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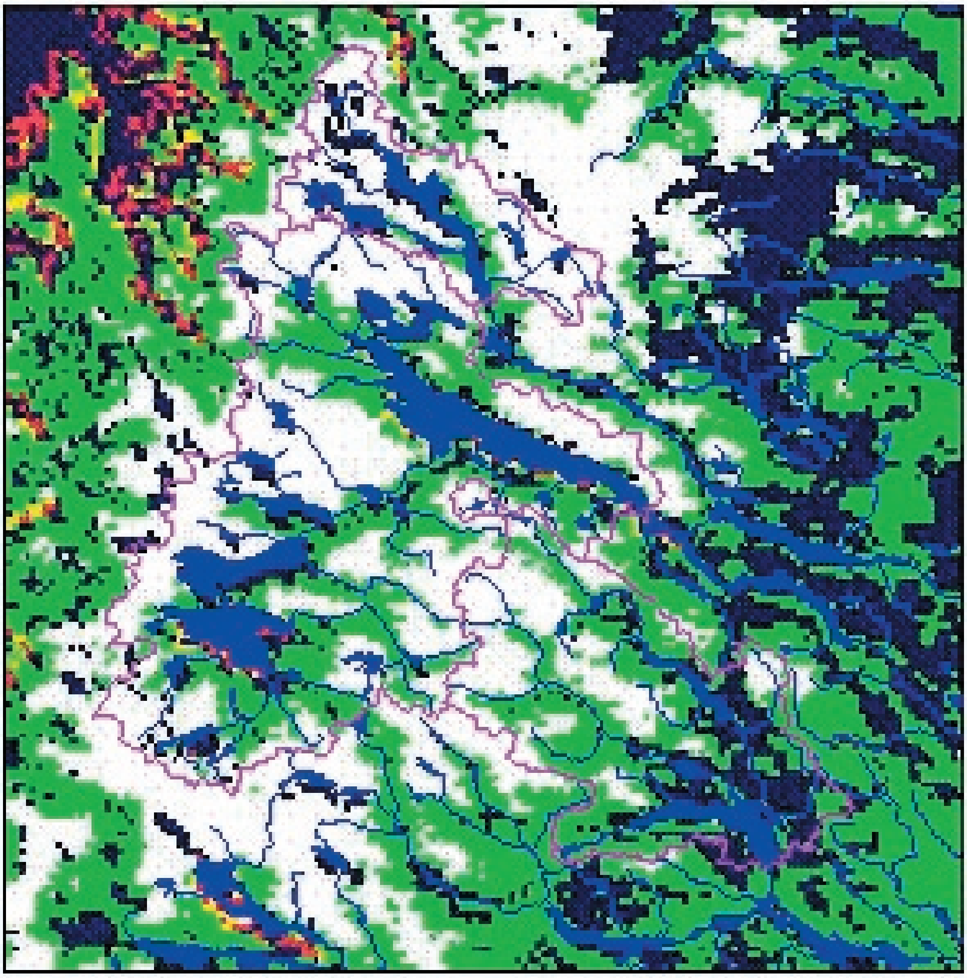

Satellite data on snow cover in the HBV model. Method development and evaluation.

Barbro Johansson, Johan Andreasson, Johan Jansson

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Summary

Hydrological forecasts are essential, both for the prevention of flood damages and for water resources planning. In Northern Sweden, snowmelt plays an important role in the formation of runoff. Spring flood forecasts have been carried out since the middle of the 1970s, using the HBV runoff model. In the HBV model, the snow pack is simulated from interpolated daily observations of point precipitation and temperature. The acquirement of representative data is often difficult as the highest precipitation occurs at high altitudes, which are sparsely populated and difficult to reach. Remote sensing data on the snow pack should thus be important as an additional source of information.

The project presented in this report had two aims:

- To modify the HBV model to include remote sensing data as input to the simulations.
- To evaluate the influence of such data on the accuracy of simulated runoff.

The remote sensing data available to the project came from NOAA-AVHRR images, which provided data on snow covered area under cloud free conditions. The evaluation was carried out for a medium-sized catchment in the mountainous region in the northwest of Sweden. Satellite data were available for five different years.

To facilitate the use of remote sensing data, a gridded version of the HBV model was developed. Procedures and criteria were developed to automatically calibrate the HBV model against both runoff and snow cover data. This was done to minimise the risk of compensating errors in the parameter values of the model.

Due to clouds, remote sensing data are not available on a regular basis. Consequently they were not utilised as model input in the same sense as precipitation and temperature. When available, they were instead used to correct errors in the simulated snow pack. Model routines were developed to compare observed and simulated snow cover and to automatically make the corrections.

For the evaluation, the data set was divided into two periods. The model was calibrated independently for each period and verified for the other. The results were contradictory and not conclusive. For the first period, the precipitation appeared to be systematically overestimated, which led to compensating errors in the parameter fitting and an erroneously modelled snow distribution. Attempts to correct the snow pack for the second period thus failed. For the second period, there were no apparent systematic errors in the precipitation input. After calibrating the model for this period, satellite data could be used to considerably improve the accuracy in the runoff simulations for the first period. The overestimation of precipitation and thereby the snow pack could be corrected for.

The most effective way to overcome the problem of systematic errors in the input data for the calibration period is longer data records. Another possibility is more sophisticated calibration routines than the ones developed within this project. A grid by grid comparison of modelled and observed snow cover showed systematic deviations. It indicates that there are improvements to be made in the snow model, and that remote sensing data can be useful in such work.

Contents

1 Introduction

Hydrological forecasts are essential, both for the prevention of flood damages and for water resources planning. In Northern Scandinavia, snow melt plays an important role in the formation of runoff, and the highest peaks as well as the highest runoff volumes normally occur during the melt season. Operational spring flood forecasts have been carried out in Sweden, Norway and Finland since the middle of the 1970s.

In Sweden the snow pack has traditionally been modelled from observed precipitation and temperature at the meteorological stations, in Norway and particularly in Finland supported by direct observations of the snow pack. However, ground based observations can by necessity only represent a small part of the region of interest. The acquirement of representative data is made especially hard by the fact that the highest precipitation occurs at high altitudes, which are sparsely populated and difficult to reach. Since a long time, hydrologists have thus looked to remote sensing as an additional source of information (Rango and Martinec, 1979).

In spite of the expectations, it has proved difficult to incorporate remote sensing data into operational hydrological modelling in Scandinavia (see e.g. Brandt and Bergström, 1994). This has been due to deficiencies both in the remote sensing data and in the hydrological models. Operationally, satellite information on snow is mainly provided by optical sensors like NOAA-AVHRR (Hastings and Emery, 1992) and TERRA-MODIS (Masuoka et al., 1998). This limits the availability to cloud-free conditions and data on snow covered area (SCA). In theory, the snow water equivalent (SWE) may be observed by microwave sensors like SSM/I and SAR (Bernier et al., 1999, Pulliainen and Hallikainen, 2001), but this has so far not been done successfully in a mountainous environment. Nearer to an operational application is the use of SAR images to map SCA under cloudy conditions (Rott et al., 2000, Malnes and Guneriussen, 2002).

