Satellite-observed Snow Covered Area and Spring Flood Prediction in the HBV-model

Norwegian Water Resources and Energy Directorate
2004

Report No. 4-2004

Satellite-observed Snow Covered Area and Spring Flood Prediction in the HBV-model

Commisioner: The Research Council of Norway and NORUT IT

Editor:

Authors: Eli Alfnes and Hans-Christian Udnæs

Print: NVE's printing office
Number printed: 25
Front page: Satellite image of Southern Norway showing Snow Covered Area on 7th May 1999. The test catchments are marked with red boundaries
ISSN: 1503-0318

Abstract: Investigations of satellite derived snow covered area (SCA) used in runoff models show that SCA could be included in the model calibration with only small reduction in runoff performance. Updating the runoff models based on the satellite derived SCA showed ambiguous results. In high mountain areas the predicted flood events were improved, whereas the procedure was less successful at lower altitudes.
Keyword: Snow; Runoff simulations; Satellite derived snow covered area

Norwegian Water Resources and Energy Directorate
Middelthuns gate 29
P.O.Box 5091 Majorstua
N-0301 OSLO

Telephone: 22 95 95 95
Telefax: 22 95 90 00
Internet: www.nve.no

March 2004

Contents

Preface

This report is a deliverable in the research project SnowMan - Snow Parameter Retrieval from Remote Sensing data for Improved Monitoring and Management of Water Resources. SnowMan is supported by the Research Council of Norway under the programme “Overvåking av marine/terrestriske systemer” (project No. 143540/431).

The main objective of SnowMan is to improve methodology for remote sensing of snow parameters and the use of snow parameters in hydrological models in order to achieve better water management practices related to snow.

The partners in SnowMan are NORUT IT (co-ordinator), the Norwegian Computing Center (NR), the University of Oslo and the Norwegian Water Resources and Energy Directorate (NVE). The project is divided into five workpackages (WP). This report sums up work carried out by NVE in WP4 -Integration of snow parameters in hydrologic model, Task 4.1 - Snow parameters in a lumped hydrologic model**.**

The report has been written by Eli Alfnes with contributions from Hans-Christian Udnæs and Liss M. Andreassen. Project partner NR processed satellite SCA data.

Oslo, March 2004

Kjell Repp
Director of the Hydrology Department

Liss M. Andreassen
Project Leader

Summary

A study testing operational use of satellite-observed snow covered area (SCA) in the HBV-model was carried out in order to improve the spring flood prediction. The study included a) calibration of HBV-models against both discharge and SCA, and against discharge only, and b) updating of the HBV-models based on satellite observed SCA. Ten test catchments were selected for the study. The results show that the HBV-models calibrated against SCA in addition to discharge simulate discharge nearly as well as models calibrated against discharge only. The simulated SCA was markedly improved when SCA was included in the calibration.

Large deviations between simulated and observed SCA was found in 22 cases and updating scenarios were calculated for 15 of those. The results were ambiguous. In catchments with high mean altitude the predicted flood events were improved. Most of the successful updates took place during the winter 2001 when the main wind direction deviated from normal. The model updates were less successful at lower altitudes. In these catchments the change of model input led to larger deviation between simulated and observed discharged than the non-updated models. The diverged results were mainly attributed to differences in spectral signature of dry and wet snow.

1 Introduction

The amount and timing of snowmelt runoff from snow and glaciers are important information for flood prediction and hydropower operations in Norway. Two examples are the large flood in south-eastern Norway in 1995 and the electricity shortage in Norway during winter and spring 2003. In these situations updated information on snow conditions were of large importance for the Norwegian Water Resources and Energy Directorate (NVE). At present, the HBV model is used by the national flood forecasting and warning service at the NVE to simulate runoff in the river systems. Satellite imagery from NOAA AVHRR are used to observe the snow covered area (SCA). However, these observations have not been used for operational model updating so far.

Previous works in the projects Snowtools (Guneriussen *et al.* 2000) and Hydalp (Rott *et al.* 2000) showed that updating of the HBV model with remotely sensed SCA data tended to reduce the model performance. The main reason for this could be that SCA data was not used in the model calibrations. In the first phase of SnowMan, three catchments (Vinde-elv, Sjodalsvatn and Akslen) were used to test the use of satellite derived SCA in hydrological models. The study showed than when the HBV models were calibrated against satellite-derived SCA, in addition to runoff, the models simulated SCA more consistently with these data, without major reduction in the precision of the simulated runoff (Engeset and Udnæs 2002; Engeset et al. 2003). Updating of the model input, when obvious errors in the simulated SCA were detected, were performed with promising results.

In this study ten test catchments with operational HBV models were selected. The catchments represent different scales and regions in Norway. Time series of satellite derived SCA were used both in the model calibrations, and to detect and update the models when the simulated SCA deviated significantly from the observed SCA. The calibration and validation periods were four years each.

The objective of this study was to examine if the national flood forecasting could be improved by using AVHRR-derived snow covered area in the operational hydrological model.

2 Methods

2.1 Satellite observed SCA

Snow covered area was calculated from NOAA AVHRR satellite images. These images were processed either by NVE according to the NVE method (Schjødt-Osmo and Engeset, 1997) or by the Norwegian Computing Center using the Norwegian-Linear-Reflectance (NLR) method (Solberg and Andersen, 1994). Both methods convert reflectance values from band 2 into SCA. It is assumed that the bare-ground reflectance, and the reflectance of snow covered areas, are constant in space at every AVHRR-scene. Reflectance values for 100 % and 0 % snow cover are found from glaciers and snow-free areas. The snow cover percentage for each 1x1 km^2 pixel is then calculated as a linear function of the reflectance in the pixel compared to the 100 % and the 0 % reflectance.

2.2 Hydrological modelling

The Nordic HBV model (Sælthun, 1996) used in this study is a modified version of the HBV model (Bergström, 1992). The model structure is a sequence of four submodels for snow, soil moisture, dynamics and routing. The model is divided into ten elevation intervals. The model inputs are observed precipitation and temperature. The main output from the simulations is runoff, but SCA for each elevation interval is also simulated. After snow accumulation the model always simulates 100 % SCA, and simulated SCA is not reduced until the first occurrence of snow melt.

The model was automatically calibrated for the ten test catchments using the parameter estimating routine PEST (Doherty et al., 1994). Data from the four-year period from 1st September 1995 to 31st August 1999 was used for calibration. The model was calibrated in two modes for each catchment: (1) against runoff only (called the Q-models), and (2) against both runoff and SCA (called the QS-models). For two of the catchments the runoff was represented by the calculated reservoir inflow. These runoff data may have large errors in the day to day variations, but the accumulated runoff is supposed to be correct.

As the HBV-model is highly over-parameterised, standard values were assigned to some of the calibration parameters. Internal model parameters, like maximum content of liquid water and the refreezing coefficient, were not calibrated. The snow parameters allowed to be calibrated were the correction factors of the input values (temperature and precipitation), and the degree-day melting factor. This was based on experience from studies of similar models and snow pillow data in Norway (Engeset et al., 2000), where these parameters were found to be of large importance for the dynamics of the snow reservoir. As satellite-based SCA rarely reaches more than 75 % on a catchment scale (Engeset et al., 2003), the satellite-based SCA was transformed linearly to cover the interval 0-100 % before used in the model calibration.

The weighting factor of the observations is of great importance in the automatic calibration process. In this study the simulated results were compared to and evaluated against observed discharge, deviation from accumulated discharge and, when calibrated against SCA, satellite observed SCA. In order to avoid that one of the observation types was dominating the calibration process, the weighting factors where chosen so each of the observation types contributed approximately equally to the model performance coefficient (Φ). Thus the number of observations and the typical magnitude of each observation type were taken into account in the weighting factor.

Four independent years (1st September 1994 – 31st August 1995 and 1st September 1999 – 31st August 2002) were used to evaluate the models with respect to runoff and SCA, and to investigate if updating the model input would improve the simulations. Engeset et al. (2003) showed that model inputs successfully could be updated in order to improve the simulated runoff when there was a major difference between observed and simulated SCA. In our work the model input was updated with a) a percentage change of the winter precipitation and/or b) temperature modifications immediately ahead of and during the melt season. An updating scenario was triggered by either a) a deviation between observed and simulated SCA greater than 20 % at a single occasion or b) three succeeding deviations of at least 10 % within 10 days.

