HYDROLOGICAL APPLICATIONS OF SATELLITE SNOW COVER MAPPING IN THE SWISS ALPS

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ABSTRACT

In snow hydrology the importance of runoff modelling has been recognized even before remote sensing techniques became available. The areal extent of the seasonal snow cover is the main input variable for snowmelt runoff modelling. Based on Landsat, SPOT and NOAA/AVHRR data, runoff has been computed and forecasted in 13 basins of the Swiss Alps by the SRM model, apart from another 100 basins around the world. Satellite snow cover monitoring also serves for determining the duration of the snow cover, the areal water equivalent, as well as to evaluate the effect of a changed climate on snow conditions and runoff. A computer program is designed to exploit archived satellite data for evaluations of the snow accumulation in the past years.

INTRODUCTION

In Switzerland, remote sensing of the snow cover is especially important for hydrological applications, because 40% of the territory lies above 1,400 m a.s.l. as illustrated by Figure 1. At this altitude, 35% of precipitation is snow and 65% at 2,600 m a.s.l. (Dracos, 1980). Until the advent of remote sensing, water resources in the form of snow could only be estimated from terrestrial measurements which are insufficient particularly in altitudes above 2,000 m. Periodical mapping of the seasonal snow cover by satellites provides data for various hydrological purposes, as will be outlined in the following sections.

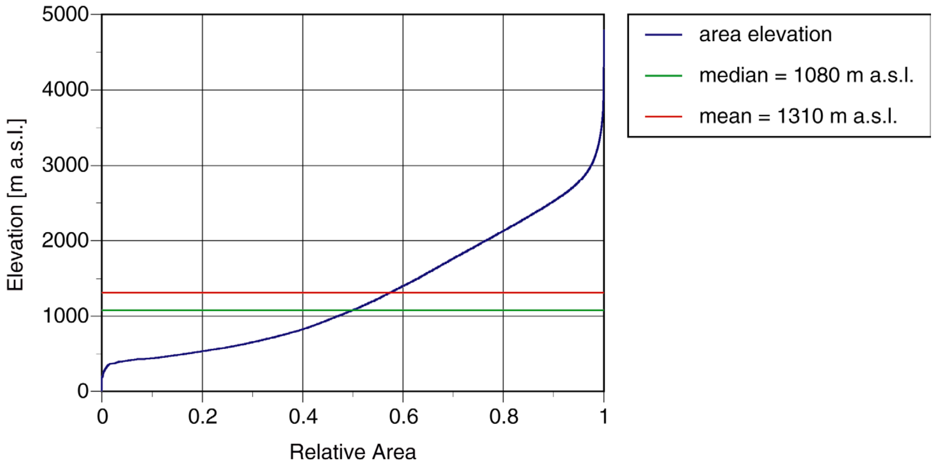

Figure 1: Area-Elevation for Switzerland (41'242 km)

Remote sensing of the alpine snow cover

Before the advent of remote sensing by satellites, the snow cover area was evaluated from orthophotos (Martinec, 1973). Figure 2 shows a comparison of the seasonal snow cover in the basin Dischma (43.3 km^2, 1,668 – 3,146 m a.s.l.), as seen from an airplane and by Landsat-MSS. An efficient periodical snow cover mapping on a larger scale is only possible owing to the development of the remote sensing technology. Figure 3 shows that a large part of the Swiss Alps has been mapped with the aim of computing the snowmelt runoff. In view of the great elevation range, the snow coverage is evaluated separately for elevation zones in 500 m steps, in order to facilitate snowmelt runoff computations.