On a specific day, the melt rate depends mainly on the extension of the snow pack and on the meteorological conditions. Consequently, it is not necessary to know the thickness of the snow pack for short forecasts one or two days ahead. The SRM (Martinec, 1975) is a well-known runoff model where snow extension is used as input. The model can thus directly utilise satellite data of SCA for short-range forecasts. However, the rivers in Northern Sweden are regulated with large reservoirs. Forecasts of reservoir inflow are made a couple of weeks or even months ahead, based on the amount of water stored in the snow pack. Consequently it has been important to model the SWE accurately. The SWE is simulated in the HBV rainfall-runoff model (Bergström, 1995), which is the main tool for operational spring flood forecasts in Scandinavia. The model was originally developed in Sweden (Bergström, 1976), but there are now Norwegian and Finnish versions, adjusted to the specific conditions in those countries. The HBV is a conceptual model based on representing the physical processes with simplified, yet physically logical, algorithms. Model parameters are determined through calibration, mainly against observed runoff. The model is run for catchments, but these are divided into smaller sub-units, with different precipitation, temperature and land use characteristics.

This report deals with the modification of the Swedish version of HBV model to handle remote sensing data. It proposes a method to improve the accuracy of both the simulated SWE and SCA in the HBV model through the use of remote sensing data on SCA. Grids of 4x4 km^2 were selected as sub-units for the snow part of the model. Routines were developed to calibrate the model against time series of both runoff and SCA. Routines were further

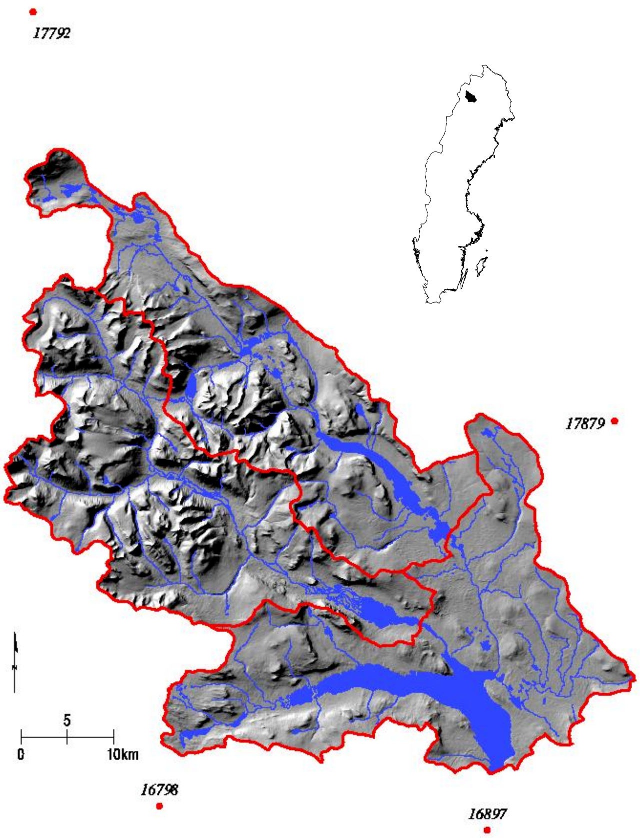


Figure 1.
Relief map of the test catchment, Tjaktjajaure.

developed to automatically adjust the simulated snow pack from remote sensing observations. The work was inspired by a previous evaluation carried out within the Hydalp project (Johansson et al., 2001). Both in Norway and Finland, there are similar ongoing studies to evaluate the use of AVHRR data on snow in the HBV model (Engeset et al., 2003, Metsämäki et al., 2003).

2 Data

Simulations were carried for the Tjaktjajaure basin (Fig. 1) in North Western Sweden. The catchment size is 2230 km^2 with an elevation range from 450 to 2000 m. Approximately 18 % is covered by forests and some 6% by lakes and glaciers respectively. Information on elevation and land use came from the databases of the Swedish National Land Survey.

There are daily runoff observations available at the outlet of the basin. Daily precipitation and temperature were taken from a gridded database with a resolution of 4×4 km^2 at the Swedish Meteorological and Hydrological Institute. The database was created by optimal interpolation of point observations. To account for the topographical influence, wind information was utilised in combination with an elevation database (Johansson, 2002).

Classified NOAA-AVHRR images provided information on snow covered area. A limited number of images were available for 5 different years: 1992, 1996, 1998, 1999 and 2002 (Table 1). The images from the 1990s were originally analysed within the EU sponsored Hydalp project (Rott et al., 2000) with a semi-automatic scheme. The data for 2002 were analysed with an automatic scheme developed within the EUMETSAT Land SAF project (Jansson,

1992		1996		1998		1999		2002	
Date	Clouds	Date	Clouds	Date	Clouds	Date	Clouds	Date	Clouds
06-02	0	06-04	0	05-03	49	05-21	0	04-30	55
06-09	6	06-08	15	05-14	62	05-27	10	05-06	52
06-19	42	06-15	55	06-03	34	06-07	0	05-15	35
06-25	3	06-25	8	06-07	2	06-08	18	05-19	60
		06-30	21	06-09	63	06-09	32	05-20	48
				06-12	76	06-12	0	05-22	30
				06-15	26	06-13	24	05-25	68
						06-16	28	05-27	60
						06-25	54	05-28	64
						06-26	2	05-29	55
						06-29	72		
						06-30	78		
						07-05	19		

Table 1. Dates with available classified NOAA-AVHRR images on snow covered area.

2002). The resolution of the classified AVHRR images is 1x1 km^2 and from that an average of SCA for the 4x4 km^2 grids was computed.

3 Method

3.1 The snow routine of the HBV model

The snow routine of the HBV model simulates the snow pack from observed or forecasted precipitation and temperature. Catchments are divided into sub-units with different accumulation and melt rates depending on location (Lindström et al., 1997). A threshold temperature is used to distinguish between snowfall and rainfall. There is not an abrupt, but a gradual change in precipitation type within a temperature interval around the threshold value according to:

snowfall $t < tt - ttint/2$
snow + rain $tt - ttint/2 < t < tt + ttint/2$
rain $t > tt + ttint/2$

t = sub-unit temperature (^oC)
tt = threshold temperature (^oC)
ttint = temperature interval (^oC)

Snow melt is calculated using the degree day method:

$$M = DF * (t - ttm)$$

M = melt rate (mm/day)
DF = degree day factor (mm/(day*^oC))
ttm = threshold temperature for snow melt

The snow pack is assumed to retain melt water as long as the amount does not exceed a certain fraction of the snow. Spatial variation within each sub-unit is allowed for by subdividing

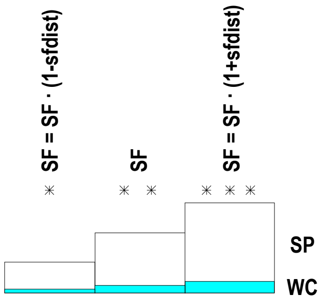


Figure 2.
Sub-division of model units into equally sized subareas with different snow accumulation. Example with three subareas. SF = snowfall, sfdist = snowfall distribution factor, SP = snow pack, WC = melt water content

them into equally sized subareas with snow accumulation at different percentages of the mean value (Fig. 2). This allows snow covered area (SCA) to decline more smoothly in the melt season.

3.2 Gridded snow model

In the main version of the HBV model used in Sweden, a catchment is divided into sub-catchments and further into elevation bands and land use classes (forests, open land, lakes and glaciers). The basic sub-unit is then a land use class within an elevation band. To get a better description of the spatial snow distribution, a model version was developed replacing the elevation bands with 4x4 km^2 grids. The same grid-mesh was used as for the precipitation and temperature field (Fig. 3). The snow routine of the HBV model was applied to each land use class within each grid. SWE and SCA were then averaged over each grid for comparison with remote sensing data.

