USE OF SATELLITE-DERIVED SNOW DATA IN A HBV-TYPE MODEL

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ABSTRACT

The work reported in this paper, focuses on the use of satellite-derived snow cover area (SCA) data in the precipitation-runoff model, HBV. SCA is derived from optical satellite imagery to test if the hydrological model may simulate runoff better when SCA is used as additional input to the model. HBV models are calibrated for three catchments in the mountainous area in southern Norway. Several parameter sets are calibrated automatically against runoff, and against runoff and SCA. Simulations are then carried out for a verification period. For all catchments the additional calibration against SCA caused clear improvements in simulation of SCA. For two of the catchments there were minor reductions in the precision of the runoff simulations. In the simulation period, the models calibrated against SCA and runoff did not prove to simulate runoff better, or worse, than the traditionally calibrated models the first days following an updating of SCA and runoff. The precision of the utilised method of deriving SCA from AVHRR images is probably too low for most catchments. Operational updating of the SCA in the simulations will therefore only be of interest when there are obvious errors in the simulations.

INTRODUCTION

The work reported in this paper, focuses on the use of satellite-derived snow cover area (SCA) data in the precipitation-runoff model HBV (1). SCA is derived from optical satellite imagery. The main objective is to test if the hydrological modelling may improve using SCA as input. This requires models calibrated using SCA data as well as runoff. Traditionally, runoff only is used to calibrate the models.

The amount and timing of snowmelt runoff from snow and glaciers are important information for flood prediction and hydropower operations in Norway. Satellite-based remote sensing instruments have proven to be an efficient tool for monitoring snow parameters. The cloud cover has so far limited full operational utilisation of optical sensor products. Operational utilisation of radar data has primarily been limited by high costs. In 1987 Martinec and Rango (2) illustrated the usefulness of satellite derived snow cover data for hydrological modelling. A number of hydrological models for runoff monitoring and forecasting are used throughout Europe, many of which, in principle, can be updated by earth observation data. The most used hydrological model in central Europe, the SRM model (3), is designed for input from remotely sensed snow cover. From the International Symposium on Remote Sensing and Hydrology in 2000 (4) and in the Operational Hydrology report from WMO 1999 (5), a number of authors (i.e. 6,7,8) describe works on modelling snowmelt runoff using the SRM model and remote sensed snow cover.

The HBV model is used for operational forecasts in a large number of Scandinavian catchments. The model is used for flood warning, and planning, design and operation of hydropower systems, impact assessments and climate change studies. The model is a more general-purpose model, also designed for catchments without snow. The model simulates the snowpack using meteorological station data. Previous works in the Snow-Tools (9) and Hydalp (10) projects showed that updating of the HBV model with remotely sensed data on SCA, tended to reduce the model performance. The main reason for this could be that SCA data were not used in the model calibrations. For the highly parameterised HBV model, a number of different parameter sets can give equally good calibrations with respect to runoff (11,12). The SCA simulations can nevertheless differ using these parameter sets. Calibration against both runoff and SCA will ensure that the remotely sensed SCA is comparable to the simulated SCA. Calibration of many different parameter sets that simulates runoff and SCA equally well during a calibration period will give an opportunity to choose the parameter set that simulates runoff and SCA best in an operational forecast situation. The Norwegian Water Resources and Energy Directorate (NVE) updates HBV models on a daily basis for 63 catchments throughout Norway as part of NVEs national flood warning services. The main motivation for this work is thus to see if the national flood warning could be improved by using AVHRR-derived snow covered area in the operational hydrological model (13). Other direct beneficiaries from an improved simulation of the water balance are stakeholders in the fields of hydropower production planning, distribution grid load forecasting, national electricity demands and availability forecasting and climate change issues and studies.

This research is part of the technical and methodological development of the national flood forecasting service at NVE. Parts of the work reported in this study are carried out under the application development project DemoSnow (funded by the Norwegian Space Centre). NVE is partner in two research projects on snow remote sensing and modelling, in which scientific advances are translated into improved public services: the projects SnowMan (Norwegian Research Council funding) and EnviSnow (European 5th framework programme funding).