3 Test sites

Ten catchments were selected in this study. The catchments represent different altitude ranges, area sizes and geographical location (Fig. 1 and Tab. 1). They were chosen in order to run models operationally and to cover essential rivers in Norway. For all catchments the snow melt flood in spring and summer is usually the dominating flood each year. To be able to observe SCA from satellites, only catchments with non forested or sparse forested areas were chosen.

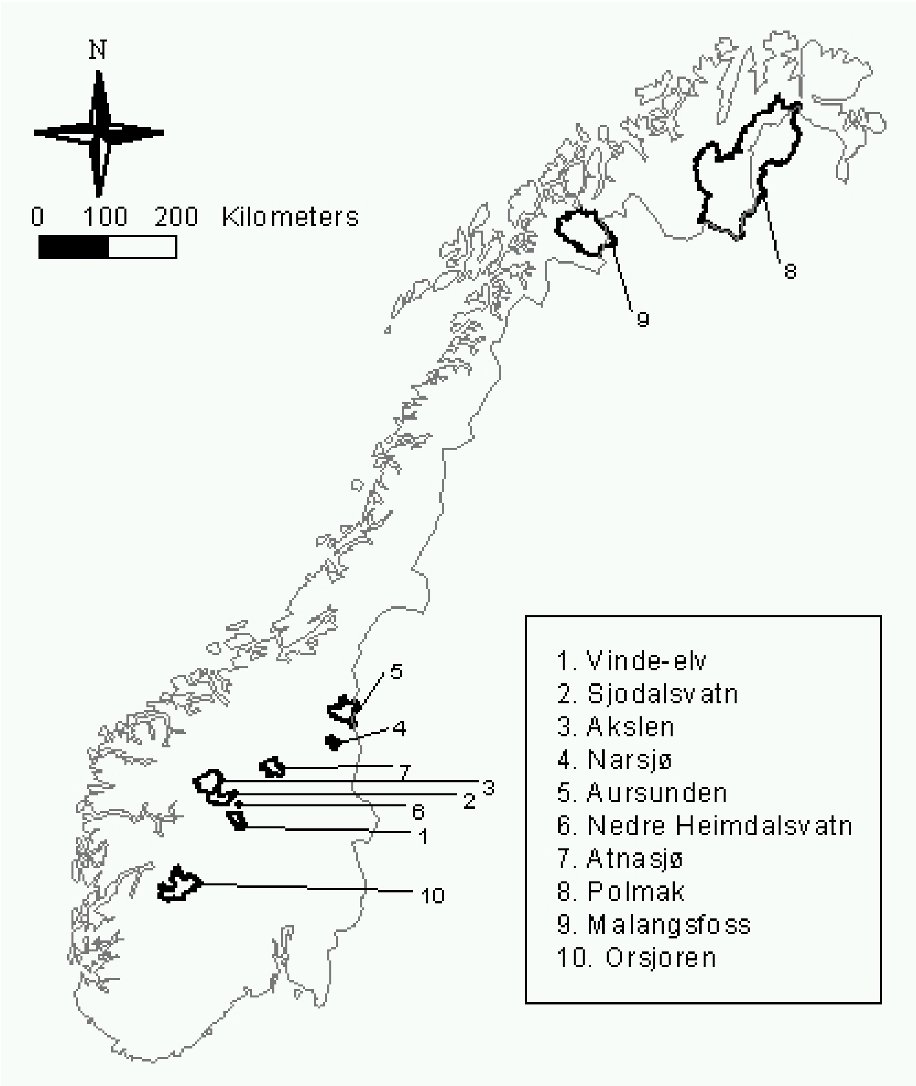


Figure 1 Location map of the ten catchments in Norway used in the study.

Table 1 Description of the ten test catchments used in the HBV simulations. The catchments are sorted by decreasing median altitude.

Catchment	No. in map (Fig. 1)	Annual runoff (mm)	Area (km^2)	Altitude median-max-min (m a.s.l.)			Alpine (%)	Forest (%)
Akslen	3	966	791	1476	2472	480	84	16
Sjodalsvatn	2	1257	474	1465	2400	940	100	0
Nedre Heimdalsvatn*	6	875	130	1303	1843	1053	96	4
Orsjoren	10	840	1192	1231	1531	951	98	2
Atnasjø	7	671	465	1186	2114	701	78	22
Vinde-elv	1	487	268	985	1686	560	59	41
Narsjø	4	575	119	934	1595	737	66	34
Aursunden*	5	764	835	840	1553	690	59	41
Malangsfoss	9	847	3118	719	1677	20	70	30
Polmak	8	384	14165	355	1067	20	51	49

** Catchment where runoff is represented by calculated reservoir inflow.*

4 Results and discussion

4.1 Model calibration and simulation

Four years, 1st September 1995 to 31st August 1999, were used for calibration. A total of 96 Q-models and 96 Q+SCA-models were automatically calibrated for each catchment using the PEST routine. The five best models of these were chosen for validation. Generally, several of the Q-models and QS-models for each of the catchments were able to simulate runoff well. However, most of the QS-models obtained a small decrease in the coefficient of determination of the discharge (R^2_Q) of 0.01 – 0.02 units compared to the Q-models. Examples from two of the catchments are shown in Figure 2 and 3. Looking at the five best models for each of the catchments, the R^2_Q ranged from 0.76 to 0.94 (median = 0.85) for the Q-models, and from 0.73 to 0.94 (median = 0.83) for the QS-models (Tab. 2). The absolute values of R^2 for Vinde-elv, Sjodalsvatn and Akslen deviates from those found earlier for those catchments (Engeset et.al., 2003). This is caused by modified weighting factors and different calibration and validation periods used in the two projects and does not influence on the general results of the two studies. The timing of the flood peaks was satisfactory for all catchments in most of the years. However, for some of the catchments the amplitude of the flood peaks matched poorly. As expected, using SCA in the calibration increased the model performance with respect to SCA. While the R^2_{SCA} ranged from 0.32 to 0.99 (median = 0.81) for the ten catchments regarding the five best Q-models for each catchment, the R^2_{SCA} of the QS-models ranged from 0.89 to 0.99 (median = 0.94). The improvement in simulated SCA was remarkable, especially for catchments where the Q-model simulations resulted in low R^2_{SCA}. This is in agreement with the results found in the preliminary study using only three of the catchments (Engeset et al., 2003), although it is not as convincing when looking at all ten catchments.

Table 2 Model performance of the best five models from the automatic calibration.

	Q models				Q + SCA models			
	R^2_Q		R^2_{SCA}		R^2_Q		R^2_{SCA}	
Catchment	calib.	valid.	calib.	valid.	calib.	valid.	calib.	valid.
Akslen	0.83	0.85	0.90	0.58	0.82	0.83	0.93	0.61
Sjodalsvatn	0.79	0.84	0.76	0.65	0.78	0.84	0.95	0.83
N. Heimdalsvatn	0.76	0.72	0.45	0.63	0.73	0.70	0.90	0.92
Orsjoren	0.77	0.71	0.75	0.63	0.75	0.72	0.95	0.78
Atnasjø	0.81	0.83	0.90	0.75	0.79	0.83	0.91	0.66
Vinde-elv	0.87	0.84	0.72	0.93	0.83	0.77	0.92	0.83
Narsjø	0.88	0.86	0.82	0.22	0.87	0.86	0.94	0.46
Aursunden	0.92	0.88	0.91	0.51	0.90	0.88	0.97	0.71
Malangsfoss	0.88	0.81	0.92	0.45	0.86	0.79	0.94	0.52
Polmak	0.94	0.90	0.99	0.92	0.94	0.90	0.99	0.91

The R^2-values are the averaged R^2 of the five best models selected from the calibration.