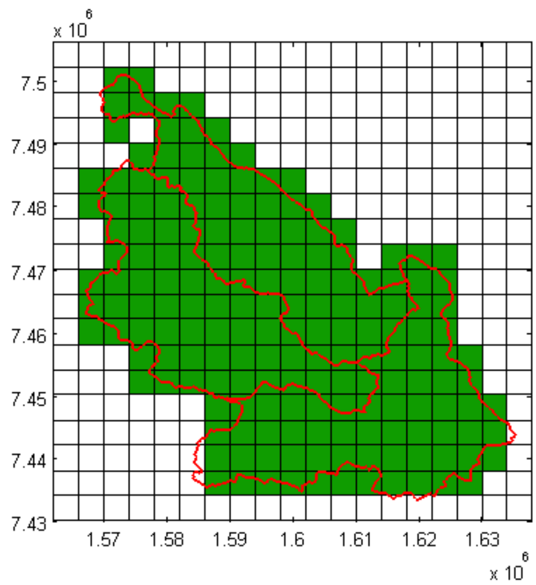


Figure 3.
Grid-mesh used for snow simulations with the HBV model in the Tjaktjajaure basin. Grid size is 4x4 km^2.

3.3 Model calibration

Traditionally the parameters of runoff models are determined through calibration against observed runoff, and not verified against internal model variables. This leads to a risk for compensating errors (Bergström et al., 2002), and it may well be that the model performs well with respect to runoff, in spite of an incorrect snow distribution. In such a case, adjustment of the snow cover from observations might introduce new errors in estimated runoff. If remote sensing data are to be proved useful, it is thus necessary that they are available also during the calibration process.

The R^2 criterion for runoff presented by Nash and Sutcliffe (1970) is widely used for calibration and evaluation of rainfall-runoff models. Its value ranges from $-\infty$ to 1. A value greater than zero means that the simulated runoff gives a better estimate of the variations in actual runoff than a long-term mean of the observations.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left[Q_{com}(i) - Q_{rec}(i)\right]^2}{\sum_{i=1}^{n}\left[Q_{rec}(i) - \overline{Q_{rec}}\right]^2} \qquad (1)$$

where: Q_{com} = runoff computed with the HBV model
Q_{rec} = measured runoff
$\overline{Q_{rec}}$ = average runoff during the calculation period
n = number of days in the calculation period

To enable calibration with snow covered area (SCA) it was necessary to create a new criterion (Eq. 2). It is based on the R^2-criterion for runoff, but describes the accuracy of the spatial variation rather than the accuracy of the temporal variation.

$$R^2_{SCA} = \frac{1}{n} \cdot \sum_{j=1}^{n}\left[1 - \frac{\sum_{i=1}^{zones}\left[SCA_{com} - SCA_{RS}\right]^2}{\sum_{i=1}^{zones}\left[SCA_{RS} - \overline{SCA_{RS}}\right]^2}\right] \qquad (2)$$

where: SCA_{com} = snow covered area calculated with the HBV model
SCA_{RS} = snow covered area from remote sensing
$\overline{SCA_{RS}}$ = average SCA in the satellite image
zones = total number of compared grids
n = number of satellite images

Remote sensing of the snow pack works best for open areas (Klein et al., 1998, Vikhamar and Solberg, 2003, Metsämäki et al., 2002). It was therefore decided to compare the model results with observations only for grids that consisted of more than 80% open land (i.e. bare mountain and field). Grids with more than 30% clouds were also excluded from the calculation of the criterion. The same distribution between snow covered area and bare land as for the cloud free area was assumed when the cloud-covered area was between 0 and 30%.

To calibrate the HBV model, a weighted criterion was used combining the criterion for snow covered area with the R^2-value for runoff and a penalty for the volume error (Eq. 3).

$$R^2_{Autocal} = w_1 \cdot R^2 + w_2 \cdot R^2_{SCA} - w_3 \cdot reldif \quad (3)$$

where:
- R^2 = the calibration criterion for runoff by Nash and Sutcliffe (1970)
- R^2_{SCA} = the calibration criterion for SCA
- *reldif* = the relative volume error in runoff
- $w_{1,2,3}$ = weighting factors

The model was calibrated using the automatic scheme proposed by Lindström (1997).

3.4 Adjustment of the simulated snow pack

Errors in the simulated snow pack may be caused by an over- or underestimation of precipitation, by problems in separating snow from rain or from an over- or underestimation of melt rates. The assimilation of remote sensing data into the snow model is based on the assumption that, once calibrated, the model correctly simulates the snow distribution within a region, and that the error lies in the estimation of the total snow pack.

For each day and grid, the model provides a value of the SWE and SCA. To correct the simulated snow pack, the observed SCA is compared to the simulated for the period around the date of the observation. When a date is found with a simulated SCA close to that of the remote sensing image, the model state of that date is transferred to the date of the image, and model simulations are restarted from the date of the image. If the simulated SCA is underestimated, a model state from a previous date is selected. If the simulated SCA is overestimated, model simulations are made a few days ahead, assuming a temperature well above zero to induce snow melt. Through this method, both the simulated SCA and SWE are corrected. An automatic procedure was developed to find the best model state and transfer it to the date of the image. To match the simulated and observed SCA the previously described R^2_{SCA} criterion was used.

4 Results

4.1 Model calibration

The period 1991-09-01 – 2001-08-31 was used for model calibration and verification. To better judge the model performance, the period was divided into two parts. The model was calibrated for each 5-year period, with and without remote sensing data, and then verified for the other five. Daily runoff data for the whole period were used to calculate the R^2 and *reldif* criteria. The R^2_{sca} criterion was computed for days with satellite images with a total cloud cover of less then 50 %. For calibration including snow information, the weights w_1, w_2 and w_3 in Eq. (3) were set to 0.4, 0.4 and 0.2 respectively. For calibration without snow data, w_1 was set to 0.8. Table 1 summarises the results. The inclusion of snow in the calibration did only to a small extent affect the criteria values for runoff, particularly looking at the explained variance (R^2). For the error in the total runoff volume (*reldif*), there is a difference for the

	Results 1991-1996						Results 1996-2001					
	R^2		R^2_{SCA}		*reldif*		R^2		R^2_{SCA}		*reldif*	
	cal	ver	cal	ver	cal	ver	cal	ver	cal	ver	cal	ver
Calibration with snow	0.86	0.86	0.53	0.43	0	-5.5	0.90	0.90	0.33	-0.17	-3.9	1.5
Calibration without snow	0.87	0.86	0.38	0.50	0	-1.9	0.91	0.89	0.06	0.31	-0.3	1.6

Table 2. Results from model calibration. Criteria values for calibration and verification periods. Model was calibrated separately for the two 5-year periods 1991-09-01 – 1996-08-31 and 1996-09-01 – 2001-08-31 and in both cases verified for the other 5-year period.

1996-2001 calibration when the calibration with snow shows an error of about 4 %. Calibrating against runoff only, this error is normally forced to zero in the calibration process. In this case it was not possible to simultaneously fit both the snow distribution and the runoff volume.

The mean values of the snow criteria for 1998 and 1999 are lower than for 1992 and 1996, but this is somewhat misleading and mainly due to more images with a very high snow or cloud content. Such images have a low variance, which tends to decrease the R^2_{sca} value. However, contrary to the runoff criteria, the snow criteria differ considerably between the calibration and verification periods. The dependence on the calibration period is probably caused by overfitting. There are only a few satellite images available in each period (Table 1), and that increases the risk of overfitting. Seen over the full calibration period 1991-1996, the runoff volume is well estimated, but within these five years it is sometimes too high and sometimes too low. The fitted model parameters are those that gives the best estimate as an average. Both in 1992 and 1996, the simulated spring flood volume is slightly higher than the observed (7 % and 5 % using the fitted parameters for 1991-1996, Fig. 4a). It indicates that the winter precipitation is overestimated for these two years, but as they are the only years with snow observations, the calibration procedure still strives to find snow parameters that fit the simulated to the observed snow pack. A systematic error in the estimation of the snow pack is thus introduced, compensated for in other model parameters. In the second calibration period (1996-2001), the spring flood runoff volume is well described in both years with snow observations (Fig 4b), and the snow pack is probably estimated accurately. Consequently, the snow parameters from the first calibration period are not applicable to the second calibration period. With longer records and longer calibration periods, it should be possible to avoid such systematic errors. The calibration period would contain years where the snow pack was over- as well as underestimated.