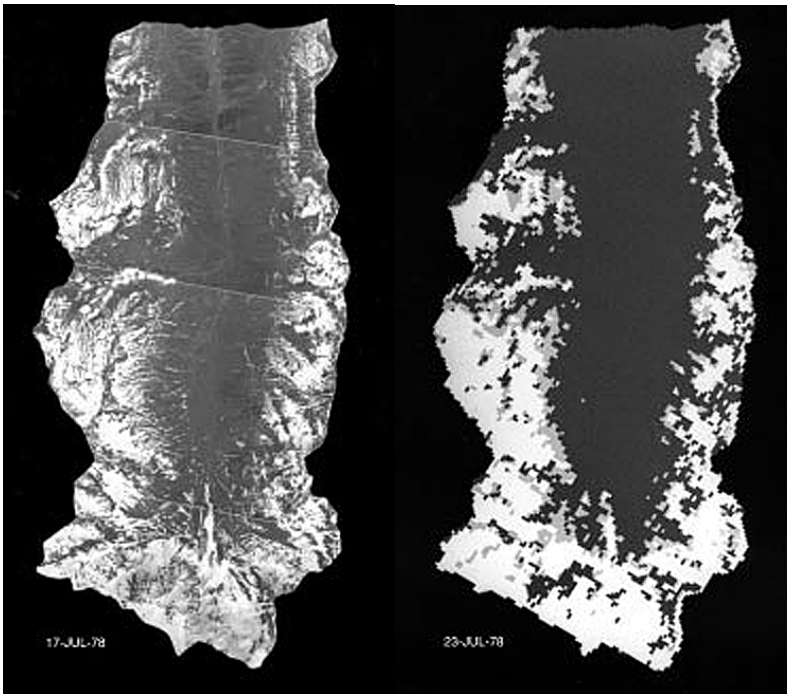

Figure 2: Comparative snow cover mapping in July 1978 in the basin Dischma (43.3 km, 1,668 – 3,146 m a.s.l., Eastern Swiss Alps). Left: Orthophoto, right: Landsat-MSS

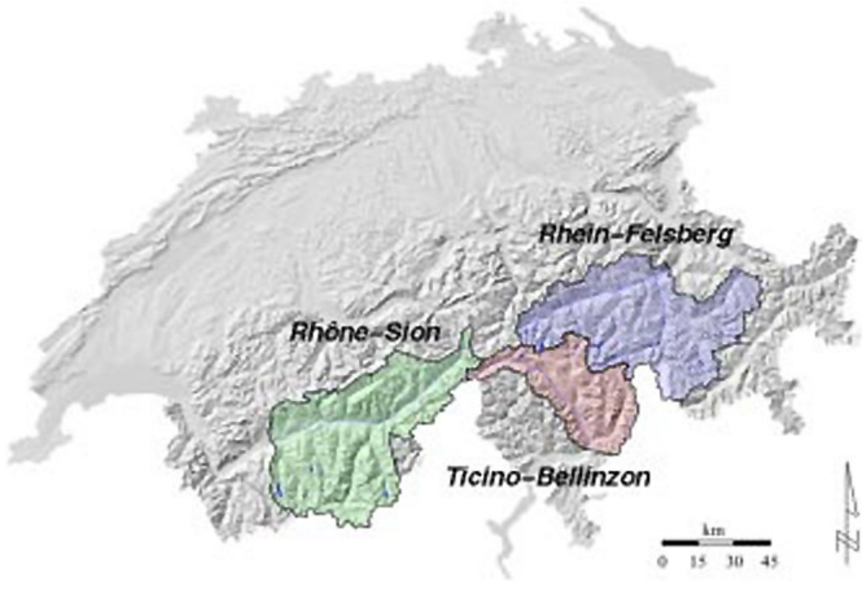

Figure 3: Location of various basins in Switzerland

A different approach was adopted in the Rhône basin at Sion with the aim of evaluating the duration of the snow cover (Brander et al., 2000): In a sequence of high resolution satellite images by Landsat-TM, the pixels were classified either as snow covered, transition zone or snow-free. For each pixel, the depletion behaviour was studied and the date was determined when it became snow-free. From these dates, snow cover duration maps have been compiled as shown in Figure 4 for the seasons of 1985 and 1998. These maps serve snow resource managers as snow reliability maps.

