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Advances in remote sensing of snow and ice for modelling the runoff process

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ABSTRACT: Satellite monitoring of the seasonal snow cover in the visible range of the spectrum has been constantly improved thanks to a better spatial resolution. Sensors were introduced enabling snow, clouds and glacier ice to be distinguished. Thanks 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. Each progress resulted in an improvement of the performance of the SRM snowmelt runoff model, because the snow coverage mapped by satellites is used as a direct input and because new methods of data evaluation were developed. Among the presented examples are: Regional distribution of the snow water equivalent in the basin Rhine-Felsberg (3250 km^2, 562 - 3425 m a.s.l.), runoff modelling in the basin Rhône-Sion (3371 km^2, 491 - 4634 m a.s.l., 17% glacier area), evaluation of the effect of climate change on winter snow accumulation, on snow covered areas and runoff in the basin Rhine-Felsberg.

1 INTRODUCTION

Thanks to its contrasting appearance on the Earth's surface, snow is since 30 years one of the main targets of remote sensing. The role of snow cover mapping in snowmelt runoff computations has been recognized even earlier (Garstka et al., 1958, Leaf, 1967). However, expensive terrestrial expeditions were necessary and therefore the use of directly measured snow covered areas was restricted to small experimental basins. In the framework of the comparison of snowmelt runoff models organized by the World Meteorological Organization (WMO, 1986) all models with one exception simulated an artificial snow cover from precipitation and temperature data. A recent European project (HYDALP, 2000) showed that satellite monitoring of the snow cover is increasingly recognized as a useful tool for runoff forecasts. This paper deals with improvements of snow cover and glacier mapping by satellites and with parallel refinements of runoff modelling.

2 SNOW COVER MAPPING

At present, most runoff models still rely on producing a synthetic snow cover from precipitation and temperature data. Remote sensing data is used only for an auxiliary comparison with the modelled snow cover (Udnaes et al., 2002). The snowmelt runoff model (SRM) uses satellite data as a direct input variable from the beginning. It was thus possible to recognize problems of this approach and to develop solutions.

At first, orthophotos were used to verify the evaluation of Landsat-MSS images of the snow cover. Fig. 1 shows the seasonal snow cover in the test basin Dischma in the Swiss Alps (43.4 km^2, 1668 - 3146 m a.s.l.), as evaluated from Landsat data and as photo-

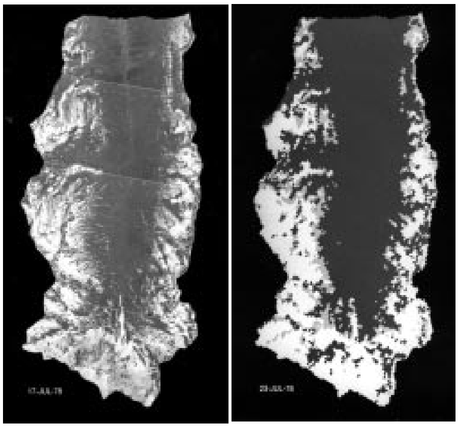

Figure 1. Comparison of an orthophoto and of a Landsat-MSS image of the seasonal snow cover in the test basin Dischma (43.4 km^2, 1668 - 3146 m a.s.l.)