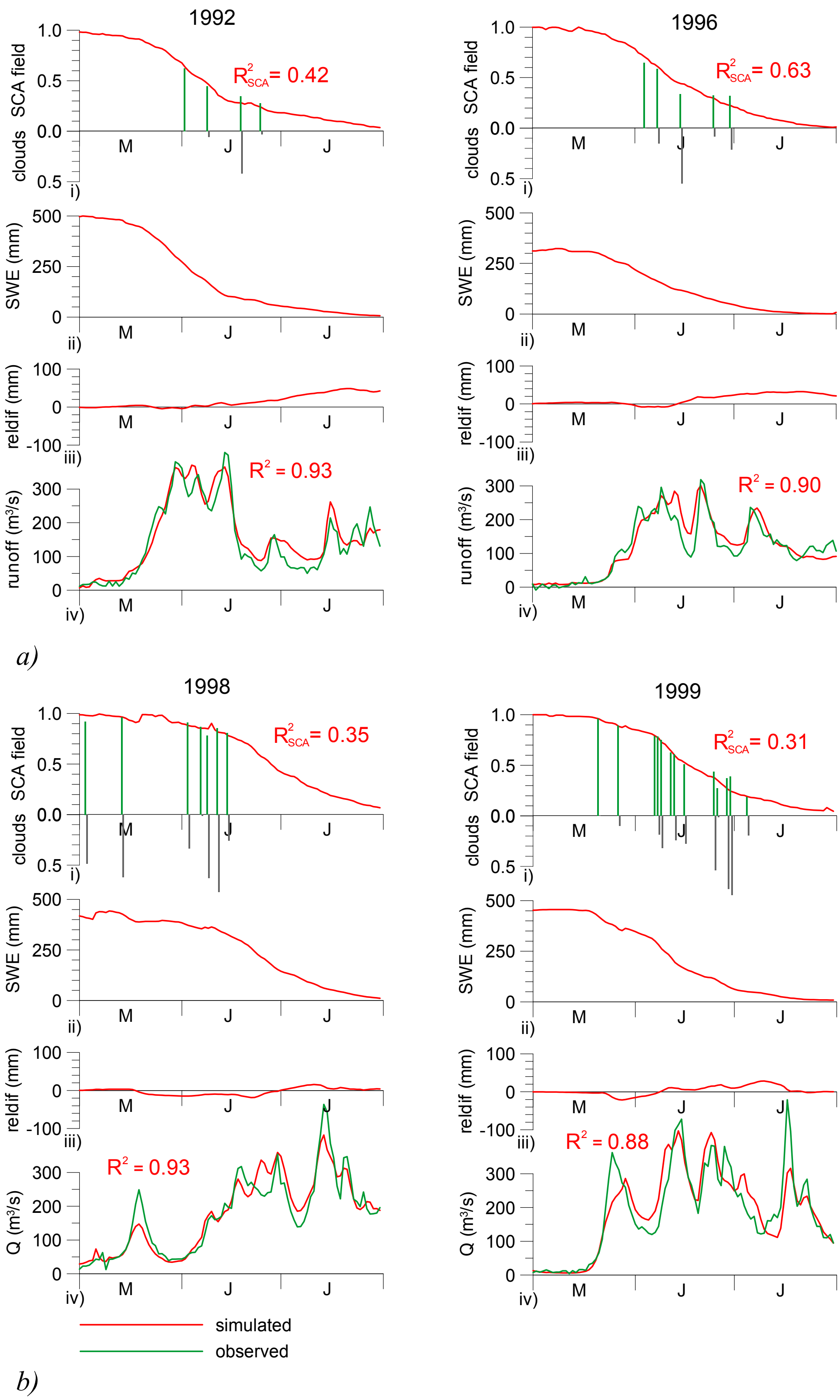


Figure 4. Model simulations and observations of snow and runoff for Tjaktjajaure for the melt seasons with remote sensing data on snow cover. i) Snow covered area for open land within the catchment. Green bars shows satellite observations for cloud free areas, grey bars the clouded area. ii) Snow water eqivalent. iii) Accumulated volume error for runoff (in mm) iv) Simulated and observed runoff.

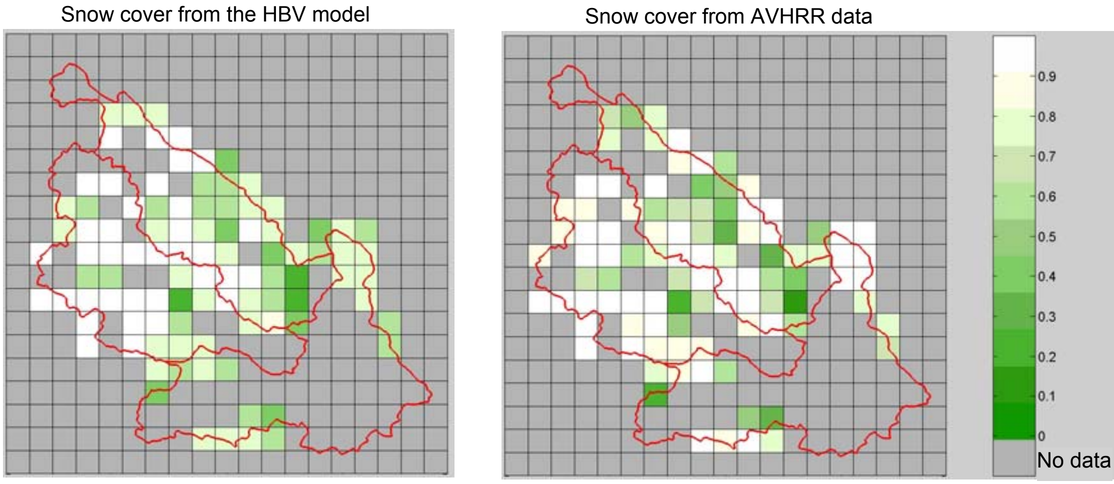


Figure 5. Simulated and observed snow covered area for model grids within the Tjakjajaure basin. Example from 1999-06-08.

The general pattern of the snow distribution of the snow is fairly well described by the model as compared to the satellite images (Fig. 5). However, there are some systematic deviations that occur both in 1992/96 and 1998/99. Figures 6a and b shows the average difference between model and observations for each grid for the images from 1992/1996 and the images from 1998/99. The differences tend to be positive and negative for the same grids in both periods (Fig. 7a). Partly the deviations can be explained by elevation (Fig. 6c and 7b), with more snow at high altitudes in the model and vice versa. Most likely the deviations are caused by model deficiencies, although there is a possibility that the complex topography influences the interpretation of the satellite images (Teillet et al., 1982). Model errors may be related to input data (precipitation and temperature), to redistribution of snow by the wind (Källgården, 2001, Marks et al., 2002) and to the effect of radiation on melt rates (Bruland and Killingtveit, 2002). A rough comparison with a relief map (Fig. 6d) of the catchment indicates that the largest overestimation occurs at mountain peaks, which implies that neglecting wind redistribution is the main error source.