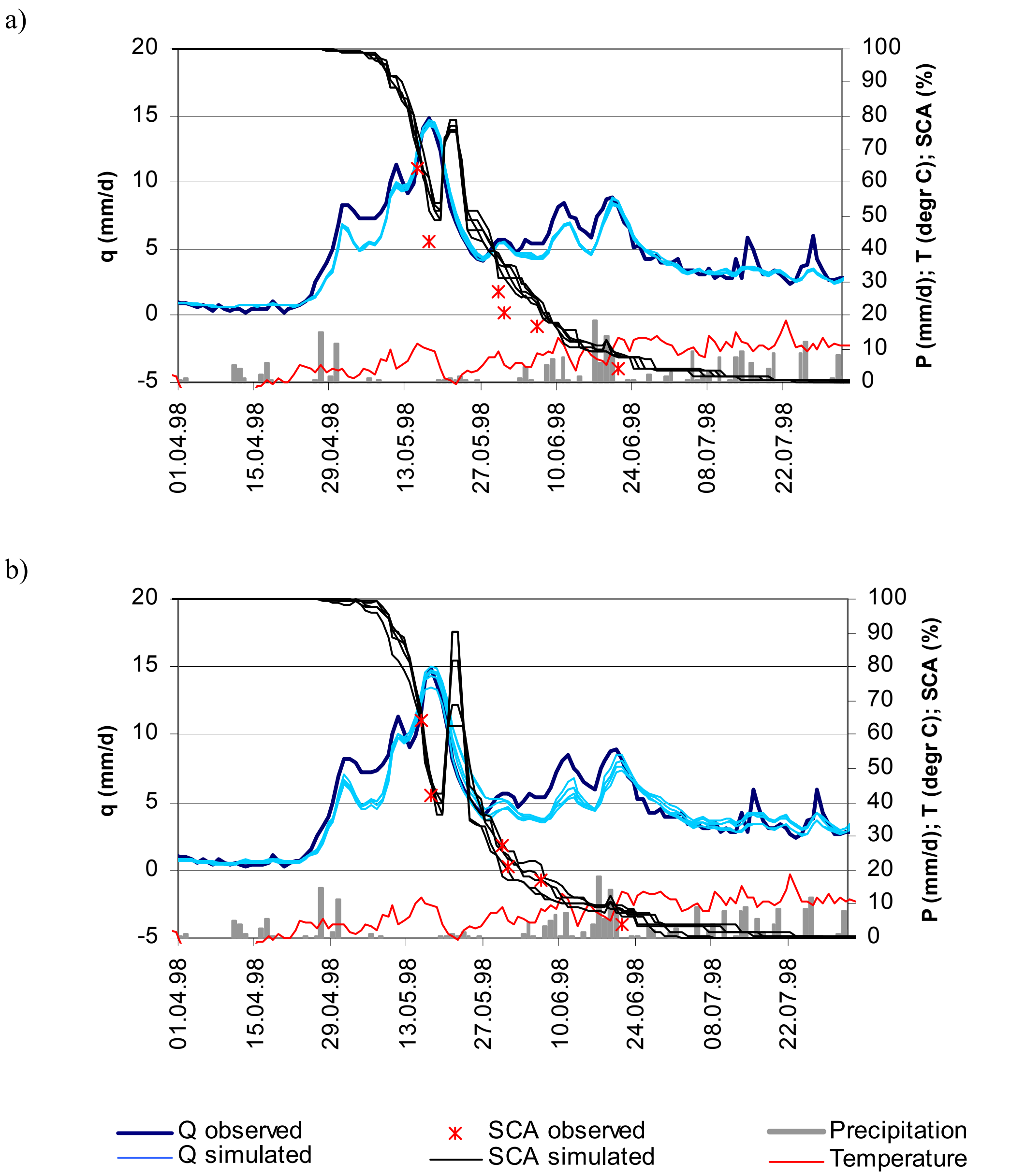


Figure 2 Example of calibration results of a) the Q-models and b) the Q+SCA-models for Aursunden, which has a generally high R^2_Q. R^2_Q decreased from 0.92 (Q-models) to 0.90 (Q+SCA-models) and R^2_{SCA} increased from 0.90 (Q-models) to 0.97 (Q+SCA-models) when including SCA in the calibration.

As already mentioned, four independent years (the winters 94/95 and 99/00 – 01/02) were used to validate the models. Model runs of the five best models (both Q and QS) with respect to R^2_Q from each catchment were validated against observed runoff and SCA. In general, the Q+SCA-models were of the same quality as the Q-models with respect to runoff. Three catchments had higher R^2_Q and seven had lover R^2_Q than in the calibration period. Similar changes in model performance were found both for the Q- and the Q+SCA-models. Therefore, the changes in model performance could most likely be attributed to the model input (precipitation and temperature) and the representability of the meteorological observations. The high performance in terms of SCA obtained in the Q+SCA calibration was not maintained in the validation period. The models for all ten catchments experienced a decrease in R^2_{SCA}, two of them with 40 %.

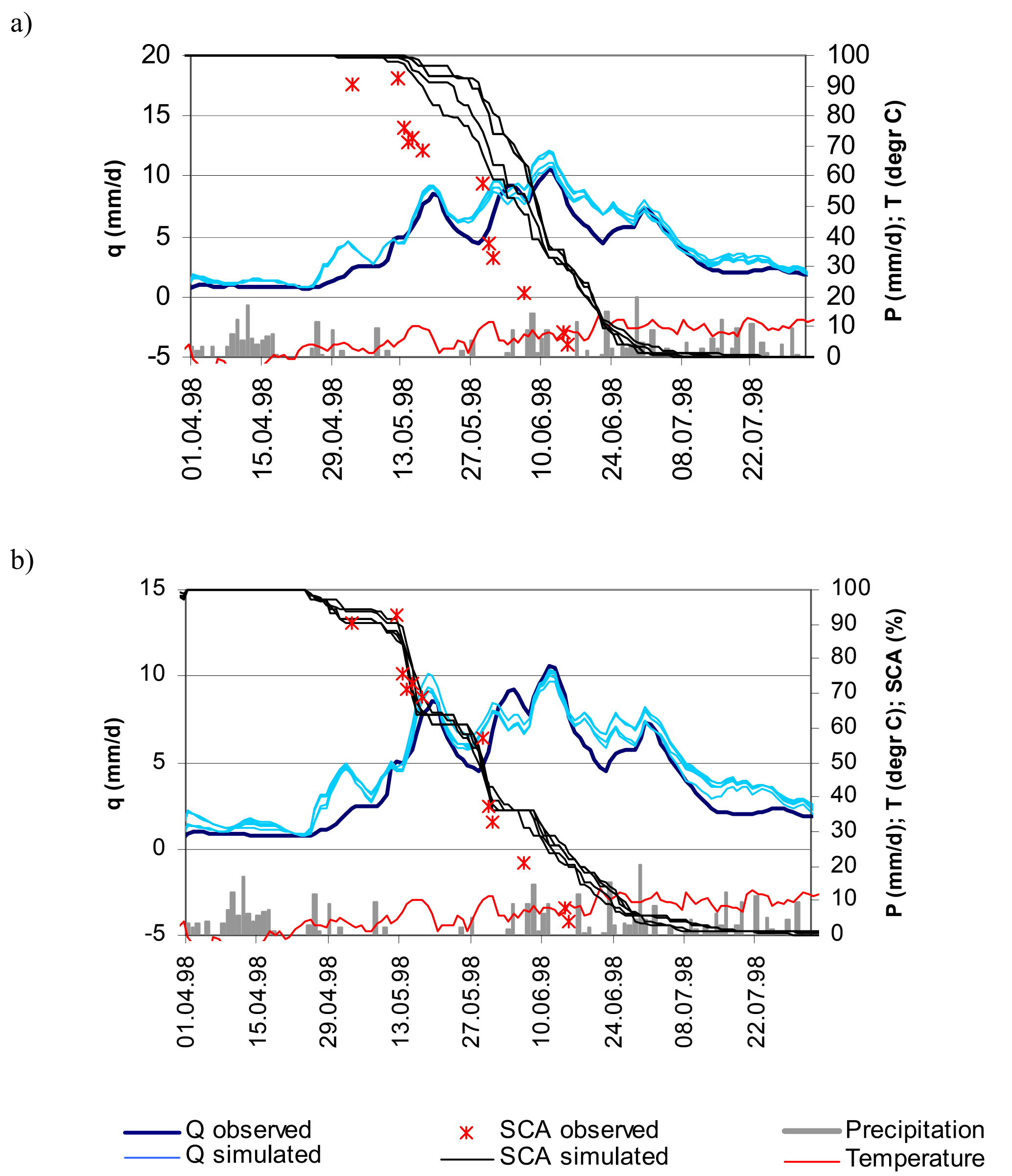


Figure 3 Example of calibration results of the a) Q-models and b) the Q+SCA-models for Orsjoren, which has a generally low R^2_Q. R^2_Q decreased from 0.77(Q-models) to 0.75 (Q+SCA-models) and R^2_{SCA} increased from 0.75 (Q-models) to 0.95(Q+SCA-models) when including SCA in the calibration.