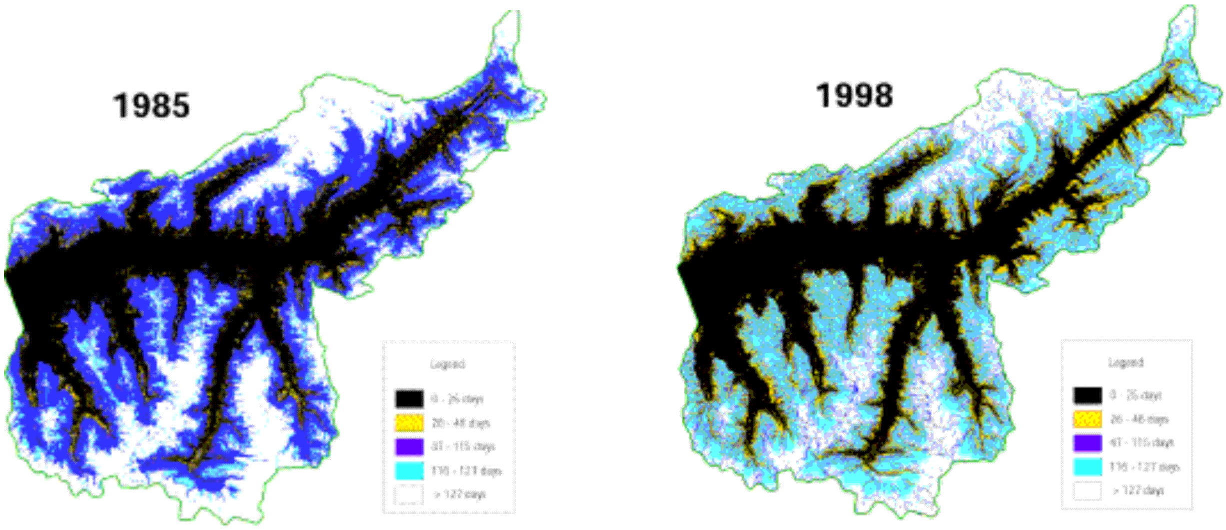

Figure 4: Snow cover duration map for the basin Rhône-Sion

Snow cover mapping in the visible range of the spectrum is often hampered by clouds. Owing to refined data processing combined with a Geographic Information System (GIS), a method was developed to restore satellite images of the snow cover partially obscured by clouds, thus improving the frequency of usable scenes. Clouds can be distinguished from the snow cover enabling pixels obscured by clouds to be identified. Then, the satellite images are combined with the so-called Snow Cover Units, SCU (Ehrler et al., 1997). These are obtained by overlaying the features such as ground properties, climatic region, elevation, aspect and slope.

Studies with microwave sensors aim at achieving all-weather snow cover monitoring and at obtaining further information about the snow cover and glaciers (Haefner and Piesbergen, 1997, Nagler and Rott, 1997).

Runoff simulations and forecasts

The areal extent of the seasonal snow cover is the principal input variable for the Snowmelt Runoff Model (SRM). The importance of this information is evident from a simplified version of the model formula:

(1)

$$Q_{n+1} = c(M_n \cdot S_n + P_n)A \cdot \frac{10000}{86400}(1 - k_{n+1}) + Q_n k_{n+1}$$

where

- Q is the average daily discharge [$m^3 s^{-1}$],
- c the runoff coefficients expressing the losses,
- M the daily snowmelt depth [cm],
- S the ratio of snow covered area to total area,
- P the precipitation contributing to runoff [cm],
- A the area of the basin or zone [km^2],
- K the recession coefficient,
- n the sequence of days,
- $\frac{10000}{86400}$ the conversion from [cm $km^2 d^{-1}$] to [$m^3 s^{-1}$]

The meltwater production is directly proportional to the snow coverage which gradually declines from 100% to zero during the snowmelt season. The periodicity of the satellite overflights is exactly what is needed to monitor this process. Also, satellites cover larger areas than terrestrial snow cover maps and aircraft photography. Consequently, remote sensing enabled the SRM model to be applied in larger and larger basins in the Swiss Alps which are listed in Table 1.