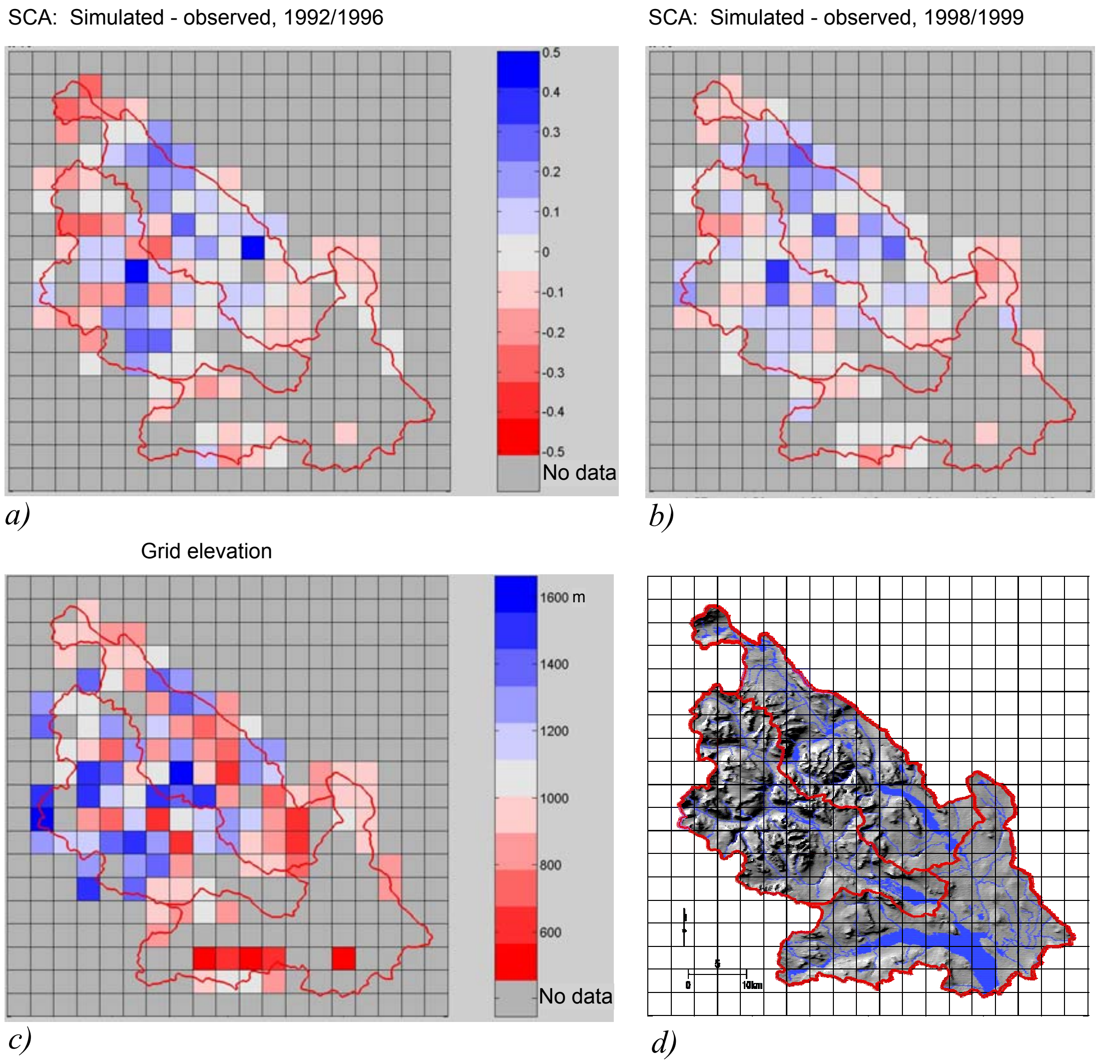


Figure 6 a,b) Mean difference between simulated and observed SCA for days with remote sensing data. Grid by grid comparison 1992/1996 and 1998/1999 respectively. The difference expressed as percentage points / 100. c) Grid elevation. d) Relief map with grid overlay. Grid size is 4x4 km^2.

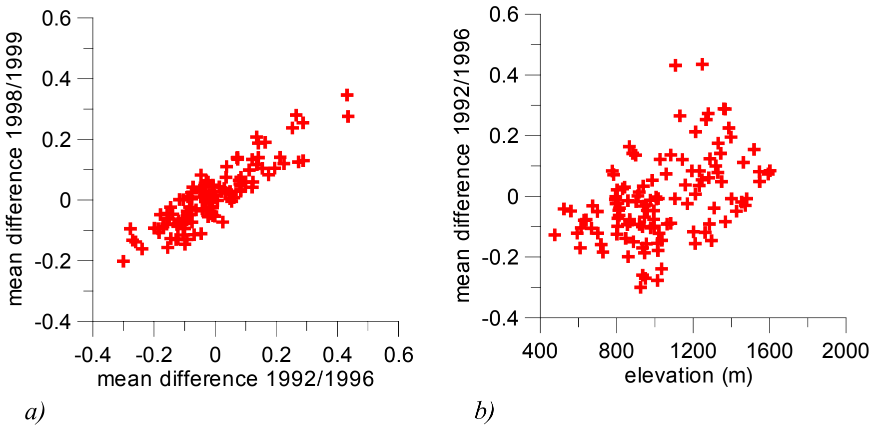


Figure 7 a) Grid by grid comparison of mean simulated-observed SCA for 1992/1996 and 1998/1999 respectively. b) Grid by grid comparison of elevation and mean simulated-observed SCA for 1992/1996.

4.2 Adjustment of the simulated snow pack

Trying to match the SCA of a model state with the satellite image, the automatic procedure searched within a period of ±6 days of the date of the image. It was assumed that a matching model state had been found if the following requirements were fulfilled:

- The improvement in the R^2_{SCA} criterion was greater than 10 % as compared to the original model state on the date of the image.
- A criterion value above zero was reached.
- There was no heavy precipitation within the search period.

The procedure is illustrated in Fig. 8 with an example from June 1992. The observed and simulated SCA was compared for grids dominated by open land and with a cloud cover of less than 30 % (Fig. 8a). In this case the SCA on June 2 was overestimated by the model, and the model state was replaced by one from three days later. The adjustment did not only affect the snow water equivalent for grids included in the comparison, but the whole catchment (Fig. 8b), resulting in a decrease of the total snow pack by 70 mm (see also Fig. 9).

The tests with the adjustment of the snow pack confirmed the results from the calibration. The model was run for the melt seasons 1992 and 1996 with the model parameters from the 1996-2001 calibration. As with the parameters from the 1991-1996 calibration, the spring flood volume was overestimated in both years (Table 3, Fig. 9a). The adjustment of the simulated snow pack led to a clear improvement and decreased the volume error. However, when the same procedure was carried out for 1998 and 1999 with the model parameters from 1991-1996, the tests showed a deterioration of the model performance after adjustments of the snow pack (Table 3, Fig. 9b). The original volume error was small in both years, and the adjustment of the snow pack resulted in an overestimation of the runoff volume. This is a consequence of the systematic error in the 1991-1996 calibration.

The graphs of SWE and accumulated precipitation (Fig. 9ii) indicate that snow melt has the largest influence in the beginning of the melt season, and that towards the end of July it is rainfall that dominates the runoff generation.

Melt season	R^2		R^2_{SCA}		*reldif*	
	unadjusted	adjusted	unadjusted	adjusted	unadjusted	adjusted
1992	0.90	0.93	0.39	0.53	12.5	0.9
1996	0.90	0.92	0.46	0.67	5.8	-2.8
1998	0.92	0.90	-0.40	0.01	1.8	7.9
1999	0.86	0.83	-0.05	0.20	-1.8	3.1

Table 3. Criteria values for model simulations during the melt seasons 1992, 1996, 1998 and 1999. Simulations made with and without adjustment of the snow pack from remote sensing data. Simulations for 1992/1996 made with model parameters from the 1996-2001 calibration and simulations for 1998/1999 with parameters from the 1991-1996 calibration.