4.2 Model updating

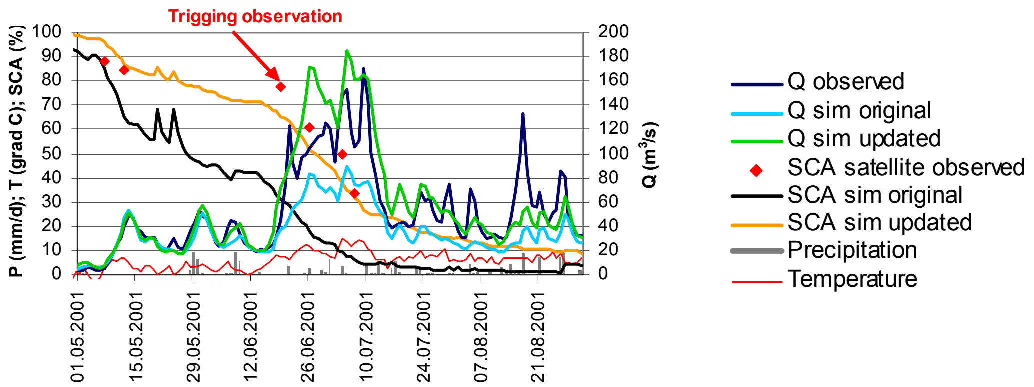
Positive trigger response, defined as deviations between simulated and observed SCA (described in chapter 2.2, last pharagraph), was found in 22 cases (each representing one model year). Of these cases seven model years with a positive response were subjective rejected from updating either because the flood event already had finished or because the observed SCA showed a large decrease in SCA when no indication of snowmelt were seen in the observed discharge. Updating scenarios were calculated for the remaining 15 cases. The updating scenarios were validated in terms of R^2-values of Q and SCA, timing and amplitude of the flood peaks and mass recovery (calculated as simulated discharge divided by observed accumulated discharge of the hydrological year). In the following we describe in detail the updating scenarios for the 10 test catchments.

4.2.1 Akslen

The Q+SCA and the Q-models simulated the SCA with R^2_{SCA} = 0.90 and 0.93, for the Q- and the Q+SCA-models respectively, in the calibration period, and 0.58 and 0.61, respectively, in the validation period.

Akslen case 1 – updating the model input 2001

In 2001 the main spring flood was highly underestimated and the main decrease in SCA started several weeks too early in the model (Fig. 4). The total volume of the spring flow was also underestimated by 30 %. On 19th June the simulated SCA was 47 percent units lower than the observed SCA. The difference between simulated and observed SCA was decreased to a satisfactory level (within 10 percent units deviation) by increasing the winter precipitation by 200 % (results not shown). However, this led to an overestimation of the flow ahead of and during the main flood peak. Decreasing the temperature with 1°C from 1st May to 15th July and increasing the winter precipitation by 150 % simultaneously led to a better estimate of both SCA and the early spring flow (Fig. 4). This improved the R^2_{SCA} from 0.61 to 0.90 and the R^2_Q from 0.83 to 0.85. The main flood was slightly overestimated (although less than in the case when only precipitation was updated), but the mass recovery increased from 0.75 in the original model to 1.08 in the updated model.



Winter precipitation 00/01 increased by 150 % and spring temperature reduced by 1°C.

Figure 4. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Akslen.

4.2.2 Atnasjø

The dynamics of the catchment was simulated well in the HBV-models, with respect to both discharge and SCA,. The Q+SCA-model simulates a slightly larger snow reservoir and estimates SCA a little better than the Q-model in the calibration period. In the validation period the Q-model was better than the Q+SCA-model. The performance with respect to discharge was very similar for the two models.

Atnasjø case 1 – winter precipitation decreased in 2000

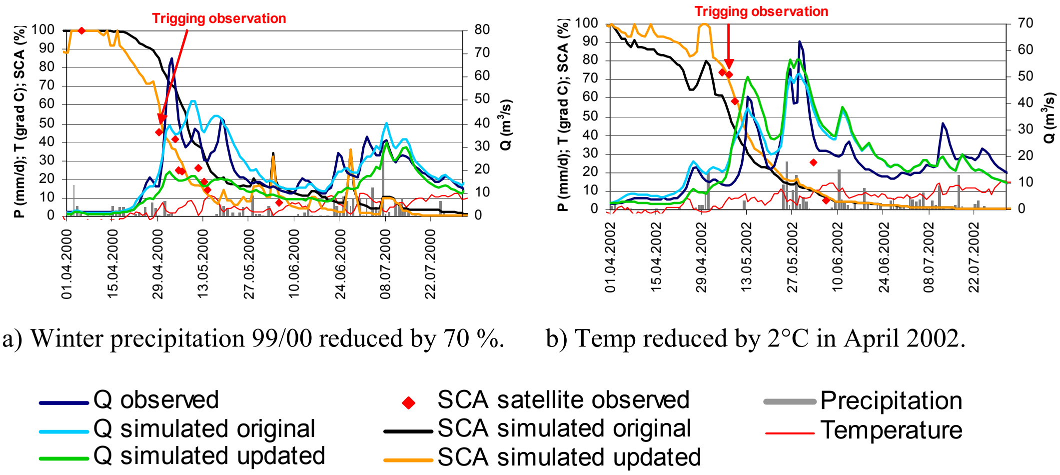
On 29th April 2000 the simulated SCA was 40 percent units higher than the observed one (Fig. 5a). This was followed by succeeding overestimations of SCA. Reducing the winter precipitation by 70 % led to a much better fit of SCA, R^2_{SCA} increased from 0.66 to 0.84, but the flood was dramatically underestimated (Fig. 5a).

Atnasjø case 2 – overestimated SCA in 2001

In the middle of the melt season 2001, a trigging observation where simulated SCA was 30 percent units above the observed one was recorded. However, since the previous observations of SCA corresponded relatively well with the simulated ones and the simulation so far reproduced the observed flood event almost perfect, no update of the model input was performed.

Atnasjø case 3 – updating the model input 2002

In 2002 the simulated SCA was 21 percent units higher than the observed SCA on 7th May (Fig. 5b). Increasing the winter precipitation 2002 with 40 % led to a simulated SCA within 10 % deviation from the observed one. However, it also resulted in a large overestimation of the discharge throughout the melt season (results not shown). Reducing the temperature with 2°C in April did also improve the simulated SCA satisfactorily. However, the first (small) flow peak was then underestimated and the next one overestimated (Fig. 5b). None of the updating scenarios improved the simulated discharge compared to the original HBV-model.



a) Winter precipitation 99/00 reduced by 70 %. b) Temp reduced by 2°C in April 2002.

Figure 5. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Atnasjø.

4.2.3 Aursunden

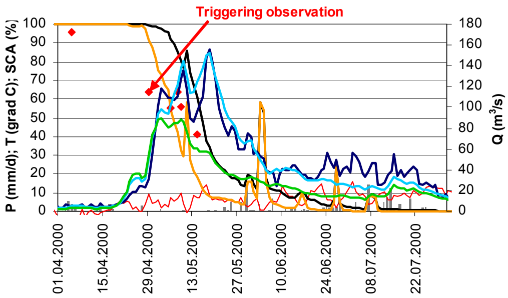
The catchment Aursunden is a reservoir, with regulated outlet. The discharge used in the model is therefore calculated from reservoir inflow. An increase in R^2_{SCA}, from 0.91 to 0.97, was obtained by calibrating against SCA in addition to the discharge. The improvement was largest in the validation period, which also maintained the R^2_Q of the Q-models. Two of the years in the validation period showed large discrepancies between simulated and observed SCA. The simulated discharge was close to the observed also when the simulation of SCA failed.

Aursunden case 1 – updating the winter precipitation 2000

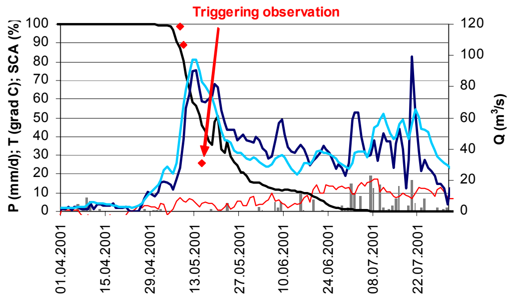
In 2000 the SCA was overestimated although the simulated discharge fitted well to the observations. Reducing the winter precipitation in order to obtain a better fit to the observed SCA (29th May and later) led to an underestimation of the flow peaks (Fig. 6a).

Aursunden case 2 – no update of model input winter 2001

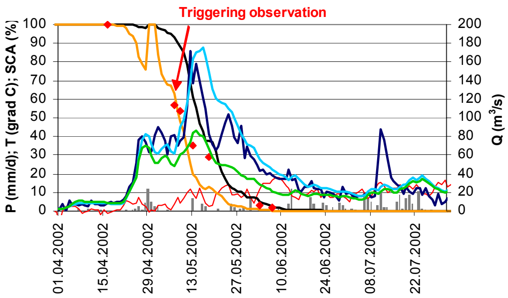
On 15th May 2001 the observed SCA was 25 percent units lower than the simulated (Fig. 6b). The observed value was interpreted as unlikely because the flood peak had already cumulated and the simulated discharge and SCA fitted well before that date.