Table 1: Satellite snow cover mapping and runoff modelling in Switzerland

	Basin	Size [km^2]	Elevation range [m a.s.l.]	Years (seasons)	R^2 [1]	D_v [%]	Published
1.	Dischma	43 .3	1668-3146	10	0.86	2.5	1975
2.	Rhône-Gletsch	38 .9	1755-3630	1	n/a	n/a	1980
3.	Sedrun	10 8	1840-3210	2	0.79	1.9	1985
4.	Landwasser	18 3	1500-3146	1	n/a	n/a	1982
5.	Tavanasa	21 5	1277-3210	2	0.82	3.1	1985
6.	Tiefencastel	52 9	837-3418	2	n/a	n/a	1982
7.	Ilanz	77 6	693-3614	2	n/a	n/a	1982
8.	Massa-Blatten	19 6	1447-4191	1	0.92	11. 1	1999
9.	Ticino-Bellinzona	15 15	220-3402	1	0.86	0.6	2000
10.	Inn-Martina	19 43	1030-4049	1	0.82	4.3	1995
11.	Inn-Tarasp	17 00	1165-4049	1	0.77	8.0	2000
12.	Rhine-Felsberg	32 49	562-3425	7	0.7	7.2	1998
13.	Rhône-Sion	33 71	491-4634	1	0.95	0.0 2	2000

The global satellite monitoring enabled the model to be used in further 100 basins in the world, mostly by independent operators and various institutions. Examples of runoff simulations in Switzerland are shown in Figure 5, Figure 6, Figure 7, and Figure 8.

Figure 5: Runoff simulation in Rhine-Felsberg (3,249 km, 562-3,425 m a.s.l.)

1 R^2 = coefficient of determination, D_v = difference of the runoff volume (absolute values).

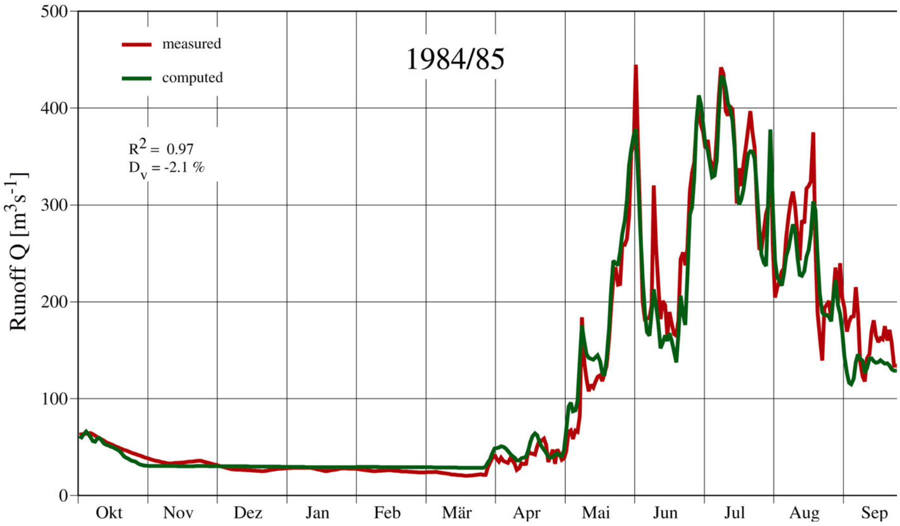

Figure 6: Runoff simulation in Rhône-Sion (3,371 km, 491-4,634 m a.s.l.)