METHODS

Retrieval of snow cover area from satellite imagery

NOAA AVHRR satellite images were processed according to the method described by Schjødt-Osmo and Engeset (14). This method is based on the assumption 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 an area is then calculated as a linear function of the reflectance in this area compared to the 100% and the 0% reflectance.

Calibration of model using discharge and snow cover area observations

The model is first calibrated against runoff data only – this is referred to as the *Q model*. The three-year period from 1.9.1996 to 1.9.1999 is used for calibration. Automatic calibration is carried out with the PEST software (15). As the HBV-model is highly over-parameterised , standard values are assigned to some of the calibration parameters. The snow parameters allowed to be calibrated are selected based on studies of similar models and snow pillow data in Norway (16). Secondly the model is recalibrated against both runoff and SCA data – this is referred to as the *SCA-Q model*.

Simulation

Simulations are carried out using both the Q model and the SCA-Q model. The periods from 1.9.1999 to 1.9.2000, and from 1.9.1994 to 1.9.1996 are simulated. The performance of the Q and SCA-Q models is compared based on their ability to simulate runoff. The main focus is put on assessing the simulations during high discharge periods according to the primary needs of the forecasting services.

DATASETS AND STUDY AREA

Study areas

Three catchments were selected as test areas (17) in the central mountain range in southern Norway (table 1). The catchments range from 268 to 791 km^2, have different elevation ranges, and are mainly located above the tree line. The location and topography of the catchments are shown in Figure 1.

Table 1: Study catchments characteristics.

Catchment [water gauge ident. and name]	**River**	**Area [km^2]**	**Elevation [m a.s.l.]**			**Runoff data period**	**Forested area [%]**	**Lake area [%]**	**Glacier area [%]**
			Min.	**Max.**	**Med.**				
12.207 Vinde-elv	Vinde	268	560	1686	985	1919-2001	31	7	0
2.13 Sjodalsvatn	Sjoa	474	940	2400	1461	1930-2001	~5	9	9
2.268 Akslen	Bøvra	791	480	2472	1476	1934-2001	13	2	12