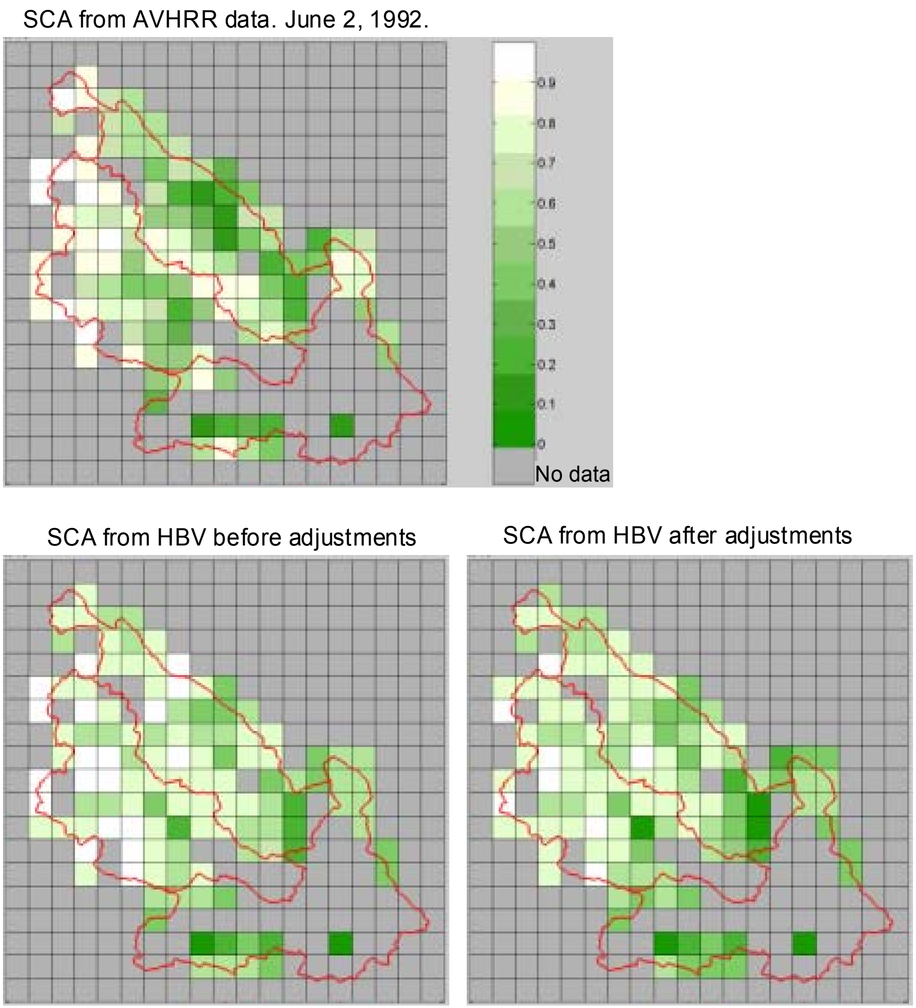


Figure 8a. Observed SCA (top) and simulated with the HBV before and after adjustments (bottom). Shown for grids dominated by open land and with less than 30 % cloud cover.

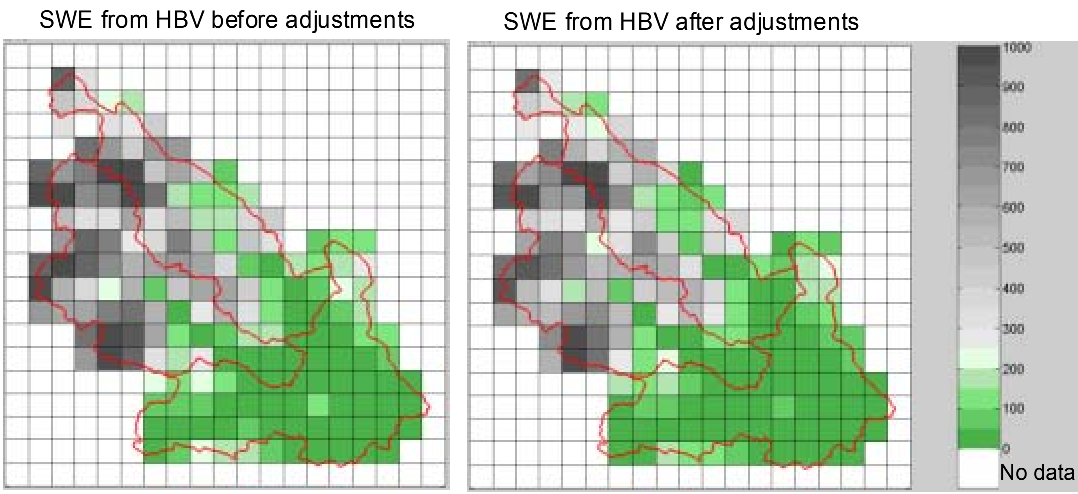
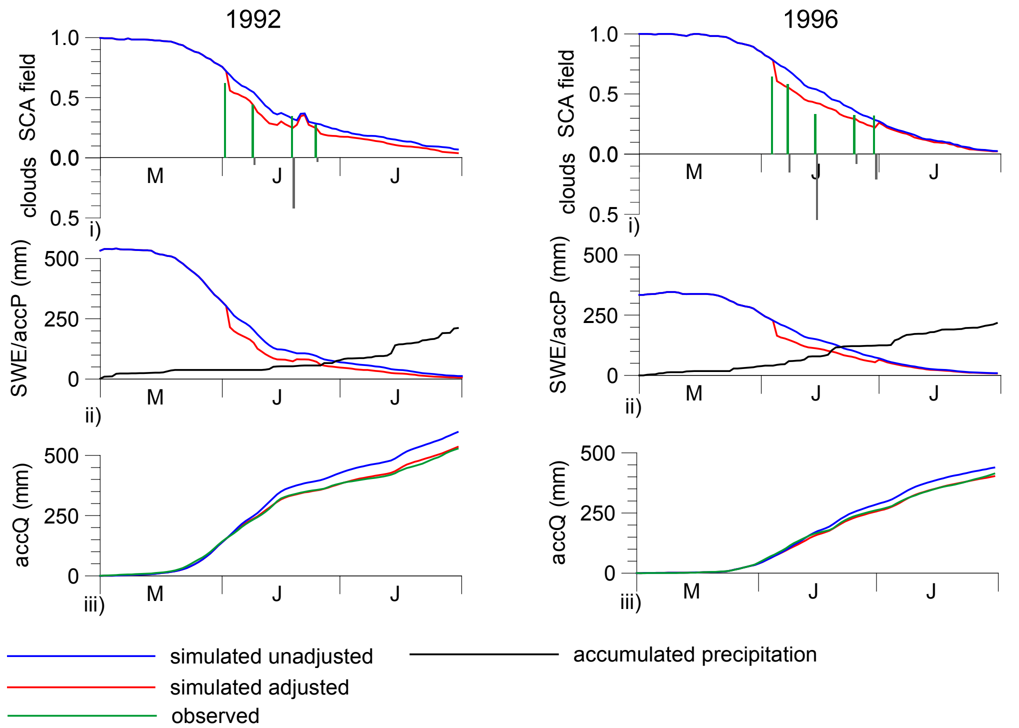


Figure 8b. Simulated snow water equivalent (mm) before and after adjustments.



i) Snow covered area for open land within the catchment. Green bars shows satellite observations for cloud free areas, grey bars the clouded area. ii) Snow water eqivalent and accumulated precipitation since May 1. iii) Accumulated runoff since May 1. Note that the y-axis scale is the same as for SWE.