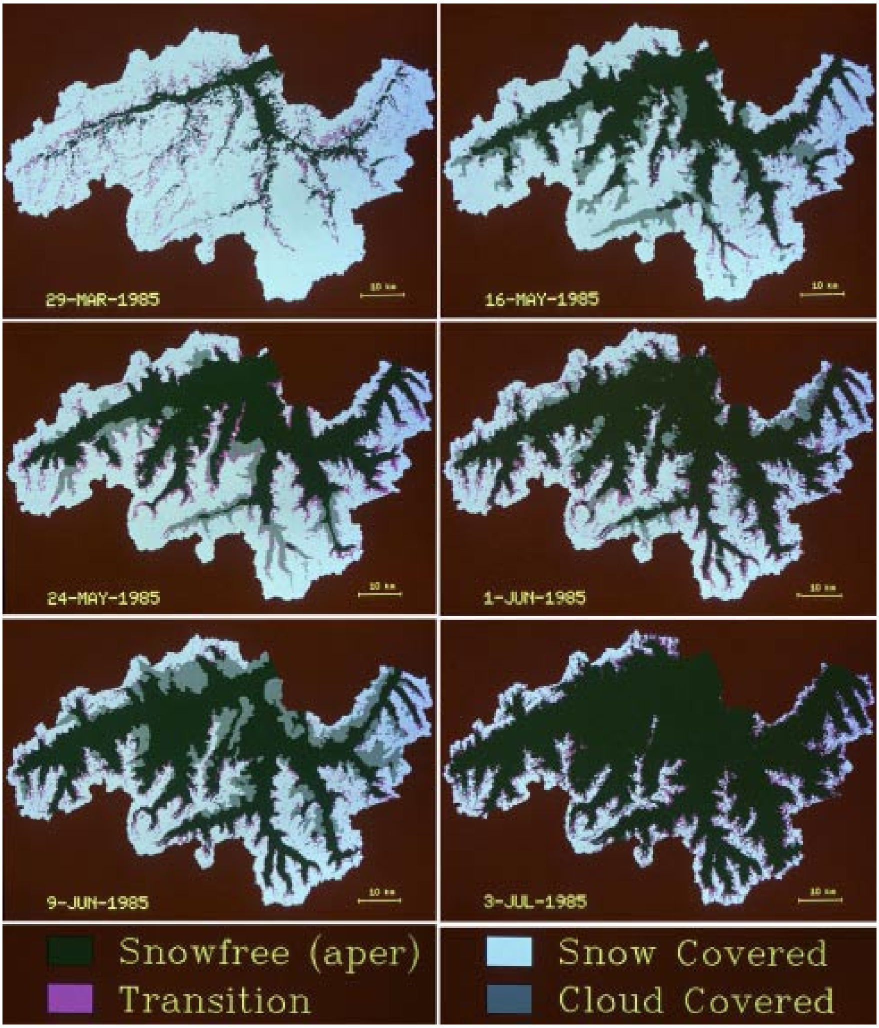

Figure 2. Sequence of Landsat-MSS images of the seasonal snow cover in the basin Rhine-Felsberg (3250 km^2, 562 - 3425 m a.s.l.)

graphed from an aircraft. An example of periodical snow cover mapping on a larger scale is shown in Fig. 2. In order to provide daily values of the snow coverage, the depletion curves must be interpolated between the measured points. Early applications of these curves revealed a problem with occasional summer snowfalls illustrated by Fig. 3. If a snowfall occurs just before a satellite overflight, the new short-lived snow cover distorts the depletion curve of the snow coverage due to a false interpolation and a non existing snow cover is taken into account for the run-off computation (Hall and Martinec, 1985). Therefore satellite images showing new snow during the snow-melt season must be eliminated from the interpolation. The new snow is not lost: one part is integrated into the seasonal snow cover and the other part becomes the precipitation input.

Another problem with remote sensing in the visible range is the interference of clouds. This concerns particularly Landsat in view of the interval of 16-18 days between overflights. By advanced processing of satellite data, clouds can be distinguished from the snow cover enabling pixels obscured by clouds to be identified. The satellite images are combined with the so-

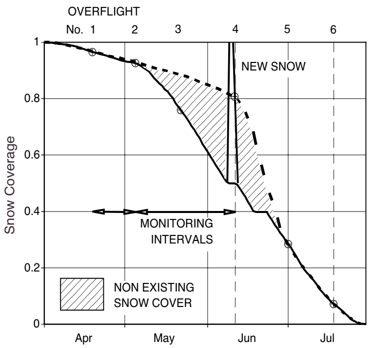

Figure 3. Hypothetical example of distortion of a depletion curve due to a temporary increase of the snow coverage by a summer snowfall and to missing Landsat data from the preceding overflight