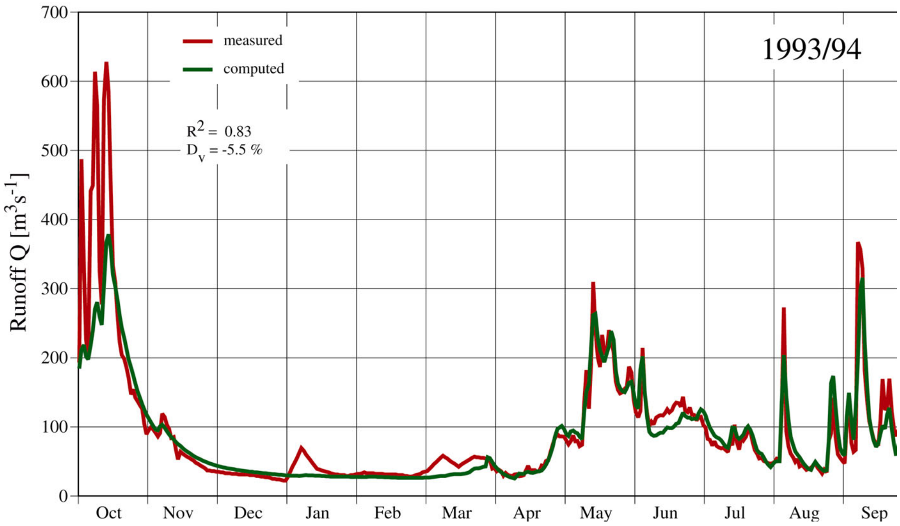

Figure 7: Runoff simulation in Ticino-Bellinzona (1,515 km, 220-3,402 m a.s.l.)

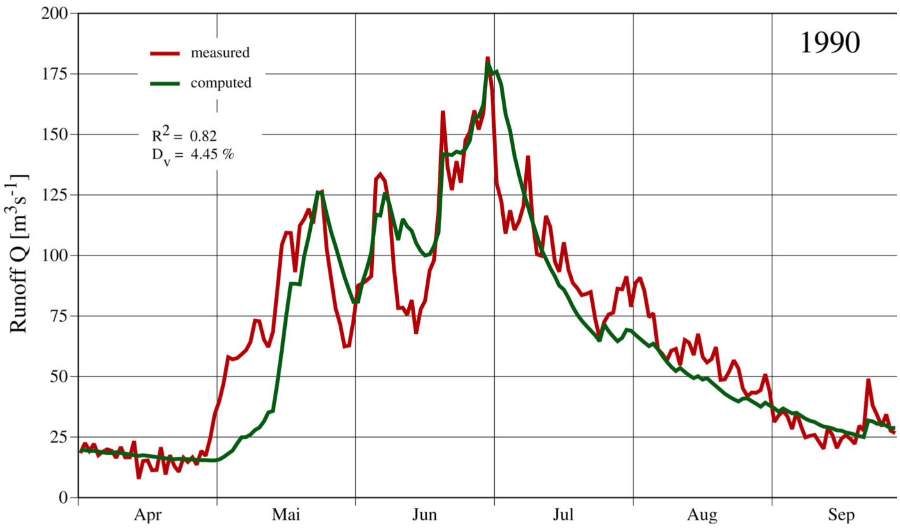

Figure 8: Runoff simulation in Inn-Martina (1,943 km , 1,030-4,049 m a.s.l.) (after Baumgartner and Rango, 1995)

For seasonal runoff forecast in terms of months, it is necessary to evaluate the water equivalent of the snow cover. To this effect, the conventional depletion curves of the snow coverage are converted by the SRM computer program (Martinec et al., 1998) to the modified curves as explained elsewhere (Hall and Martinec, 1985). These curves relate the snow coverage to computed cumulative snowmelt depths. They indicate what cumulative snowmelt depth is necessary in order to reduce the snow coverage to a certain percentage of the total area. The area below a modified depletion curve indicates the areal average water equivalent of the snow cover on the starting date. Figure shows the regional distribution of snow in terms of the water equivalent in presected partial areas of the basin Rhine-Felsberg (Martinec et al., 1991, Seidel et al., 1996). At comparable altitudes, the snow accumulation on 1 April decreases from West to East in all studied years. In the North-South direction, the distribution of anomalies is inconsistent.

