 195-28, Channel 1, from 12 September 1985 showing snow cover and glaciers of basin Rhône-Sion in bright colors elevation zone. To this effect, the scenes have been classified using supervised classification techniques with regard to snow, ice, and snow- and glacier-free. In a GIS analysis, snow cover units have been generated in order to complement the images in areas obscured by clouds. This method is described in detail elsewhere (Ehrler et al., 1997).

RUNOFF MODEL FOR SNOW AND GLACIER MELT

From this periodical mapping, depletion curves of the snow cover in glacier-free areas as well as of the snow cover superimposed on glaciers were derived. Glacier extension is known (see Table 1), so the increasing areas of exposed ice can be modelled for glacier melt computa-tion. The variables snow cover and glacier ice constitute the direct input into the SRM+G model which was used in this study. The model is an advanced version of the SRM-ETH (Brüsch, 1995) which is a relational database version of the PC-SRM (Martinec et al., 1998).

The SRM+G procedure is based on the deterministic, recursive SRM formula (Martinec, 1975) and can be arranged as stated in Eq. (1).

Snow- and glacier melt runoff formula SRM+G:

$$Q_{n+1} = Q_n k_{n+1} + (1 - k_{n+1}) . \sum_{i=1}^{N} (Q_{rain,n,i} + Q_{newsnow,n,i} + Q_{snowmelt,n,i} + Q_{icemelt,n,i}) \qquad (1)$$

$$Q_{rain,n,i} = A_{total,i} \cdot c_r \cdot P_r \cdot \frac{10000}{86400}$$

$$Q_{newsnow,n,i} = A_{total,i} \cdot c_r \cdot a_{s,n,i} \cdot T_i . (1 - S_{total,i}) . \frac{10000}{86400}$$

$$Q_{snowmelt,n,i} = (A_{nogl,i} \cdot c_s \cdot a_{s,n,i} \cdot T_i \cdot S_{nogl,i}) + (A_{gl,i} \cdot c_s \cdot a_{s,n,i} \cdot T_i \cdot S_{gl,i}) . \frac{10000}{86400}$$

$$Q_{icemelt,n,i} = A_{gl,i} \cdot c_{gl} \cdot a_{g,n,i} \cdot T_i . (1 - S_{gl,i}) . \frac{10000}{86400}$$

$$k_{n+1} = x . Q_n^{-y}$$

where

Q	average daily discharge [m 3 s -1] referring to rain, newsnow, snowmelt and icemelt
c	runoff coefficient (cs for snow, cr for rain, c gl for glacier ice)
a	degree-day factor [cm °C -1 d -1] (as for snow, ag for glacier ice)
T	temperatue at the mean hypsometric elevation of a zone [°C] (extrapolated by a temperatue gradient)
S	ratio of snow covered area to total area

P	precipitation as rain (P_r) or snow (P_s) [cm d^{-1}] according to the critical temperature (snow contributes to runoff with a delay when temperatures rises above 0°C)
A	area of a zone [km^2] referring to glacier, noglacier and total area
k	recession coefficient indicating the decline of discharge in a period without snow-melt or rainfall as a daily ratio. x, y are constants to be determined
N	number of zones
n	sequence of days

The input to the model are daily values for temperatures, precipitation and snow coverages. Usually conventional depletion curves (CDC) are used to derive daily snow cover values by interpolating points obtained from periodical snow cover mapping. In the SRM-ETH and SRM+G versions, the interpolation is carried out in the so called *modified depletion curves* (MDC) which relate the snow coverage not to time, but to the cumulative computed snowmelt depth. An example showing a year around runoff simulation for the basin Rhône-Sion is given in Fig. 3 (Schaper et al., 2000b). Fig. 4 shows, by cumulative curves, the proportions of the runoff com-ponents. This gives a quantitative comparison of the contributions to runoff (Schaper et al., 2000a).

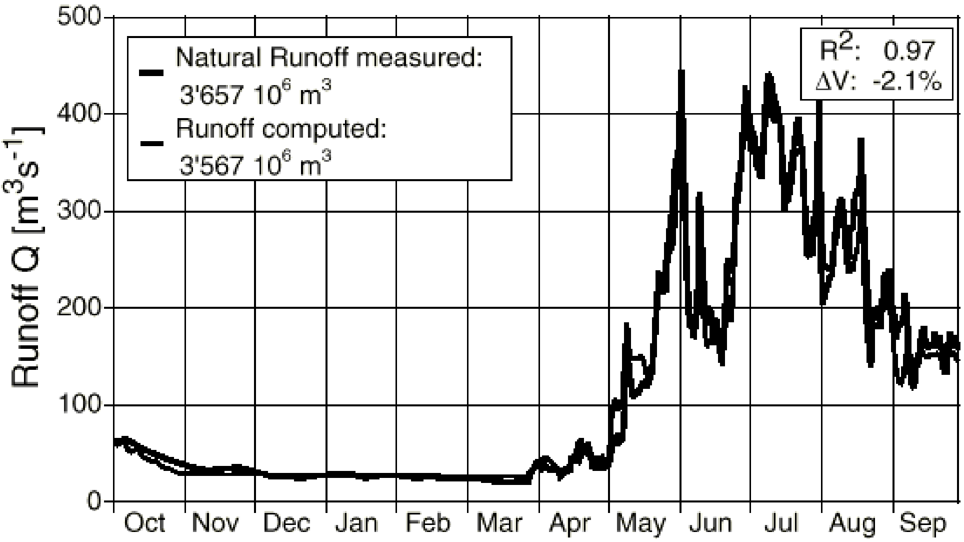

Figure 3. Natural runoff in the basin Rhône-Sion in the hydrological year 1985 compared with the computed runoff. ΔV = -2.1% means less runoff simulated than measured.