called Snow Cover Units, SCU (Ehrler et al., 1997). These are obtained by overlaying the features such as ground properties, elevation, aspect and slope. Fig. 4 shows the effect of slope on the snow coverage in the elevation zone 2100 - 2600 m a.s.l. of the basin Rhine-Felsberg (3250 km^2, 562 - 3425 m a.s.l.). For example, when the snow coverage of this zone is 50%, it is still 68% in pixels with flat terrain (slope <8°), but only 28% for a slope >36°. In order to extrapolate the snow coverage from an unobscured pixel to a pixel covered with clouds, it is necessary to identify a corresponding pixel with comparable properties referring to the mentioned features. With the use of Snow Cover Units (SCU), incorporated in a GIS, it is thus possible to restore considerably satellite images partially obscured by clouds. Consequently, the frequency of snow cover mapping by high resolution

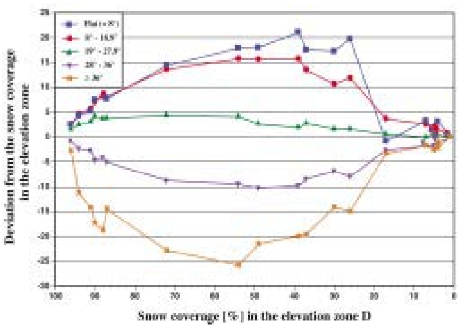

Figure 4. Effect of slope: Deviations from the average snow coverage in the elevation zone 2100 - 2600 m a.s.l., basin Rhine-Felsberg, compiled from snow cover maps in 6 years

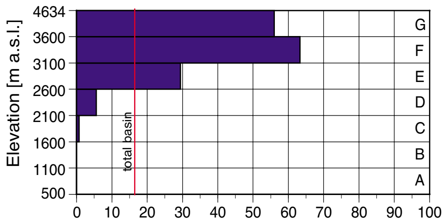

Figure 5. Areas of glaciers in the elevation zones of the basin Rhône-Sion (3371 km^2, 491 - 4634 m a.s.l.)

sensors like Landsat-TM and SPOT-XS can be significantly improved in unfavourable years, enabling the depletion curves of the snow coverage to be derived.

In glacierized basins, the model input from snow- and icemelt is more accurately computed if the snow cover and glaciers can be mapped separately. The lower albedo of glacier ice as compared even with old snow can be properly taken into account, either by adjusting the degree-day factor (which includes the radiation component) or in a more complete energy balance computation.

The basin of the river Rhône at Sion (3371 km^2, 491 - 4634 m a.s.l.) may serve as an example for this refined satellite mapping (Schaper et al., 2000). Fig. 5 shows the areas of glaciers in the respective elevation zones. Each elevation zone is thus divided into a glacier-free area and glacier area. The depletion curves of the snow coverage in these respective areas of the zones C, D, E are shown in Fig. 6. The decline of the seasonal snow cover overlaying glaciers is lagging behind the decline in the glacier-free areas. For example, in the zone D on 30 June 1985, snow covered 25% of the glacier-free area and 55% of the glacier area. Such results can be obtained thanks to the good spatial

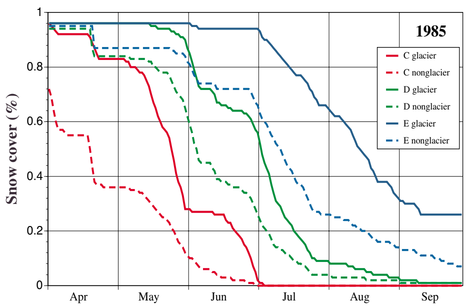

Figure 6. Depletion curves of the snow coverage for glacier-free and glacier areas of the zones C, D, and E within the basin Rhône-Sion