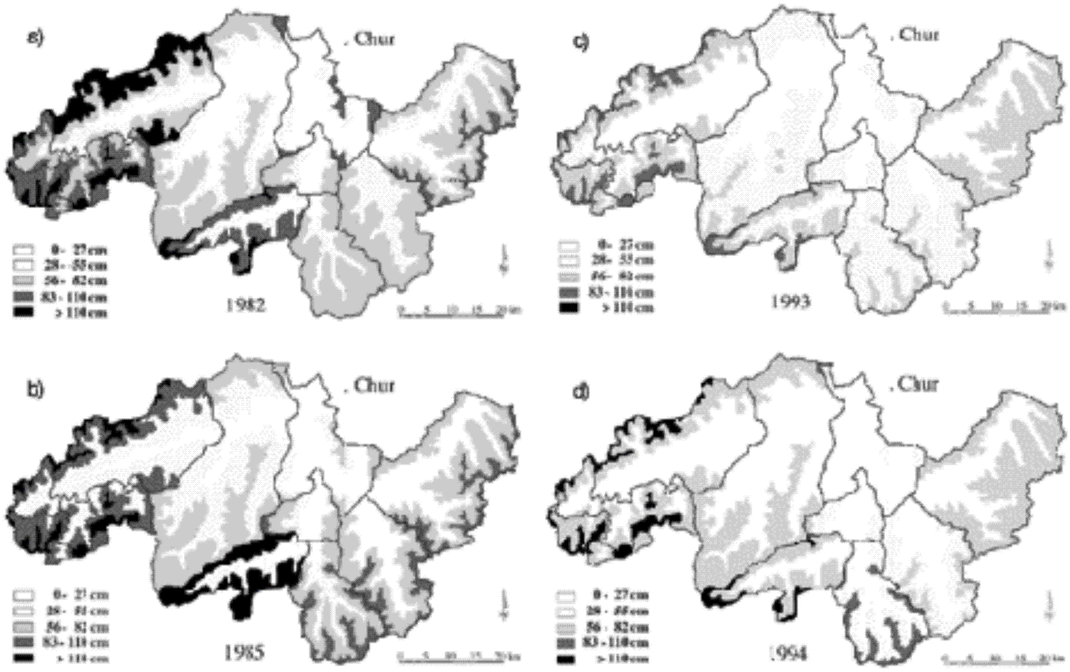

Figure 9: Distribution of snow in terms of areal average water equivalent in the Rhine-Felsberg basin on 1 April 1982, 1985, 1993, and 1994

This information is available at the end of the snowmelt season. In order to be used for seasonal runoff forecasts, such evaluations must be related to index point measurements carried out at the forecast date. Apart from seasonal runoff forecasts, modified depletion curves can be used to characterize snow conditions in the Alpine regions. At present, archived data serve to evaluate snow cover areas in the past years. This information can be made relevant for seasonal runoff forecasts by deriving the regional distribution of snow accumulation in historical years.

Short-term runoff forecasts are also feasible, since temperature forecasts and quantitative precipitation forecasts are becoming available with an improving quality (Brüsch 1996, Seidel et al., 1990, Kleindienst et al., 1999). To this effect, the snow coverage as the third model input variable must always be extrapolated ahead from the forecast date by forecasted temperatures as explained in detail elsewhere (Hall and Martinec, 1985).