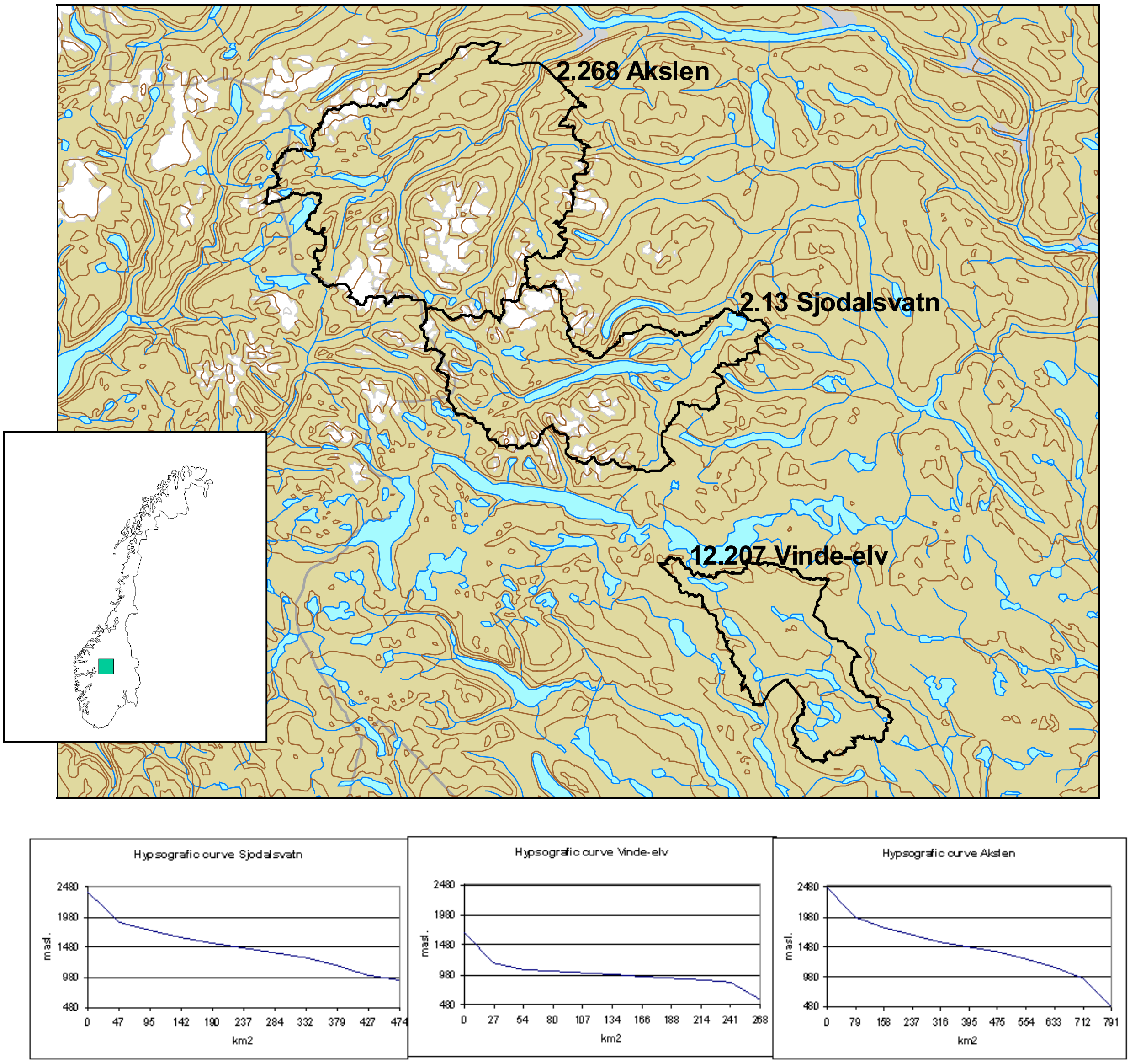

Figure 1: Map of study catchments and hypsographic curves.

Satellite image data and SCA maps

17 AVHRR images were processed to produce SCA maps of 1 km^2 resolution on the following dates: 22.5.1995, 4.6.1995, 13.6.1995, 25.6.1995, 4.6.1997, 3.7.1997, 15.5.1998, 17.5.1998, 31.5.1998, 19.5.1999, 2.6.1999, 14.6.1999, 8.5.2000, 15.5.2000, 5.6.2000, 9.6.2000 and 20.6.2000. The SCA maps were used to calculate the total SCA for each catchment on the dates when cloud-free AVHRR data were available. The calculated SCA values are given in *Table 2*.

Table 2: Calculated snow covered area (%) from NOAA AVHRR images.

Year	**1995**				**1997**		**1998**			**1999**			**2000**				
Date	**22.5.**	**4.6.**	**13.6.**	**15.6.**	**4.6.**	**3.7.**	**15.5.**	**17.5.**	**31.5.**	**19.5.**	**2.6.**	**14.6.**	**8.5.**	**15.5.**	**5.6.**	**9.6.**	**20.6.**
Sjodalsv.	79	49	47	33	62	24	65	61	53	69	63	55	56	47	51	49	34
Vinde-elv	53	13	1	0	5	0	27	24	4	36	8	0	22	3	0	0	0
Akslen	71	54	48	35	64	31	63	56	51	70	61	53	61	53	44	47	37

Water balance, snow reservoir and floods

Discharge has been observed automatically using gauging stations at each of the study catchments. Figure 2 shows the discharge series for each catchment for the calibration years 1997-1999. Figure 3 shows the discharge series for the simulation years 1995-1996 and 2000.

The major floods are dominated by snowmelt for all the catchments. The Vinde-elv catchment has usually one clearly defined melting flood yearly. This flood is mainly caused by simultaneous snow melting in most of the catchment, due to the small variations in elevation. The catchment has a relatively high lake percentage, and also some more capacity for groundwater storage than the other catchments. Flooding situations, due to rain alone, rarely occur. The other catchments, Sjodalsvatn and Akslen, will usually have more than one flooding situation yearly because snowmelt often occurs at different times in the different elevation zones. These catchments may also have considerable melting contributions from glaciers during the summer and autumn. The discharge from the Akslen catchment is to a small degree restrained by natural reservoirs, such as lakes and groundwater reservoirs. In this catchment there is a fast response in runoff during most rain and melting situations. In the Sjodalsvatn catchment there are large lakes situated close to the outlet of the catchment. These lakes will store most of the melting water in the beginning of the melting period, and the largest floods will only occur after the water level in these lakes has reached a certain level. The regulating effect of the lakes is clearly illustrated by Figure 2 and 3 when variations in daily discharge at Akslen and Sjodalsvatn are compared.