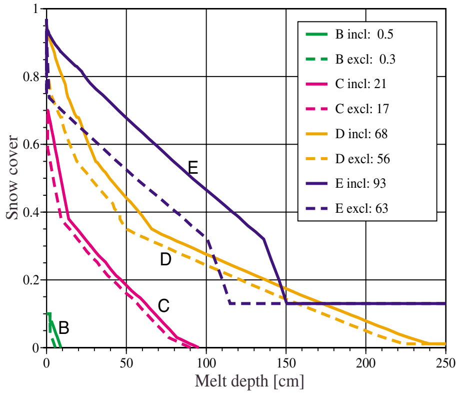

Figure 7. Modified depletion curves derived in the basin Rhine-Felsberg, 1994, and the resulting snow water equivalents on 1 April

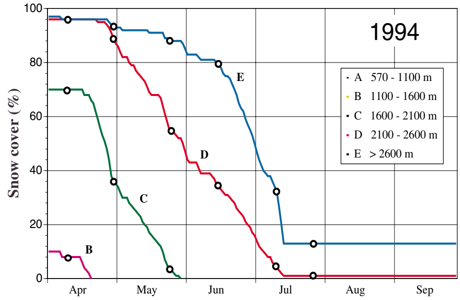

Figure 8. Conventional depletion curves derived in the basin Rhine-Felsberg, 1994

resolution of the Landsat-TM sensor and thanks to advanced methods of satellite data processing (Ehrler and Seidel, 1995) which make possible to distinguish between snow and ice.

3 AREAL WATER EQUIVALENT FROM SNOW COVER MAPPING

The depletion curves of the snow coverage can be used not only for runoff computations, as will be explained in the next section, but also to derive the areal water equivalent of the seasonal snow cover. Fig. 7 shows the so-called modified depletion curves (MDC) derived in the basin Rhine-Felsberg (Ehrler,

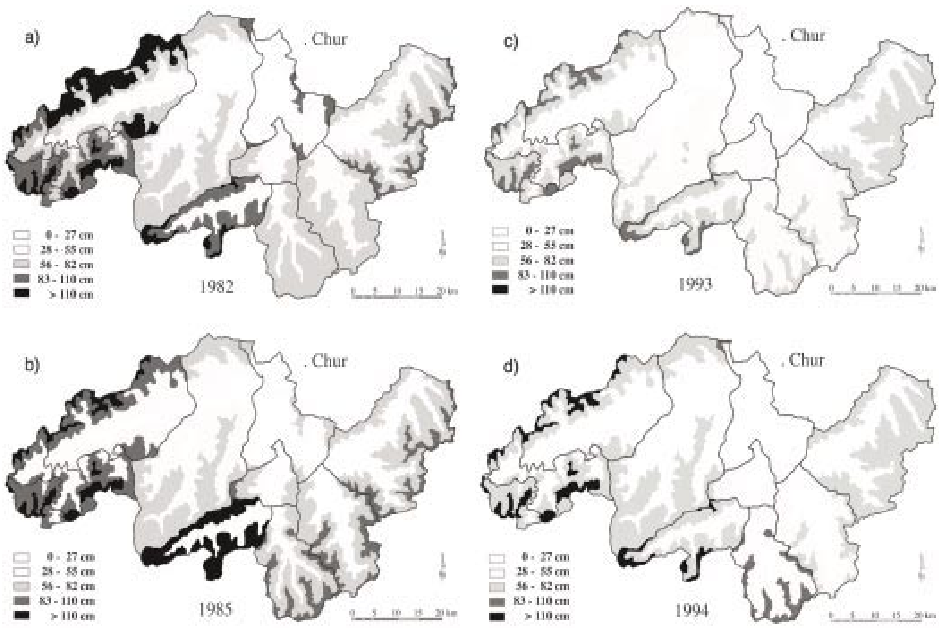

Figure 9. Areal water equivalents in 10 partial areas and 5 elevation zones of the basin Rhine-Felsberg, derived from periodical snow cover mapping and modified depletion curves