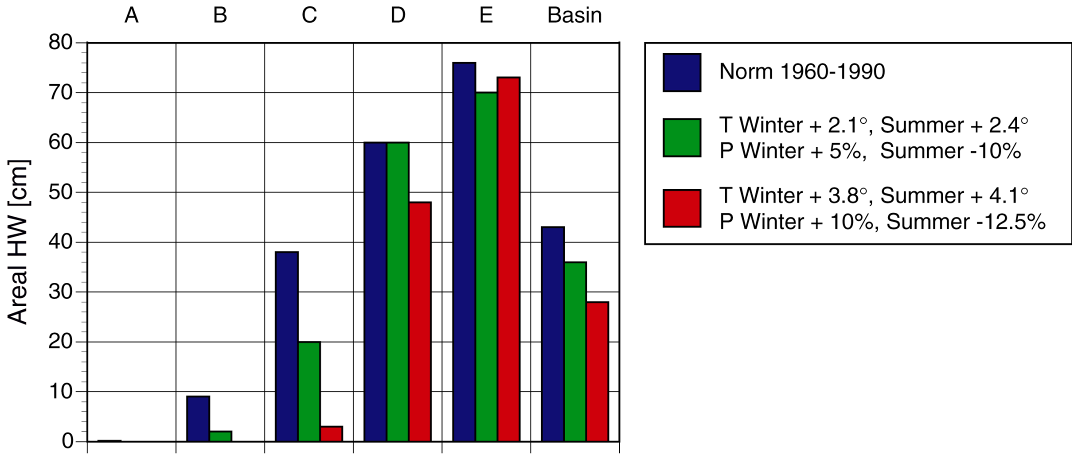

Figure 10: Changes of the areal water equivalent on 1 April in the respective elevation zones of the Rhine-Felsberg basin

Effect of climate change on snow cover and runoff

Satellite snow cover mapping in present times can also serve to derive changes of snow conditions and runoff due to the changing climate. As mentioned, the modified depletion curves of the snow coverage indicate, how much cumulative snowmelt depth is necessary in order to reduce the snow cover area to a certain percentage of the total area for the given starting snow cover. In a warmer climate, this cumulative snowmelt depth will be reached at an earlier date and the conventional depletion curves of the snow coverage will be shifted accordingly. Using these climate-affected curves together with precipitation and temperatures given by a climate scenario, the future changed runoff is computed.

It must also be taken into account that in a warmer winter more snow will be melted and some snowfalls will be converted to rainfalls. This results in a smaller snow accumulation at the start of the snowmelt season. By way of example, this change is evaluated for the climate scenarios as defined in Table 2 according to the Intergovernmental Panel on Climate Change, IPCC (Jaeger and Ferguson, 1991).

Table 2: Climate change scenarios according to IPCC for Southern Europe

Scenario	Winter		Summer	
	T	P	T	P
0 (=norm)	0	0	0	0
1	+2.1°	+5%	+2.4°	-10%
2	+3.8°	+10%	+4.1°	-12.5%

Figure 10 shows the changes of the areal water equivalent on 1 April in the respective elevation zones of the basin Rhine-Felsberg as compared with the normalized values for the period 1961-1990 (after Ehrler, 1998). In the top zone E (2,600 - 3,614 m a.s.l.), winter temperatures are too low to allow a distinct increase of snowmelt. Consequently, the effect of global warming is more or less compensated by the increase of winter precipitation. In the zone D (2,100 - 2,600 m a.s.l.), the effect is noticeable for scenario 2. The snow water equivalent is considerably reduced in the zone C (1,600 - 2,100 m a.s.l.) and in the zone B (1,100 - 1,600 m a.s.l.), in which there is no snow left for scenario 2. In the lowest zone A (575 - 1,100 m a.s.l.), there is no snow on 1 April in the present as well as in the future climate.

The depletion curves of the snow coverage are thus influenced not only by the increased snowmelt in the summer, but also by this winter adjustment of the snow accumulation on 1 April.