DERIVATION OF NORM YEAR CONDITIONS

In order to evaluate the effect of a climate scenario it is advisable to derive at first a normal-ized year which represents average conditions of the present climate (Ehrler et al., 97). The use of a normalized year makes it possible to compare the effect of a climate change in basins be-longing to different regions.

We performed normalizations of temperature and precipitation for the time period 1961 – 1991 on a daily basis. Together with normalized snow cover depletion curves these values build the norm year conditions. The normalization of the meteorological parameters is based on following formulas:

$$T_{i,norm} = T_i + (\overline{T}_{61-90} - \overline{T})$$

$$P_{i,norm} = P_i \cdot \frac{\Sigma P_{61-90}}{\Sigma P}$$

where T_i is the daily measured temperature, $\overline{T}_{61-90}$ the difference of long time monthly average of the period 1961 –1990 and $\overline{T}$ the actual monthly mean, P_i the daily measured precipitation, ΣP_{61-90} the monthly sum of the period 1961 –1990 and ΣP the monthly sum of the actual month. We derived the snow cover depletion of the norm year by reshaping curves of the snow cover depletion from the initial year to the normalized climate conditions.

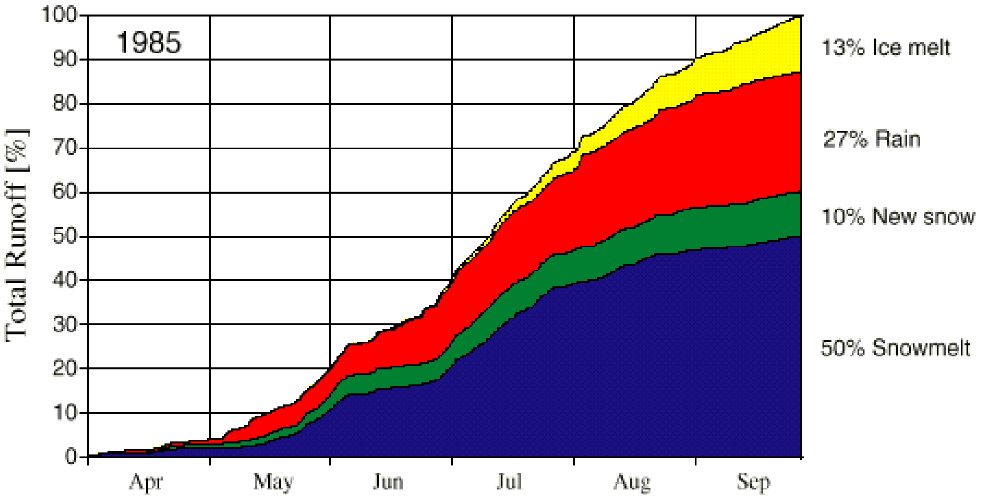

Figure 4. Contributions to runoff in April –September 1985 from the seasonal snow cover, new snow, rain and glacier.

With the norm year conditions for normalized temperature, precipitation and snow cover depletion we calculated the runoff of the norm year for the basin Rhône-Sion.

CLIMATE CHANGE SCENARIOS

As a further step, we investigated climate change simulations with various scenarios. The two selected scenarios (Table 2) are taken from the Intergovernmental Panel on Climate Change (IPCC) adapted to regional aspects by downscaling (WMO-UNEP, 1990).

Table 2. Regional climate scenarios based on downscaling of IPCC scenarios.

Basin	Year	Temperature		Precipitation	
		Winter	Summer	Winter	Summer
Rhône-Sion	2030	+0.9	+1.1	+5	-
	–2100	+2.9	+3.3	+10	-

The shown values refer to the average climate of the period 1961 – 1990. There will be no precipitation changes during summer.

The new snow cover for the climate scenarios has been determined using modified snow cover depletion curves (MDC) for each zone reshaping curves from the initial year to the average climatic conditions. MDC characterizes the snow cover depletion during the melt season (Hall and Martinec, 1985) . The MDC containes at the y-axis the extension of the snow cover as derived at certain dates from satellite remote sensing and interpolated by the model [%] and at the x-axis the calculated melt depths as derived from meteorological data [cm]. Changes of the MDC are a measure for a changing snow situation. The initial MDC include the new snow seen by the satellite, we call this *MDCincl*. Using the SRM+G, we can derive the MDC without new snow, called *MDCexcl*. This *MDCexcl* can be adapted to a new climate situation. The procedure enables us to take account for various snow conditions with data from only one year of satellite derived snow cover depletion.