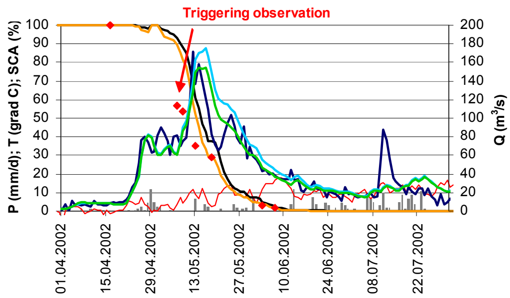
a) Winter precipitation 99/00 reduced by 40 %.



b) No update of model input 2001.



c) Winter precipitation 01/02 reduced by 40 %.



d) Winter precipitation 01/02 reduced by 20 %.

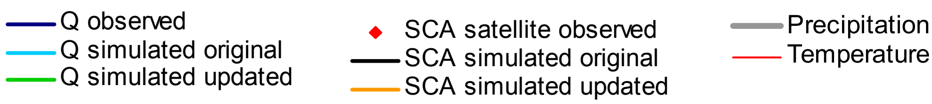


Figure 6 Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Aursunden.

Aursunden case 3 – updating the winter precipitation 2002

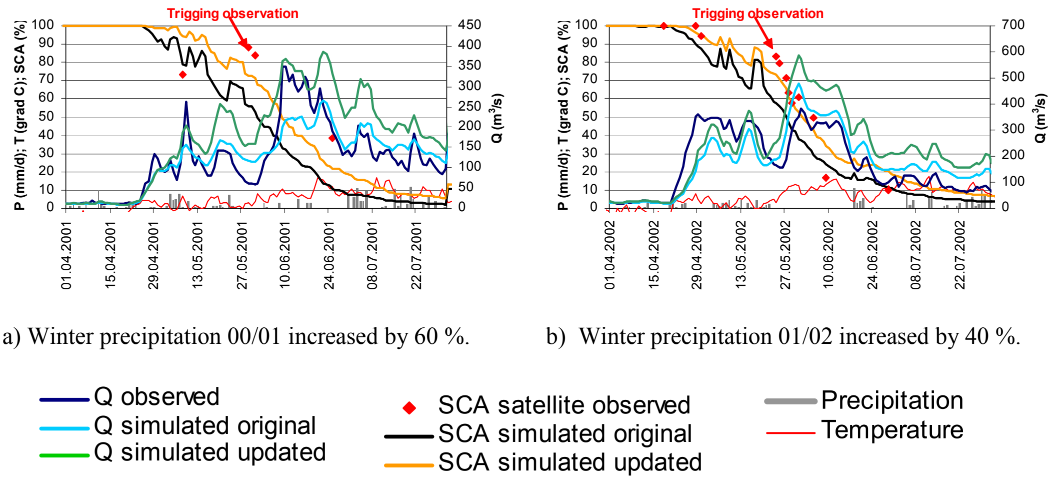
In 2002 the simulated SCA was 36 percent higher than the satellite observed SCA on 7th May. A reduction to 60 % of the observed winter precipitation resulted in a good fit to observed SCA just before the main flow peak (Fig. 6c). The mass recovery was reduced from 1.13 to 0.78 of that observed. This clearly points on the risk of reducing the precipitation, as it led to a highly underestimated spring flood. Reducing the winter precipitation somewhat less, to 80 % of that observed, gave a better fit to the discharge curve (Fig. 6d) and a mass recovery of 1.02. The R^2_{SCA} was improved from 0.71 to 0.78, whereas the R^2_Q remained almost unchanged. However, the deviation between simulated and observed SCA early in the melt season was still larger than 20 %.

4.2.4 Malangsfoss

The HBV-models of the catchment Malangsfoss had high R^2 values for discharge and SCA both in the Q- and the Q+SCA-models. The R^2_Q was 0.88 and 0.86, respectively, and the R^2_{SCA} 0.92 and 0.94, respectively, in the calibration period. In the validation period the R^2_{SCA} was markedly lower, indicating that updating of the model input could improve the simulations.

Malangsfoss case 1 – increasing the winter precipitation 2001

The first observation of SCA fitted well with the simulated one (Fig. 7a). Three weeks later, when the snowmelt had proceeded, the observed SCA was 32 percent units higher than the simulated, although the simulated discharge agreed well with the observed one. Increasing the winter precipitation by 60 % reduced the deviation between simulated and observed SCA to a satisfactory level. However, the flood was then overestimated through most of the melt period, except for the main flood peak which was better estimated by the updated model.



a) Winter precipitation 00/01 increased by 60 %.

b) Winter precipitation 01/02 increased by 40 %.

Figure 7 Simulated SCA and discharge compared to the observed ones with and without updating the input date in Malangsfoss.

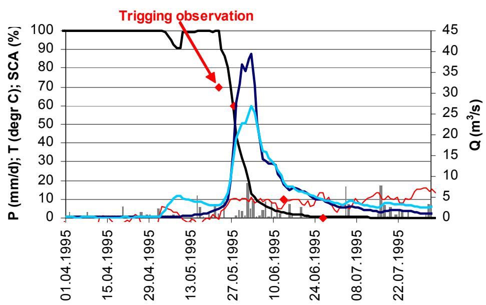
Malangsfoss case 2 – increasing the winter precipitation 2002

The simulated SCA was lower than the observed ones through the main part of the melt season. On 25th May the simulated SCA was 25 percent units below the observation. Increasing the winter precipitation with 40 % gave a much better correspondence to the observed SCA (Fig. 7b). However, the main flood peak was highly overestimated and the mass recovery much too high (1.28 compared to 1.00 in the original simulation).

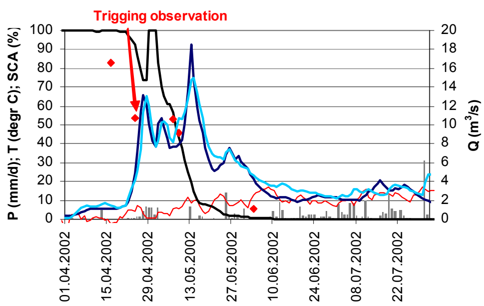
4.2.5 Narsjø

A marked improvement of the model performance with respect to SCA was achieved when including satellite observations in the calibration. The R^2_{SCA} increased from 0.82 to 0.94 in the calibration period and from 0.22 to 0.46 in the validation period.

In total, three trigging observations was made during the validation period, 22nd May 1995, 29th April 2000 and 24th April 2002. All of them had an observed SCA of at least 30 percent units lower than the simulated. The simulated discharge, both with respect to snow melt start and volume, fitted well with the observed ones up to the time of the trigging observations (see Fig. 8a and b for 1995 and 2002, respectively). In Narsjø, snow melt starts early compared to the reference points for the snow signature, which may increase the uncertainty of the satellite observed SCA considerable. The observed SCA was therefore considered as unlikely, and no updating of the model was performed.



a) Observed SCA at 70% before the snow melt started in 1995. Model input not updated.



b) Observed SCA 40 percent units below the simulated SCA, and simultaneous a perfect simulation of discharge in 2002. Model input not updated.

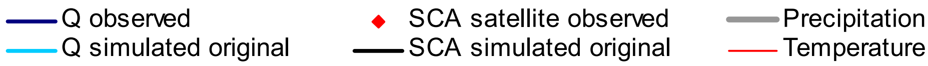


Figure 8. Simulated SCA and discharge compared to the observed values in the catchment Narsjø 1995 (a) and 2002 (b).

4.2 6 Nedre Heimdalsvatn

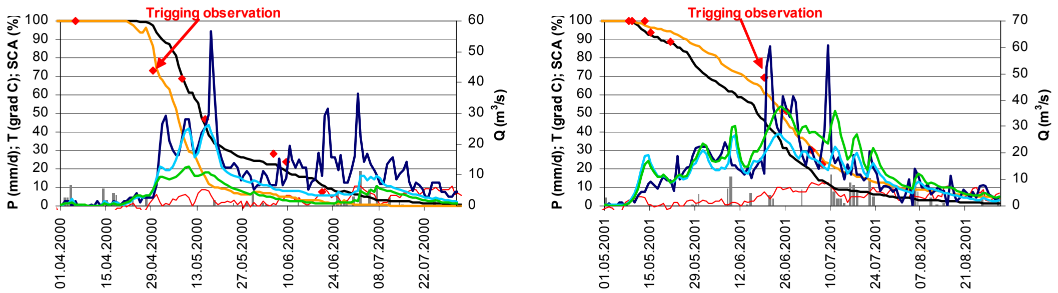
The catchment Nedre Heimdalsvatn is a reservoir, with regulated outlet. As for Aursunden the discharge is calculated from reservoir inflow. The model performance with respect to SCA, was markedly better with the Q+SCA than the Q-model both in the calibration and the validation period, except for 2001 where the Q-model simulated SCA better than the Q+SCA-model.