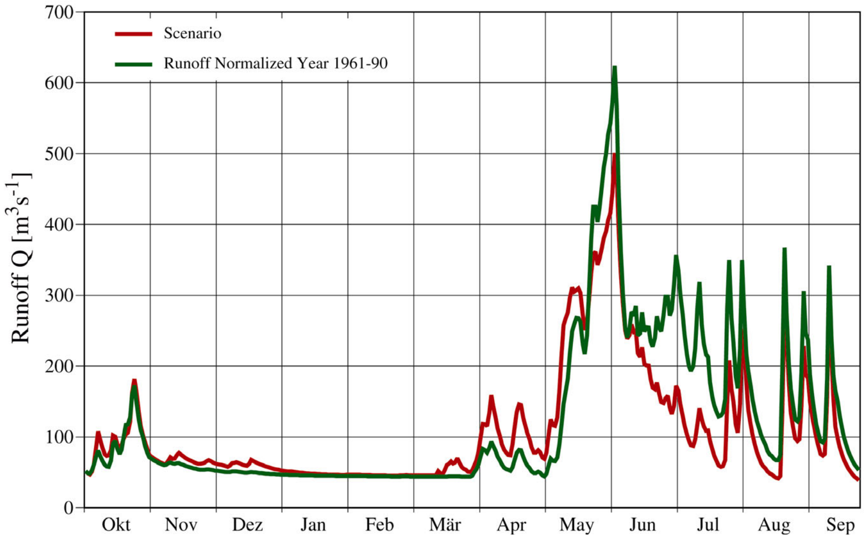

Figure 11: Effect of climate scenario 1 on runoff (see Table 2)

Figure 11 illustrates the effect of the climate scenario 1 on runoff. There is a slight increase of runoff in winter, more runoff in April and in the first part of May, followed by a decrease in the rest of the snowmelt season. This effect is accentuated by the scenario 2 as shown in Figure 12. There are additional rainfall peaks in the winter and the snowmelt season starts earlier. The runoff volume in the winter half year increases at the expense of the summer half-year. The comparison refers to a normalized year derived for the period 1961-1990, which represents today's climate.

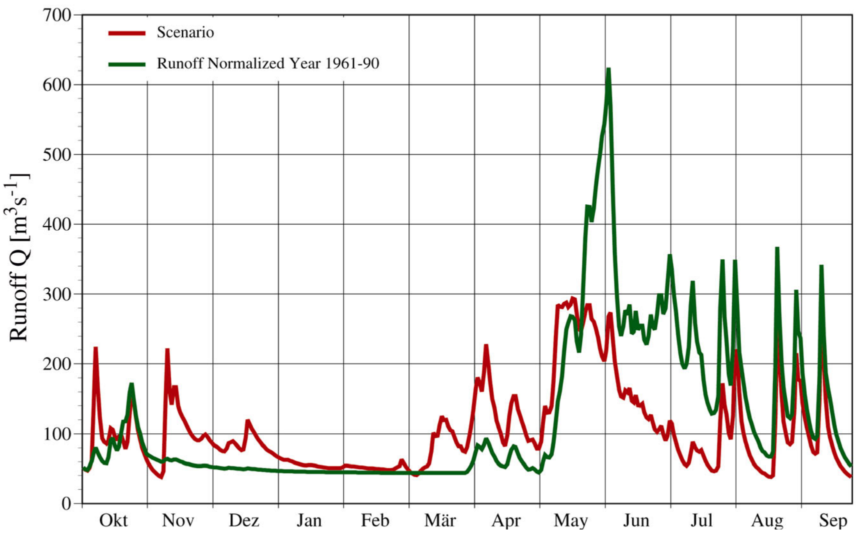

Figure 12: Effect of climate scenario 2 on runoff (see Table 2)

CONCLUSION

Examples from the Swiss Alps indicate various possibilities of applying remote sensing and GIS techniques in snow hydrology. For water management and winter tourism, assessments of the present and future snow conditions as well as changes of the runoff regime can be extended using archived satellite data.

In order to take full advantage of this material, snow conditions should be characterized not only by snow covered areas, but also (for the benefit of runoff forecasts) in terms of areal snow water equivalents. While the example in Figure 9 is limited to one Alpine basin and four years, more years and other Alpine regions can be readily evaluated by the SRM computer program.

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