The glacier vector data used in this study were derived from aerial photographs and field measurements and show an average state of the year 1973 which is a good representation for the norm year. Starting again from the norm year, we calculated the glacier areas for the two scenarios 2030 and 2100 by shifting the 2:1 equilibrium line (EL) according to the summer temperature change given in Table 2. The 2:1 EL assumes a distribution of 2 parts accumulation and 1 part ablation area on the glacier. Therefore the EL will be shifted +150 m with a 1ºC tem-perature rise. Corresponding to the EL shift we diminished the total glacier area.

Calculating the glacier scenarios for Rhône-Sion with the given summer temperature change, we derived a situation where the glaciers almost disappeared. The initial glacier area was 619 km^2. The calculated glacier areas for the climate change scenario 2030 was 560 km^2 with an EL rise of 165 m and for the 2100 scenario was 180 km 2 with an EL rise of 495 m. In the case of the more extreme scenario 2100 two third of the total glacier area disappeared. This "short-cut" method could be verified by deriving future stochastic series of precipitation and temperature in a changing climate and by year-to-year modelling of glacier behaviour. In Fig. 5 the resulting hydrographs for runoff computations for the scenario 2100 and the norm year conditions are plotted for comparison. The yearly runoff volume from the highly glaciated basin Rhône-Sion increases for the scenario 2100. We attribute this to the influence of glacier melt. This process will continue as long as the main part of the glaciers is melted. The hydrograph shows more runoff in winter and summer time. This indicates a shift from winter snowfall to winter rain. A part of the winter precipitation is not any more stored in the seasonal snow cover, but becomes promptly effective to the runoff.

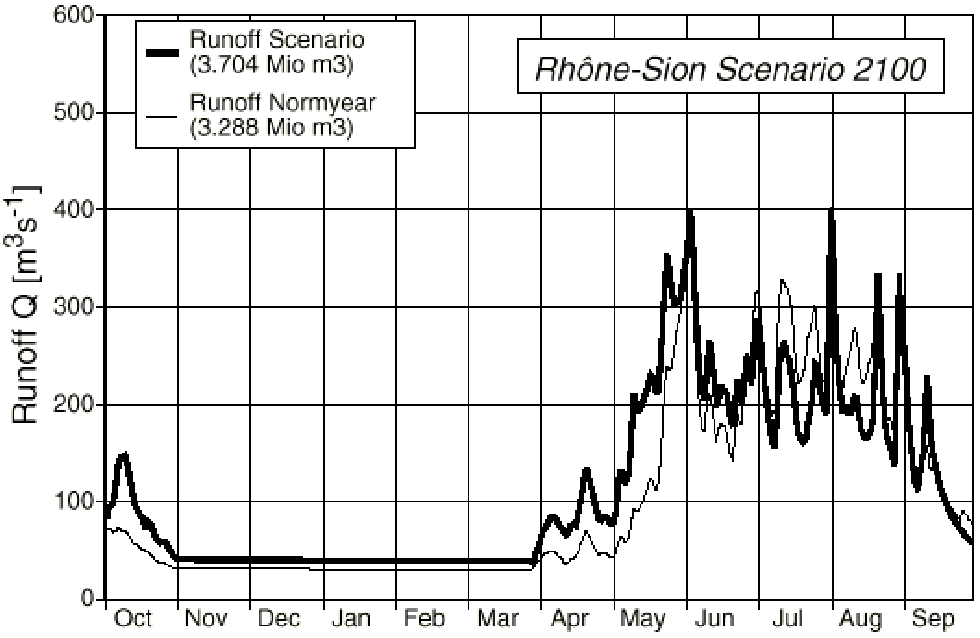

Figure 5. Runoff computation for the basin Rhône-Sion. The hydrograph for scenario 2100 shows a higher volume than for the norm year.

CONCLUSIONS

Accurate runoff modelling in a large high-alpine basin with a significant glacier area has been achieved by the following factors:

Advanced snow cover and glacier mapping using satellite data with a spatial resolution of 30 m as available from Landsat-TM and a pixel classification to the categories snow- and glacier-free, snow, ice.

Complementation of satellite images partially obscured by clouds.

Deriving depletion curves of the snow coverage taking into account daily temperatures.

Separate computation of snow- and ice melt.

Conditions for a norm year in terms of average daily values for the time period 1961 to 1990 derived for snow cover depletion, temperature and precipitation have been established. Based on norm year conditions the effect of climate change was evaluated for the scenarios 2030 and 2100, which are characterized by increasing temperatures during winter and summer and increased precipitation during winter. The results show the influence of increased summer icemelt in the basin Rhône-Sion.

The study demonstrates that enhanced monitoring of the spatial distribution of seasonal snow cover is needed in view of the climatic warming, in order to predict snow and glacier conditions as well as the changing runoff regime in high alpine basins in the 21st century.

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