1998). The time scale of the conventional depletion curves (CDC) is replaced by cumulative computed melt depths. If intermittent snowfalls are excluded, the area below an MDC_{EXCL} indicates the water equivalent on the starting date. If intermittent snowfalls are included, MDC_{INCL} serves to derive conventional depletion curves as shown in Fig. 8. As opposed to CDC's obtained directly from satellite data by normal interpolation, these curves, similarly as curves shown in Fig. 6, take into account temperature fluctuations during the snowmelt season. The method of evaluating the snow water equivalent from snow cover mapping was verified by direct terrestrial measurements in the Dischma test basin (Martinec and Rango, 1987). The areal water equivalents of the seasonal snow cover can be evaluated not only for elevation zones as shown in Fig. 7, but also in more detail by dividing a basin into partial areas mapped separately. Fig. 9 illustrates water equivalents in 10 partial areas and 5 elevation zones of the Rhine-Felsberg basin (Seidel et al., 1996). If several years are available, regional patterns of the snow accumulation can be evaluated.

4 RUNOFF MODELLING

Along with the progress in remote sensing, the number of basins around the world with SRM runoff modelling exceeded 100. The importance of snow cover mapping is evident from the simple model concept:

$$Q_{n+1} = (c_{Sn} a_n T_n S_n + c_{Rn} P_n) A \frac{10000}{86400} (1 - k_{n+1}) + Q_n k_{n+1} \quad (1)$$

where

Q	average daily discharge [$m^3 s^{-1}$]
c_R,c_S	runoff coefficients for rain and snow expressing the losses
a	degree-day factor [cm °C^{-1} d^{-1}]
T	number of degree-days [°C d]
S	ratio of snow covered area to total area
P	precipitation contributing to runoff [cm]
A	area of the basin or zone [km^2]
$\frac{10000}{86400}$	conversion from [cm km^2 d^{-1}] to [m^3 s^{-1}]
k	recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall
n	sequence of days

If snowmelt and icemelt are to be computed separately in glacierized basins, the formula is rewritten as follows:

$$Q_{n+1} = [c_{Sn}(a_{Sn} T_n S_{Sn} A_S + a_{Sn} T_n S_{Gn} A_G + a_{Gn} T_n (1 - S_{Gn}) A_G) + c_R P_R (A_S + A_G)] \bullet \frac{10000}{86400}(1 - k_{n+1}) + Q_n k_{n+1} \quad (2)$$

where

a_S	degree-day factor for snow
a_G	degree-day factor for glacier ice
S_S	snow coverage on glacier-free area
S_G	snow coverage on glaciers
A_S	glacier-free area of a zone
A_G	glacier area in a zone

For illustration of the model concept, Eq. 1 and Eq. 2 refer only to a single zone. The computer program takes into account a required number of elevation zones, includes a formula for evaluating the variable recession coefficient and an algorithm for new snow during the snowmelt period.

Based on Eq. 2 and satellite mapping of the snow and glaciers, runoff in the basin Rhône-Sion was simulated as shown in Fig. 10. If Eq. 1 is used, a mixed value of the degree-day factor can be obtained from the respective snow and ice areas.

Referring to earlier SRM simulations in the framework of a WMO project (WMO, 1986), Klemes (1990) points out that the appropriate parametrization and direct inputs of the right kind (in this case the snow cover area) enables this model to manage with just 7 parameters while some calibration models need 30 or more parameters without achieving a better accuracy.

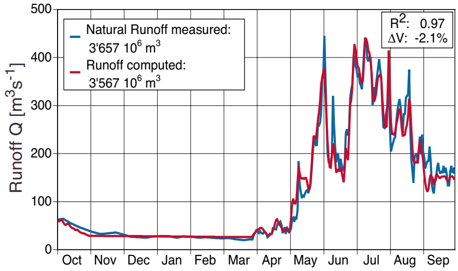

Figure 10. Natural runoff in the Rhône-Sion basin in the hydrological year 1985 compared with the computed runoff. R^2 = coefficient of determination, D_v = difference of the runoff volume (less runoff simulated than measured)

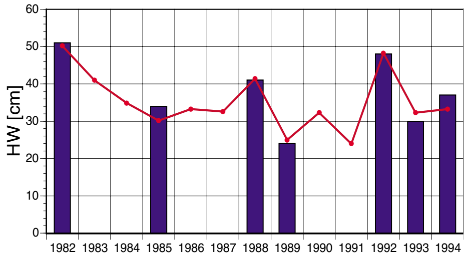

Figure 11. Average water equivalent of the seasonal snow cover on 1 April in the basin Rhine-Felsberg from MDC_{EXCL} compared with point measure–ments at Weisfluhjoch (red line), 2540 m a.s.l., with conversion factor 0.5.