Based on measurements from power suppliers and simulations with the HBV model, the years 1995, 1998 and 1999 had relative, but not extreme, high amounts of snow in the actual catchments at the beginning of May. In 1996 the amount of snow seemed to be extremely low.

The largest floods in the area are usually caused by a combination of rain and snow melting. At the end of May 1995, at a time when melting normally has started below 1000 m a.s.l., the amounts of snow were considered extremely high below this altitude. A strong increase in temperature, combined with extensive rainfall, resulted in one of the largest floods in the south east of Norway in the 20th century. Large floods were also observed in the actual catchments on this occasion. In the period 1994-2001 the largest floods observed in Akslen and Sjodalsvatn occurred at the beginning of July 1997. This flood was also a combination flood of melting and rainfall.

To isolate the contribution of snow melt in a flooding situation is a difficult task because of lack of representative precipitation observations. However, some of the observed floods appear to be pure snowmelt floods, as the floods in May 1997, 1998 and 1999 in Vinde-elv. In Akslen and Sjodalsvatn all the major floods seem to be combination floods.

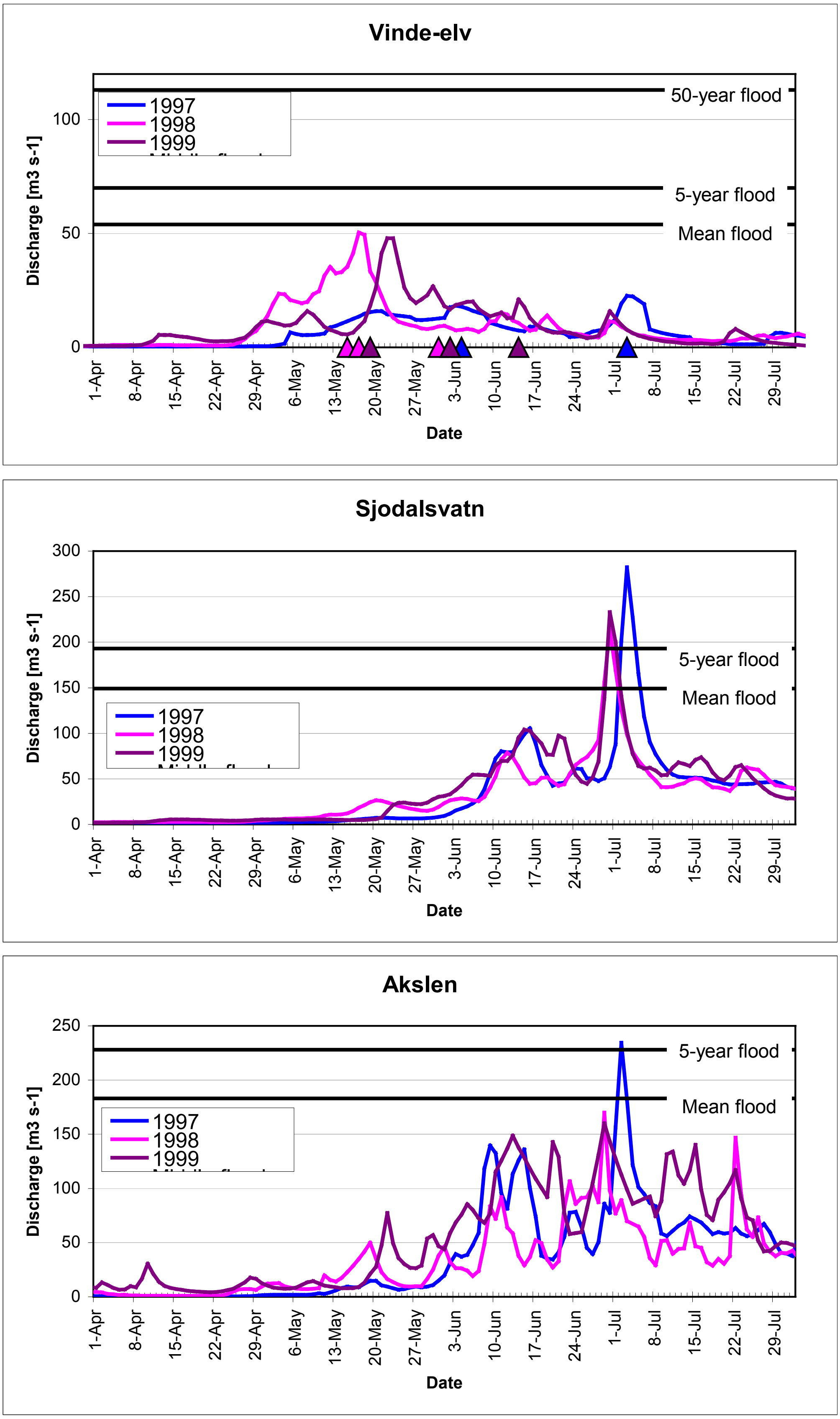

Figure 2: Discharge data during the snowmelt period (April-July) in the three years of data used in model calibration. Coloured triangles indicate available AVHRR-derived SCA maps.