Figure 9a. Model simulations and observations of snow and runoff for Tjaktjajaure for the melt seasons 1992 and 1996 with model parameters from the 1996-2001 calibration. Simulations made with and without adjustment of the snow pack from remote sensing data.

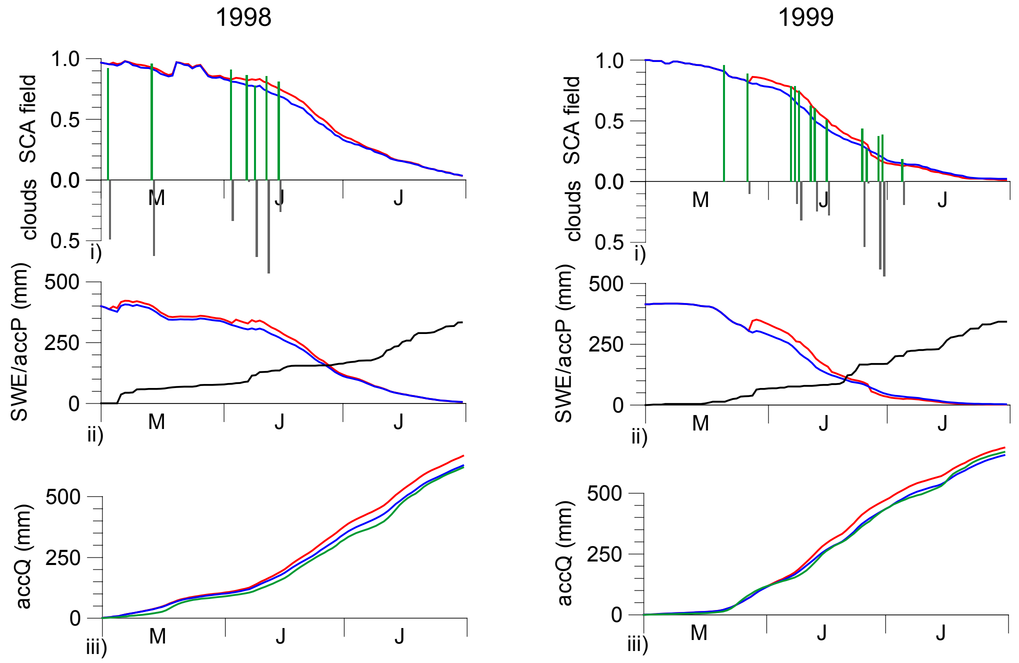


Figure 9b. Model simulations and observations of snow and runoff for Tjaktjajaure for the melt seasons 1998 and 1999 with model parameters from the 1991-1996 calibration. Simulations made with and without adjustment of the snow pack from remote sensing data. For legends, see Fig. 9a.

Melt season	R^2		R^2_{SCA}		*reldif*	
	unadjusted	adjusted	unadjusted	adjusted	unadjusted	adjusted
1992	0.91	0.94	0.41	0.54	10.7	4.1
1996	0.91	0.92	0.47	0.65	5.6	0
1998	0.88	0.88	0.02	0.02	-6.9	-1.2
1999	0.84	0.84	-0.12	0.10	-9.4	-2.5

Table 4. Criteria values for model simulations during the melt seasons 1992, 1996, 1998 and 1999. Simulations made with and without adjustment of the snow pack from remote sensing data. Simulations for 1992/1996 made with model parameters from a calibration over the melt seasons 1992 and 1996 (8 months) and for 1998/1999 with parameters from a calibration over the melt seasons 1998 and 1999 (8 months).

Calibrating the model runoff parameters over a five year period minimised the risk of overfitting, but to further investigate the influence of the calibration on the adjustment of the snow pack, another calibration approach was tried. The model was calibrated using runoff data only for the melt seasons when snow observations were available, i.e. April-July 1992, 1996, 1998 and 1999. Still the data were divided into two groups, 1992/1996 and 1998/1999. Calibrating the model over such short periods certainly leads to systematic errors, but possibly a more consistent combination of the snow and runoff parameters. The adjustment of the snow pack was tested as for the previous calibration, i.e. the model was run with and without adjustments for the melt seasons for which it had not been calibrated. For 1998 and 1999, the simulations without adjustments had larger volume errors and lower R^2 values than when the calibration had been made for the whole period 1991-96, but there was a clear improvement in the runoff volume after the adjustment of the snow pack (Table 4). For 1992 and 1996, the results were similar to the previous ones, i.e. an overestimation of the runoff volume without adjustments and a clear improvement in both runoff volume and R^2 values after adjustments. It thus seems that with this more limited calibration, the results with respect to snow and runoff are more consistent. The results stress the importance of the calibration procedure.

4.3 Data from LandSAF

The remote sensing data from the 1990s were analysed using algorithms adjusted to the Tjaktjajaure area. For 2002 a first test set of data were available from the EUMETSAT/Land SAF scheme. The analysis was then based on more general algorithms applied to the whole of Northern Europe. It was thus interesting to investigate to what extent the change in the classification scheme might affect the results. The HBV model was run for the melt season 2002 with the parameters from the 1996-2001 calibration.

The LandSAF scheme runs automatically and data are retrieved daily. In spite of this there are very few images from 2002 with a cloud cover of less than 50 %. Only three were found and therefore the comparison was made also for images with up to 70 % clouds (Fig. 10a). The high cloud cover may partly be due to the cloud mask (Dybbroe et al., 2000) which is rigorous and excludes areas with very thin cirrus clouds. Such areas were analysed for snow in the Hydalp scheme. The high cloud cover also means that there may be a big difference between the total snow covered area and that of the cloud free grids (Fig. 10b). Further, there are periods when the difference between simulated and observed SCA is remarkable. They seem to be correlated to high temperatures (Fig. 10a) and thus possibly to a rapid snow melt not ac-