5 RUNOFF FORECASTS

As a renewable source for hydroelectricity production, snow always had a prominent place in cost/benefit analyses of remote sensing (Castruccio et al., 1980). Terrestrial point measurements of the snow water equivalent in mountain basins are insufficient for evaluating snow reserves at the beginning of the snowmelt season. Such information for seasonal runoff forecasts becomes available thanks to satellite snow cover mapping and the development of modified depletion curves (see Fig. 9), but not in real time. However, relations can be derived between point measurements and areal snow water equivalent. Fig. 11 shows that the average snow water equivalent in the basin Rhine-Felsberg on 1 April may be represented by values of point measurements at Weisfluhjoch, 2540 m a.s.l., which are available in real time, by a conversion coefficient of 0.5.

Short-term runoff forecasts several days ahead are also possible because not only temperature forecasts, but also quantitative precipitation forecasts are increasingly becoming available. As the third input variable, the future course of the depletion curves of the snow coverage is extrapolated from curves updated by satellite mapping, with the use of modified depletion curves (MDC) (see Fig. 7) and of temperature forecasts. If, for example, a total snowmelt depth of 10 cm is computed for the next 5 days from the temperature forecast, MDC_{INCL}, zone D, for the snow cover of 1994 indicates the resulting decrease of the snow coverage from 0.45 to 0.40. Recalling conventional depletion curves in Fig. 8, the snow coverage 0.45 occurred on 31 May and the coverage of 0.4 can be forecasted for 5 June. The depletion curve thus projected for next 5 days is then used for running forecasts, which can be updated by measured temperatures and precipitation as soon as the data is reported.

Evidently the accuracy of runoff forecasts depends not only on the model and timely evaluations of satellite data, but also on the quality of temperature and precipitation forecasts. An example of streamflow forecasts for a hydroelctric company in the basin of the river Inn at Tarasp (1700 km^2, 1165 - 4004 m a.s.l.) is described in the Report of an European project aiming at an application of Earth Observation (EO) data in order to improve modelling and forecasting of daily runoff in Alpine and high latitude basins where snowmelt is important (HYDALP, 2000). An earlier example (Kawata and Ueno, 1987) refers to an application of Landsat data and SRM for optimizing the water level in a reservoir of a hydroelectric plant.

If short term and seasonal runoff forecasts are improved thanks to satellite snow cover mapping, an optimum water level in the river reservoirs can be maintained in order to increase the electric production by avoiding water losses due to overflow as well as flood control and water allocation.

Looking farther ahead into the future, the changing climate will infuence snow conditions and the runoff regime. These effects must also be predicted for long term planning of the water management.

6 EFFECT OF CLIMATE CHANGE ON SNOW COVER AND RUNOFF

The changing climate opens a new field of applications for hydrological models. Calibration models appear not to be suitable for this new task. Nash and Gleick (1991), for example, pointed out that various combinations of parameter values can provide equally good agreement with observed data, but would react differently to a changed climate input. The SRM model has no such problem, because parameters are estimated from real world characteristics. Even the difficulty with real time disappears because any historical year with good satellite data or a normalized year can represent today's climate. Instead of model-

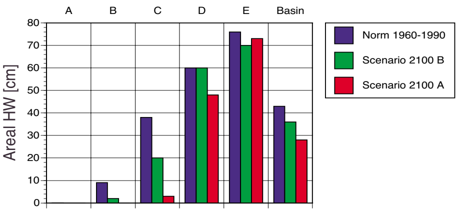

Figure 12. Effect of a changed climate on winter accumulation of snow in the basin Rhine-Felsberg.
2100 A: T Winter +3.8°, Summer +4.1°
P Winter +10%, Summer -12.5%
2100 B: T Winter +2.1°, Summer +2.4°
P Winter +5%, Summer -10%