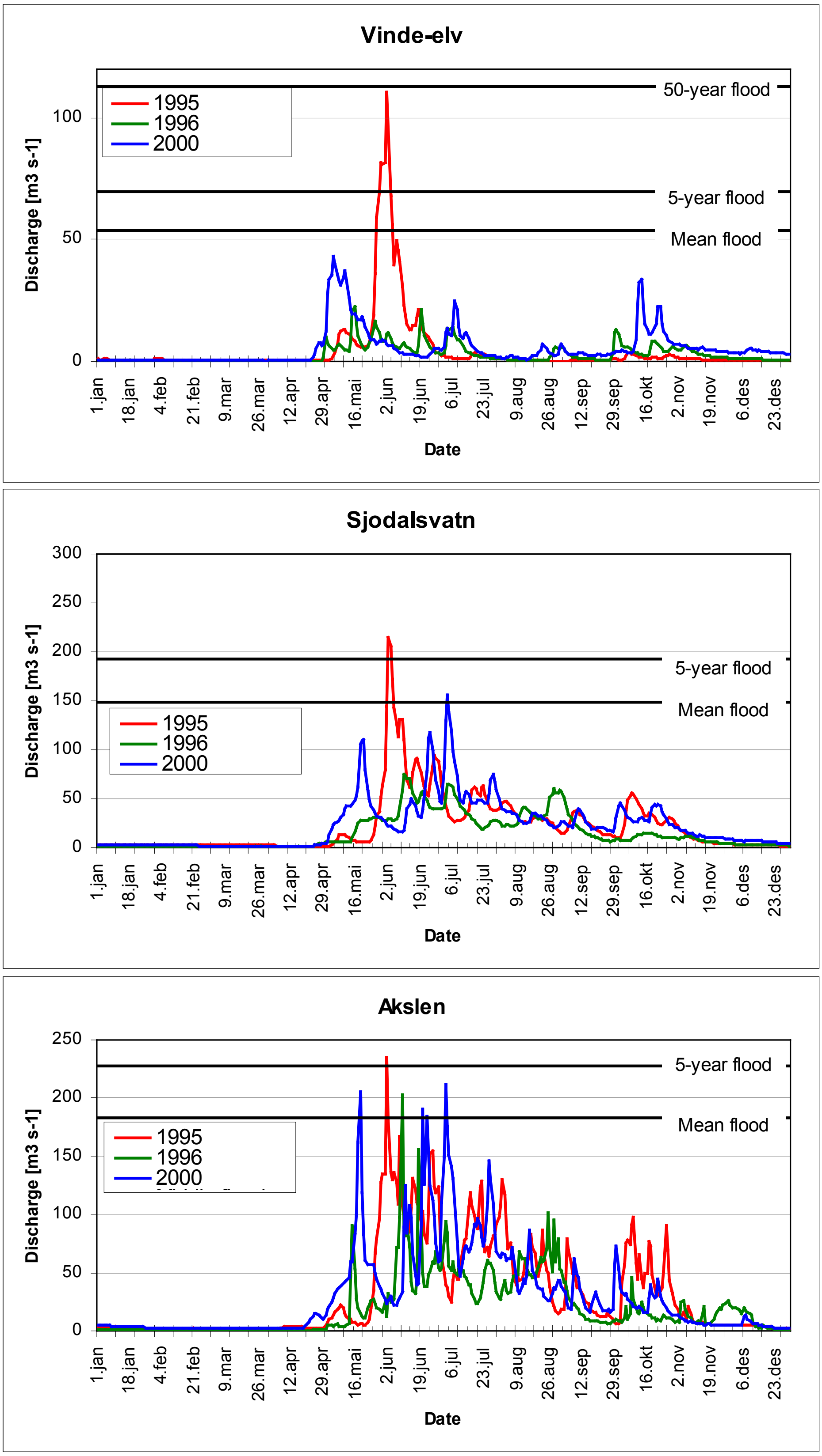

Figure 3: Discharge data in the three years of data used in model simulation.