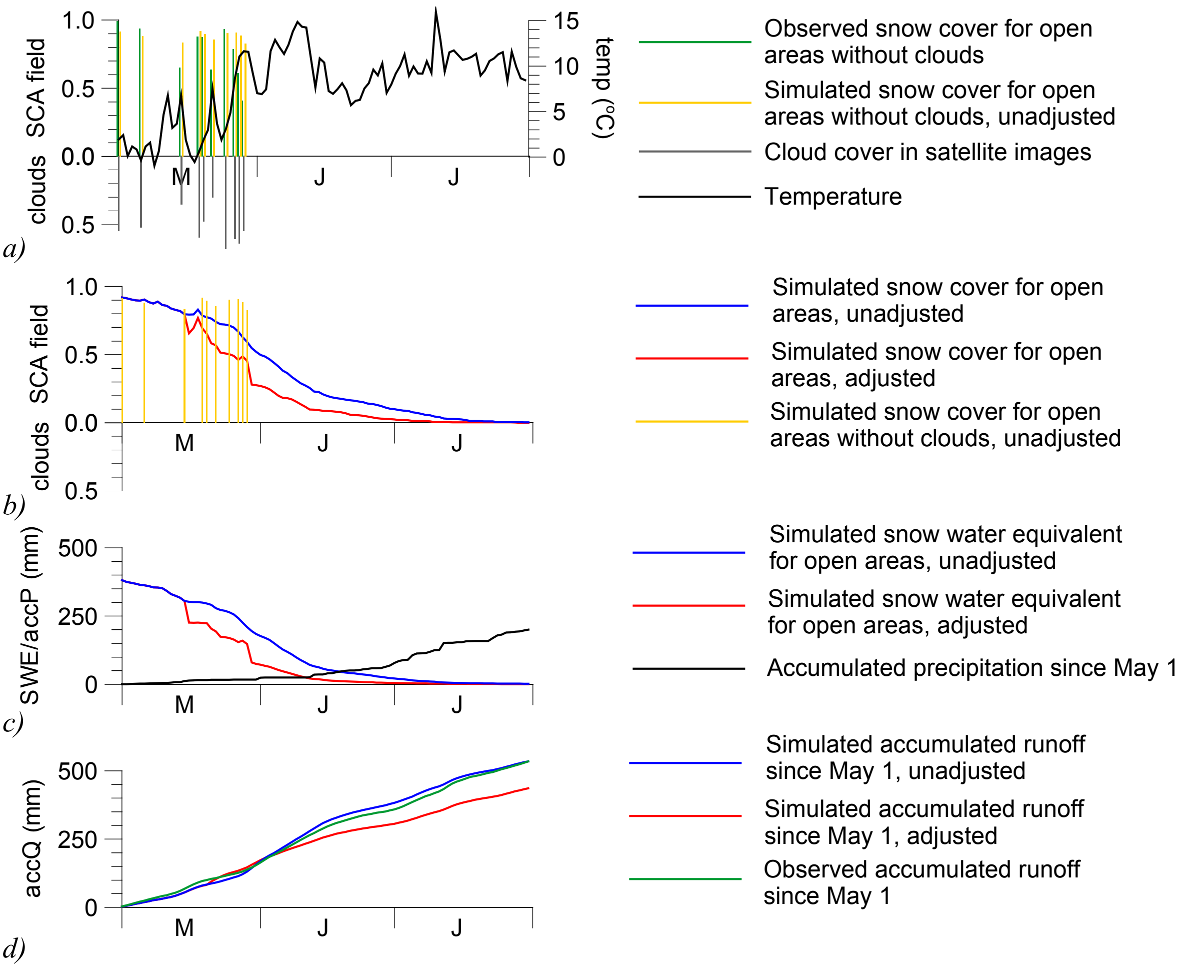


Figure 10. Model simulations and observations of snow and runoff for Tjaktjajaure for the melt season 2002. Simulations made with and without adjustment of the snow pack from remote sensing data (LandSAF). Simulations made with model parameters from the 1996-2001 calibration.

counted for in the model. However, considering that the model performs rather well with respect to runoff (Fig. 10d) and that there were no such large differences in previous years, there may also be problems in the analysis of the remote sensing data. The high temperatures may, e.g., affect the snow properties. Whatever the reason, the large differences make any attempts to adjust the snow pack a complete failure. The model performance deteriorates hugely (Fig. 10d).

5 Summary and discussion

Studies within the Hydalp project indicated that spring flood forecasts with the HBV model might be improved through the use of remote sensing data on snow covered area. The results led to the further investigations presented in this report. The aim was to modify the HBV model to include the remote sensing data as input to the simulations and to evaluate their effect on the accuracy of the simulated runoff. To facilitate the use of spatially distributed input data, a gridded version was developed for the snow routine of the model. Due to clouds, remote sensing data are generally available sporadically and then only for certain parts of a catchment. The information is also limited to snow covered area. The snow water equivalent, which is essential for spring flood forecasts, must be estimated by the model. Consequently the remote sensing data were not utilised as model input in the same sense as precipitation and temperature. When available, they were instead used to correct errors in the simulated snow pack. Model routines were developed to compare observed and simulated snow cover and to automatically make the corrections. The parameters of runoff models are often determined through calibration against observed runoff only. Due to compensating error the model may then perform well with respect to runoff in spite of an incorrect snow distribution. In such cases, adjustment of the snow cover from observations might introduce new errors in estimated runoff. It is thus necessary that snow data are available also during the calibration process. Procedures and criteria were developed to automatically calibrate the HBV model against both runoff and snow cover data.

The results from the evaluation were contradictory and not conclusive. A major problem appeared to be too short records for calibrating the snow parameters. With short records, there is always a risk of overfitting. The calibration in this study was carried out separately for two independent periods with 5 years of daily runoff data and a limited number of satellite images for two melt seasons within the 5 year period. For the first calibration period, winter precipitation appeared to be overestimated for both years with satellite data. The calibration procedure still somehow managed to find a set of model parameters that fitted the observed remote sensing data, but those parameters could not represent the snow distribution in years with an accurate estimation of winter precipitation. For the second calibration period, the situation was different. The winter precipitation for the two melt seasons with snow seemed to be well estimated, and the fitted model parameters could be assumed to more generally describe the true snow distribution. The problems with the calibration became obvious when attempts were made to correct the simulated data from observations during the verification period. Using the parameters fitted for 1996-2001 to simulate the melt seasons 1992 and 1996 a clear improvement was achieved when the snow pack was corrected. With those parameters the correction procedure recognised the overestimation of the winter precipitation and reduced the snow pack. When the parameters from 1991-1996 were applied to 1998 and 1999, the runoff volume was well simulated without any corrections of the snow pack, but a comparison with the remote sensing data indicated an underestimation of the snow pack. The adjustment led to an overestimation of the spring flood runoff volume.

There are few easily available historical records of classified satellite images with a high accuracy over Sweden. To acquire such data is costly, and it is not likely that it will be done without a strong belief in its profitability. For the future, the Land SAF scheme may provide the data, but it will take many years to collect records long enough to overcome the calibration problems encountered in this study. An alternative may be to develop more nested calibration criteria. Such criteria should prevent that the simulated snow pack is fitted to the observed for a melt season when runoff is simultaneously overestimated. A simple test was made to limit the calibration period against both runoff and snow to melt seasons when snow data were available. The two selected calibration periods were then April–July 1992/1996 and April-July 1998/1999. This appeared to lead to more consistent model parameters. The model performed better during the verification period with adjustments of the snow pack than without in both cases. However, even after adjustments, the overall model performance with respect to runoff was less good than when 5 years of runoff data had been used for the calibration.

A grid by grid comparison of modelled and observed snow cover showed systematic deviations. Elevation seemed to explain some of the differences, with more snow at high altitudes in the model. A probable explanation is wind redistribution, removing snow from the mountain peaks to lower grounds. Wind redistribution is not considered in the HBV model.

This study was focused on the modification of rainfall-runoff models in order to facilitate the use of remote sensing data. The main purpose was not to evaluate the accuracy of the data, but some problems were noticed when using snow cover estimates from two different classification schemes. Most tests were made with data from the 1990s, classified within the EU project Hydalp. In 2002 the first the first test data from the Land SAF scheme became available. The model was run for the melt season 2002 with model parameters defined through calibration against the Hydalp data. Without any adjustment of the simulated snow pack the model performed well with respect to runoff, but the adjustment from Land SAF data led to a considerable deterioration. Partly this might be explained by the previously discussed difficulties with too short records for calibration, but there were also large variations in the observed snow cover that seemed questionable. The cloud cover was very high in the Land SAF data. The cloud mask that was applied meant that also areas with very thin clouds were excluded from the analysis of the snow cover. In the Hydalp classification scheme special algorithms were developed for areas with thin cirrus clouds and such algorithms are probably necessary in Northern Scandinavia where clouds are common during the melt season.

At this stage, it is not possible to make any clear recommendations on the use or non-use of remote sensing data in snow melt forecasting in Sweden. As in many previous studies the results are ambiguous. The techniques for model calibration need to be further developed, but model development require substantial amounts of reliable data for evaluation. In this lies an obvious obstacle. Without reliable data, there will be no model development. Without an active end user, remote sensing experts may not give their best efforts to produce high quality data.

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