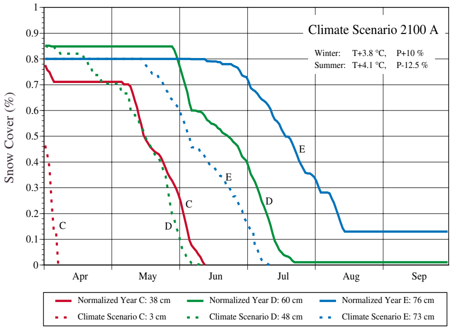

Figure 13. Effect of a changed climate on snow cover areas in the basin Rhine-Felsberg, Scenario 2100 A, depletion curves for the elevation zones C, D, E.

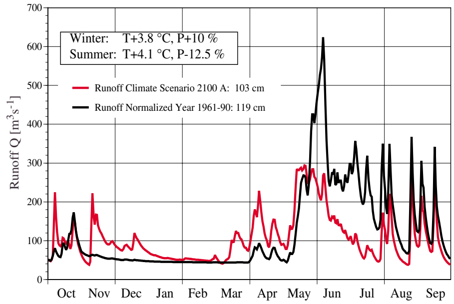

Figure 14. Effect of a changed climate on runoff in the basin Rhine-Felsberg, computed from climate-affected depletion curves and P,T values according to scenario 2100 A.

ling the present snow cover and deriving an even more fictitious future snow cover, a realistic present snow cover is transformed into a climate affected one. A deterministic approach is maintained throughout the climate part of the computer program: As an intermediate result, Fig. 12 shows the changes of the winter accumulation of snow due to climate scenarios for the year 2100, computed from differences in the winter runoff input. In the elevation zones B, C, the snow accumulation is reduced by an increased snowmelt and by conversion of some snowfalls to rainfalls in the winter. In the higher zones, this effect is reduced by the temperature lapse rate and by the increased winter precipitation. The modified depletion curves excluding new snow (MDC_{EXCL}) are adjusted to these changes, the summer snowfalls occurring in the changed climate (according to the critical temperature) are added (MDC_{CLIM}), and the climate effected conventional depletion curves CDC_{CLIM} are derived. As illustrated in Fig. 13 (Seidel et al., 1998), the decline of the snow coverage is shifted towards earlier dates. Such results, if evaluated on a larger scale, are of interest to climate modellers because less snow covered area means less albedo of the Earth's surface and more absorption of radiation. However, this snow feedback is more complex according to various authors (Cess et al., 1991). Coming back to hydrological applications, Fig. 14 shows the climate affected hydrograph for the scenario 2100 A compared with the normalized year representing todays climate. It was computed from the climate affected depletion curves in Fig. 13 and half yearly changed climate temperatures and precipitation. The WINDOWS-version of the SRM computer program can also handle more detailed climate scenarios. Due to a warmer climate, runoff is partially redistributed from the summer half year to the winter half year.

7 CONCLUSIONS

In order to take full advantage of the technological progress, advances in remote sensing should be accompanied by corresponding improvements in methods of hydrological application. Thanks to this interactive process, a better spatial resolution of snow cover mapping was achieved, sensors to distinguish between snow, clouds and glacier ice have been introduced. With the use of a Geographical Information System (GIS), a method has been developed to reconstruct the snow coverage of pixels partially obscured by clouds.

On the hydrological side, misinterpretation of satellite data was corrected by eliminating scenes which succeeded summer snowfalls (although such images were popular for demonstrating the merits of remote sensing), modified depletion curves of the snow coverage (MDC) were developed to evaluate snow water equivalent from periodical snow cover mapping and for an improved derivation of conventional depletion curves (CDC). The SRM computer program has been amended with regard to runoff forecasts, runoff modelling in glacierized basins and evaluation of the effect of climate change on snow conditions and on the runoff regime.

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