Nedre Heimdalsvatn case 1 – updating the winter precipitation in 2000

A SCA observation early in the melt season indicated that the snow reservoir was overestimated in the model. Reducing the winter precipitation by 50 % decreased the deviation from 24 to 13 percent units and led to a large underestimation of the flood (Fig. 9a). However, the next SCA observation, 9 days later, corresponded well with the original model, which also simulated the discharged much better than the updated model.

Nedre Heimdalsvatn case 2 – updating the winter precipitation in 2001

The simulated SCA curves for the melt season 2001 declined too early and the largest flood peaks were underestimated (Fig. 9b). On 19th June the simulated SCA was 23 percent units lower than the satellite observed SCA. Increasing the winter precipitation by 40 % eliminated most of the discrepancies between simulated and observed SCA. The mass recovery of the flow was improved from 0.67 to 0.89. Although the total difference between simulated and observed discharge was reduced in this case, the model still failed to predict the two largest flood peaks. However, these flood peeks may not be correct on a daily basis since they are calculated as reservoir inflow based on measured water level in the reservoir and discharge out of the reservoir.



a) Winter precipitation 99/00 reduced by 50 %.

b) Winter precipitation 00/01 increased by 40%.

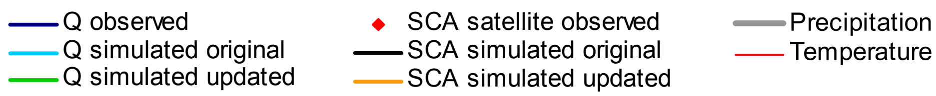


Figure 9. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Nedre Heimdalsvatn.

4.2.7 Orsjoren

Including SCA in the calibration gave a small shift in the SCA curve and advanced the decrease in SCA with a few days. This led to an improved simulation of SCA by the Q+SCA-model compared to the Q-model. R^2_{SCA} increased from 0.75 to 0.95 in the calibration period and from 0.63 to 0.78 in the validation period.

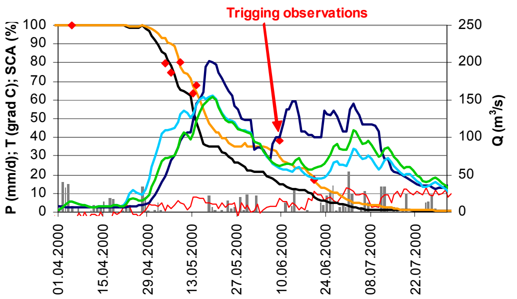
Orsjoren case 1 – rejected trigging observations 1995.

A SCA observation shortly after the initial rise of the 1995 flood indicated that the snow reservoir in the model was underestimated (data not shown). During the flood rise, the simulated discharge had reproduced the observed flow well, although it was slightly to high at the time of the SCA observation. An increase of the snow reservoir, in order to fit the observed SCA, would cause an even higher discharge at this time. Therefore no updating of the model was carried out.

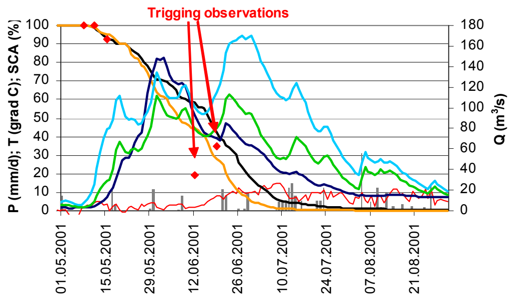
Orsjoren case 2 – updating spring temperature 2000.

In 2000 the simulated SCA fitted well to the observed during the first flood rise although the increase in discharge starts a few days to early (Fig. 10a). Later in the melt season the simulated SCA was much lower than the observed and a second flood rise was not captured by the model. Decreasing the temperature with 1°C during the melt period, 20th

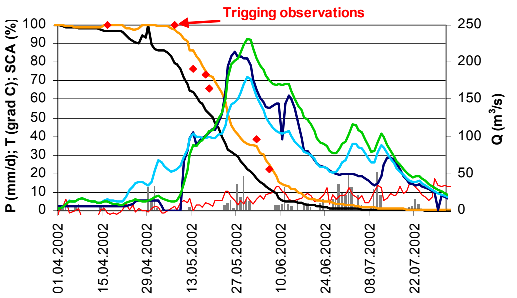
April to 30th June, improved the timing of the first flood rise (Fig. 10a). As a consequence the SCA was slightly overestimated during the first flood. However, the modelled SCA fitted better to the observed SCA later in the melt season. A small improvement was achieved for the second flood, although it was still underestimated. The R^2_Q improved from 0.72 to 0.74 and the R^2_{SCA} from 0.78 to 0.80.



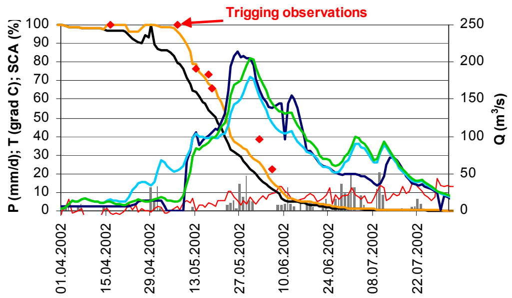
a) Temperature reduced by 1°C from 20th April to 30th of June 2000.



b) Temperature reduced by 2°C from 1st May to 15th May 2001 and winter precipitation 00/01 reduced by 40%.



c) Winter precipitation 01/02 increased by 20%, and temperature reduced by 2°C from 15th April to 7th May 2002.



d) Temperature reduced by 2°C from 15th April to 7th May 2002.

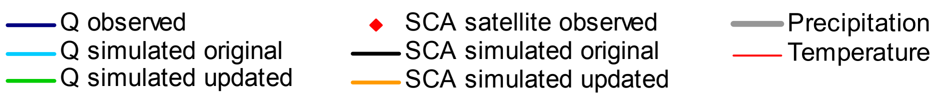


Figure 10. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Orsjoren.

Orsjoren case 3 – updating winter precipitation and spring temperature 2001.

In 2001 both the SCA and the melt flood was overestimated by the model (Fig. 10b). The rise in discharge started too early and a small flow peak, which was not seen in the observations, was simulated by the model. The main flood peak was simulated well by the model, but an later flood event was highly overestimated. On 12th and 19th June the SCA was overestimated by 46 and 13 percent units, respectively, by the model. Decreasing the winter precipitation by 40 % led to a much better correspondence between observed and simulated SCA. The accumulated runoff was also improved, although the overestimated initial flow peak was still present. Reducing the temperature in the beginning of May, in addition to the reduction in winter precipitation, improved the fitting of the first flood rise (Fig. 10b). The corresponding delay in the decrease of SCA results in an overestimated SCA on 12th June. The main flood peak was still underestimated, whereas the tail of the flood was much closer to the observed one although slightly to high.

Orsjoren case 4 – updating winter precipitation and spring temperature 2002.

SCA was underestimated by the model through the whole melt season 2002. Snow melt started too early and the flood peak was underestimated (Fig. 10c). On 7th May the SCA was underestimated by 20 percent units. Increasing the winter precipitation by 20 % and reducing the temperature with 2°C from 15th April to 7th May improved the simulated SCA, but led to overestimation of the runoff (128 % of observed) (Fig. 10c). Leaving the precipitation unaltered and only reducing the temperature gave a better result. SCA was then simulated very well and the flood dynamics corresponded better with the observed (Fig. 10d).

4.2 8 Polmak

The melt season in the Polmak catchment is short. The catchment has a large area, but still a rather uniform response in terms of snow melt. The HBV-models reflected the dynamics very well with $R^2_Q = 0.94$ and 0.90 respectively, in the calibration and validation period. Only a few satellite observations of SCA were available. The observations, fitted relatively well with the simulations, $R^2_{SCA} = 0.99$ in the calibration period for both the Q- and the Q+SCA-models, and 0.92 (Q-model) and 0.91 (Q+SCA-model) in the validation period. One trigging observation was found in the validation period, on 20th May 2000 (Fig. 11). However, this was the only SCA observation during snow melt that year and occurred after the melt flood had started. The simulated and observed discharge agreed well up to that date, thus no updating of the model input was performed.