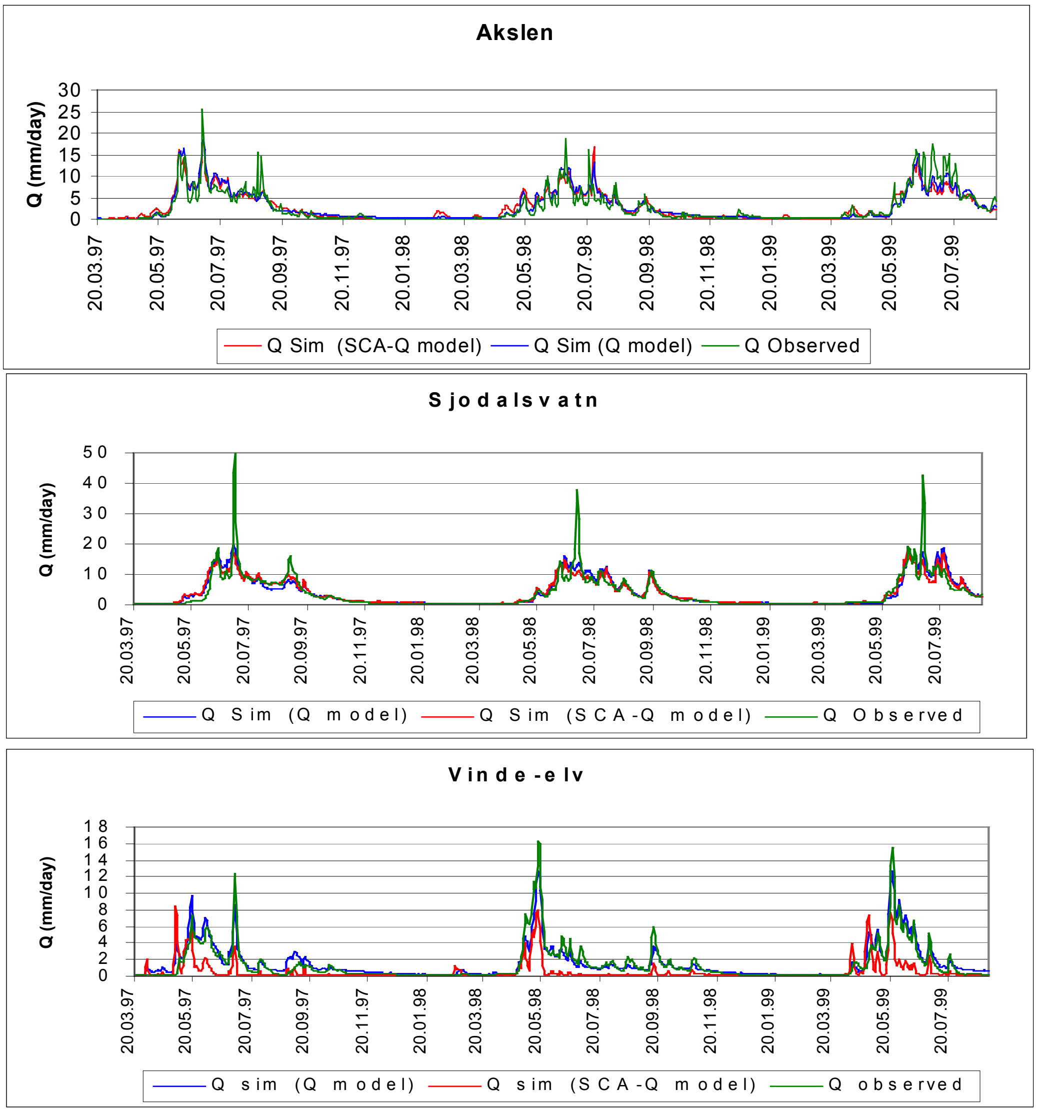

Figure 4: Simulated and observed runoff compared for the calibration period.

RESULTS

Calibrations

A number of parameter sets are automatically calibrated for each of the three catchments, with and without calibration against SCA in addition to runoff. For the models calibrated against runoff, the results show large deviations between HBV-simulated and AVHRR-observed SCA. The calibration uncertainty was confirmed to be large as several optimal parameter combinations gave different runoff simulations of approximately equal quality. For the models calibrated against runoff and SCA, the results show better simulations of SCA, but some reduction in the quality of the runoff simulations, particularly for one of the catchments, Vinde-elv. Results from the best calibrations are shown in Table 3 and in Figure 4. The quality of the runoff calibrations is measured by the R^2-value (13) where $R^2 = 1$ describes a perfect calibration. For two of the catchments, Akslen and Vinde-elv, the calibrations against runoff are fairly good, even if the simulations tend to underestimate the largest floods. The calibrations for Sjodalsvatn have lower quality, mainly in the flooding situations.

Table 3: Simulated SCA, by Q model and SCA-Q model, compared to AVHRR-derived SCA, 1997-1999.

	AKSLEN			SJODALSVATN			VINDE-ELV		
	sim SCA Q mod %	sim SCA SCA-Q mod %	obs SCA AVHRR %	sim SCA Q mod %	sim SCA SCA-Q mod %	obs SCA AVHRR %	sim SCA Q mod %	sim SCA SCA-Q mod %	obs SCA AVHRR %
04.06.97	82	70	64	73	52	62	17	6	5
03.07.97	28	22	31	24	13	24	0	0	0
15.05.98	84	68	63	97	81	65	74	29	27
17.05.98	78	65	56	93	78	61	59	18	24
31.05.98	66	53	51	83	60	53	15	3	4
19.05.99	86	72	70	99	83	69	89	34	36
02.06.99	69	58	61	87	70	63	26	6	8
14.06.99	45	39	53	73	50	55	7	1	0
mean |sim SCA - obs SCA|	14	7		19	11		23	2	