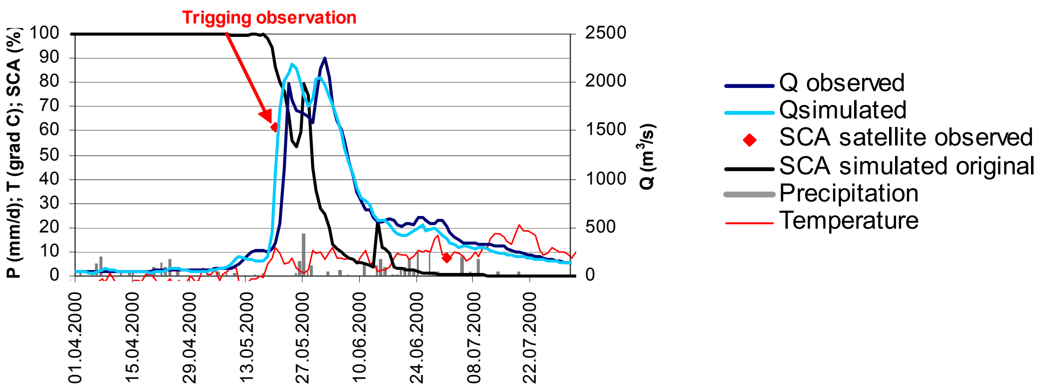


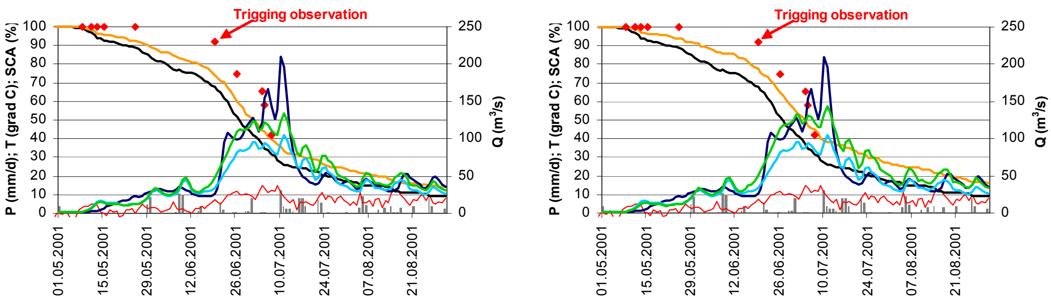
Figure 11 Simulated and observed SCA and discharge in the catchment Polmak 2000.

4.2.9 Sjodalsvatn

The Q+SCA-model simulated SCA much better in the calibration period than the Q-model, $R^2_{SCA} = 0.95$ compared to 0.76. In the validation period the SCA was better simulated with the Q+SCA-model than the Q-model, $R^2_{SCA} = 0.83$ compared to 0.65.

Sjodalsvatn case 1 – updating the winter precipitation 2001.

In 2001 the SCA was underestimated with approximately 20 % by the Q+SCA-model. The main spring flood was also underestimated. By increasing the winter precipitation by 40 and 60 % the underestimation of SCA was decreased to 18 and 14 percent units respectively (Fig. 12a and b). A better mass recovery was also obtained, increasing from 0.77 in the original simulation to 0.94 and 1.0, respectively, in the updated simulations. The flood peak were still underestimated and the tail of the main flood event became too large.



a) Increasing the winter precipitation 00/01 by 40 %. b) Increasing the winter precipitation 00/01 by 60 %.

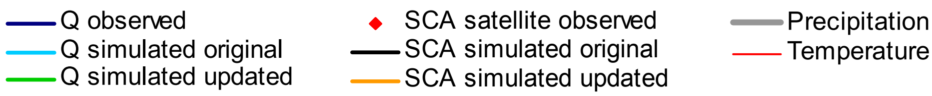


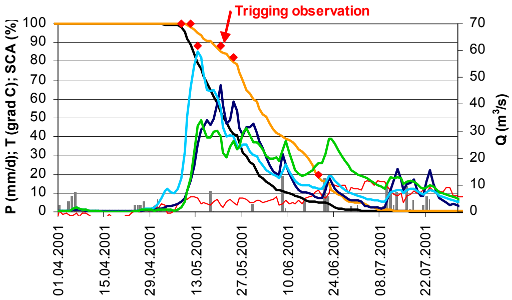
Figure 12. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Sjodalsvatn.

4.2.10 Vinde-elv

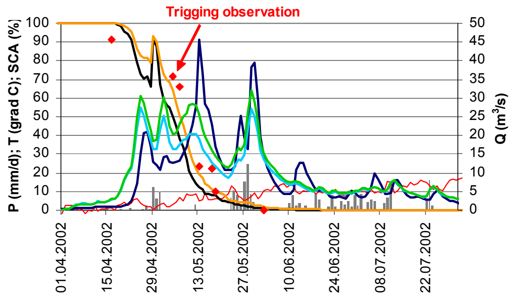
The Q+SCA-model simulated SCA better in the calibration period than the Q-model, R^2_{SCA} = 0.92 compared to 0.72 for the Q-models. In 2001 the melt started too early in the Q+SCA-model, advancing the flood peak and the decreasing the SCA (Fig. 13a). Actually, the Q-model timed the flood better this year. Both the Q and the Q+SCA-model overestimated the flood peak in 2001. In 2002 the simulated decrease of the SCA started too early. This could be due to error in the amount of accumulated snow. An observed flood peak in the middle of May 2002 was not captured in the model (Fig. 13b). Most likely this flood peak was caused by a precipitation event not measured by the meteorological station.

Vinde-elv case 1 – updating the temperature in the melt season 2001.

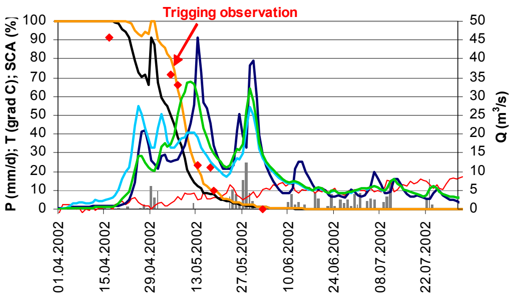
On 20th May 2001 the simulated SCA was 35 percent units lower than the satellite observed SCA. Decreasing the temperature with 2°C in the melting season (21th April to 30th June) led to a simulated SCA very similar to the observed one, R^2_{SCA} = 0.92 compared to 0.83 without updating, and the simulated discharge became more similar to the observed one in the initial phase of the melt flood (Fig. 13a). However, the main flood peak was underestimated and the discharge at the end of the melt season was highly overestimated in the updated model. The mass recovery for the hydrological year 2000/2001 was 1.0 in both cases.

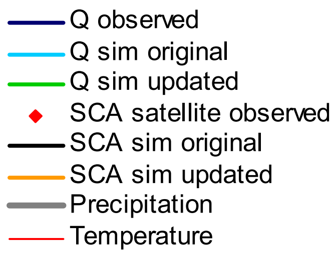


a) Decreasing the input temperature with 2°C in the period 21st April to 30th June 2001.



b) Increasing the winter precipitation 01/02 by 20 %.





c) Decreasing the temperature with 1°C in April 2002.

Figure 13. Simulated SCA and discharge compared to the observed values with and without updating the input data of the catchment Vinde-elv.

Vinde-elv case 2 – updating the precipitation and temperature in the winter season 2002.

The flow peak around 12th May 2002 was equivalent to a precipitation event of 30 mm (results not shown). At the nearby located meteorological stations the observed precipitation was only 3 to 10 mm. A local thunderstorm may have caused the observed flood event.

In addition to the highly underestimated maximum flood peak the simulation for 2002 showed an underestimation of the SCA in the melt season and a too early start of the first flow peak (Fig. 13b). The later was also seen for several other years. Increasing the precipitation during the winter season (1st October – 30th April) slightly improved the simulation results with respect to SCA, R^2_{SCA}=0.86 compared to 0.83. As could be expected, this also increased the size of the first flow peak, which was already too high (Fig. 13b). The mass recovery worsened from 1.0 to 1.1. Modification of the SWE in the model was therefore rejected in this case.

Decreasing the temperature had an overall better effect on the model performance, and preserved the mass recovery. A simulation with a 1°C temperature reduction in April resulted in a good fit of simulated versus observed SCA, R^2_{SCA}=0.87 compared to 0.83, (Fig. 13c). The timing of the first flow peak and the main flow peak was also better reproduced than in the original model.

As mentioned above, a too early start of the simulated snow melt seems to be a general problem in the Vinde-elv catchment. The reduction of the April temperature was therefore tested on the other years in the validation period. This had a positive effect on the model performance in the validation period increasing the R^2_Q from 0.77 to 0.81 and the R^2_{SCA} from 0.83 to 0.89 (results not shown). A recalibration where the effective snow melt temperature was reduced did not improve the model performance. Probably the effect was cancelled out by changes in the other calibration parameters. The R^2_Q of the recalibrated models was at the same level as in the original calibration.

4.2.11 Summary of the model updating

The model updating revealed quite diverging results. Six of the cases gave better amplitudes of the flood peak(s) and the accumulated discharge volume. These were all models representing catchments with high mean altitude (Akslen, Sjodalsvatn, Orsjoren and Nedre Heimdalsvatn), and most of them took place during the winter 2001 when the main wind direction deviated from normal (prominent snow-producing weather circulation from south-east as opposed to from west which is normal). In the remaining 9 cases, the change of model input led to larger deviation between simulated and observed discharge than the non-updated models. These cases were typical for catchments with relative low mean altitude. The observed difference in performance with respect to altitude can be attributed to the method used to detect the snow signature in the satellite images. Reference points for the snow signature are typically chosen from glaciers and mountain plateaus where a 100 % snow cover can be expected. These areas are situated at high altitudes where snow melt starts relatively late. Since the spectral signature of the snow depends on i.a. inclination angle and the state of the snow particles, the signature may vary considerable within one image. This can lead to large uncertainties in observed SCA, especially during spring time when the snow conditions may range from cold, fresh snow to highly regenerated melting snow. Regional climate variation may also contribute to the spread in spectral signature. Another factor of importance is the length of the calibration period, which in this study was limited by the availability of historical satellite images. By extending the calibration period, more of the natural variations will be included in the calibrated models, and thereby making them more robust.

4.3 Uncertainties in satellite observed SCA

As shown by the simulations for Narsjø in 2002 (Fig. 8b) an almost perfect runoff simulation can be related to a very poor simulation of SCA compared to the satellite data. In such cases it is relevant to mistrust the quality of the satellite derived SCA. Undetected clouds, low precision in the geometrical correction of the satellite image or regional variations in snow reflectance can cause such errors. For the Narsjø catchment the snowmelt usually starts early and the snow reflectance is reduced compared to snow reflectance in the higher elevated training areas used to estimate the 100 % SCA reflectance. This effect leads to an underestimation of SCA, especially early in the melting period before melting starts in the training areas. Both in 2000 and 2002 melting started earlier than normal in the Narsjø catchment compared to the higher elevated Akslen catchment. Particularly in 2000 the observed SCA seemed to be far too low (Fig. 14). Using these data to update the models would have lead to a total underestimation of the flood. The estimated SCA at 29th April was about 40 %. At this point only 20 millimeter accumulated runoff was observed since the start of the melting runoff at 21st April. The runoff data reveals a rather large flood after 29th April and it was not observed any precipitation in the days until the flood peak at May 2nd . This shows that the simulated SCA was rather too low than too high before the flood event.

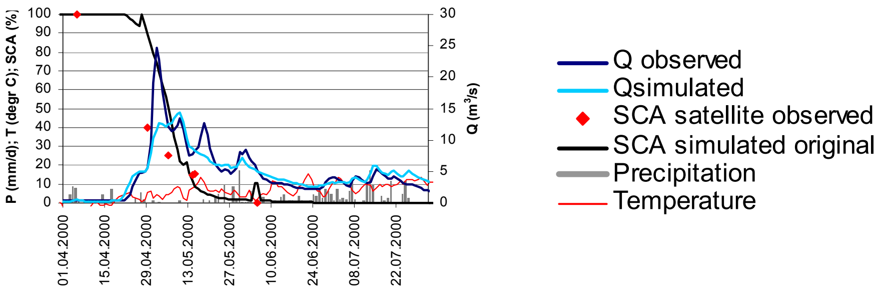


Figure 14. Simulated and observed SCA and discharge in the catchment Narsjø 2000.

5 Conclusions

This study shows that the HBV-models can be calibrated against SCA in addition to Q with only small reduction in runoff performance. The improved performance in SCA was considerable higher than the loss of performance in runoff. Generally, both the Q- and the QS-models simulated runoff well in the calibration period. In addition, the QS-models showed a good fit to the observed SCA.

Using satellite observed SCA to update the HBV-models showed diverging results. The updating was successfully in high altitude catchments whereas the method failed for lower located catchments. Using SCA from satellite images is not straightforward during snow melt, since the spectral signature may vary considerable in space. In order to improve the SCA product during snowmelt, information of the snow state could be included in the SCA algorithm.

The results of this study illustrates that satellite observed SCA in hydrological models can be useful, especially in years with unusual weather conditions. However, careful considerations of the uncertainty in the satellite SCA are needed before updating the operational runoff models.

6 References

Bergström, S. (1992) The HBV model–its structure and applications, SMHI Hydrology, RH no.4, Norrköping, 35 pp.

Doherty, J., Brebber, L and Whyte, P. (1994) PEST Model-Independent Parameter Estimation. Watermark Computing, Corinda, 177 pp.

Engeset, R., Sorteberg, H.K. and Udnæs, H.C. (2000) NOSIT Utvikling av NVE's operasjonelle snøinformasjonstjeneste. (NOSIT Developing the operational snow information at NVE, in norwegian). NVE Dokument nr 1-2000, Oslo. 46 pp.

Engeset, R.V., 2003, Udnæs, H.-C., Guneriussen, T., Koren, H., Malnes, E., Solberg, R. and Alfnes, E. (2003) Improving runoff simulations using satellite-observed time-series of snow covered area. Nordic Hydrology, 34 (4), 2003, 281-294.

Guneriussen, T., Bjerke, P.L., Hallikainen, M., Hiltbrunner, D., Johnsen, H., Jääskeläinen, V., Kolberg, S.A., Koskinen, J., Matzler, C., Pulliainen, J., Sand, K., Solberg, R., Standley, A., and Wiesmann, A. (2000) Research and development of earth observation methods for snow hydrology - SnowTools Final Report, NORUT Report, 431/47-00, Tromsø.

Rott, H., Nagler, T., Glendinning, G., Wright, G., Miller, D., Gauld, J., Caves, R., Ferguson, R., Quegan, S., Turpin, O., Clark, C., Johansson, B., Gyllander, A., Baumgartner, M., Kleindienst, H., Voigt, S., and Pirker, O. (2000) HYDALP. Hydrology of Alpine and High Latitude Basins. Final Report. Institut für Meteorologie und Geophysik, Universität Innsbruck, Mitteilungen, 4.

Schjødt-Osmo, O., and Engeset, R. (1997) Remote sensing and snow monitoring: Application to flood forecasting, In Operational Water Management, Refsgaard, J.C., and Karalis, E.A. (eds). Proc. European Water Resources Association Conference, 3-6 September 1997, Copenhagen, Denmark.

Solberg, R., and Andersen, T. (1994) An automatic system for operational snow-cover monitoring in the Norwegian mountain regions. IGARSS'94 Conference Proceedings. Pasadena, California, 8-12 August 1994.

Sælthun, N.R. (1996) The "Nordic" HBV model. Description and documentation of the model version developed for the project Climate Change and Energy Production. NVE Publication no 7-1996, Oslo, 26 pp.

Denne serien utgis av Norges vassdrags- og energidirektorat (NVE)

Utgitt i Oppdragsrapportserie A i 2004

Nr.1 Per F. Jørgensen, Peter Bernhard, KanEnergi AS: Elproduksjon basert på biobrensler. Teknisk/økonomisk potensial (s.)

Nr.2 Jan Sandviknes , Kjelforeningen-Norsk Energi: El-gjenvinning i energiintensiv industri. Teknisk/økonomisk potensial (s.)

Nr.3 Roger Sværd: Vannstander i Rotvikvatnet, Salangen kommune, Troms. Overføring av Sommarsetelva til Rotvikvatnet. (35 s.)

Nr.4 Eli Alfnes og Hans-Christian Udnæs: Satellite-observed Snow Covered Area and spring Flood Prediction in the HBV-model (26 s.)