R^2 (runoff)	0.84	0.80		0.76	0.73		0.86	0.33	

Simulations

Simulations, using the best parameter sets (up to 50 sets) for each catchment, are carried out for the entire period 1.9.1994-1.9.2000. Special attention is paid to the melting periods in 1995 and 2000 where simulations by Q models and SCA-Q models were updated when AVHRR data were available. At every updating the five Q models that perform best at that moment are used in the simulations until the next updating. Likewise, the five SCA-Q models that simulate runoff best, among those which simulate SCA fairly well (AVHRR SCA +/- 5%), are used in the further simulations.

Implications for flood forecasting

The calibrations against runoff alone have shown that simulated SCA from the Q models, and AVHRR-derived SCA, differ a lot, even if the runoff is fairly well simulated. In most situations the simulated SCA is much higher than the AVHRR-derived SCA. An updating of the states with AVHRR-data in these models would lead to reduced SCA and reduced simulated runoff in the melting period. Since most of the flooding situations seem to be underestimated in the simulations, updating of the SCA in a Q model would not be recommendable in an operational situation. However, the calibrations have shown that it is possible to calibrate HBV models that simulate SCA more in accordance with the AVHRR-derived SCA, without major reductions in the quality of the runoff simulations. There are still uncertainties connected to the precision of the AVHRR-derived SCA. For catchments like Vinde-elv, snowmelt and the corresponding reduction in snow reflectance, usually start earlier than on the glaciers. This leads to an underestimation of the SCA. Forested and shadowed areas will also contribute to such an underestimation. These are factors that should be kept in mind when AVHRR-data are used operationally. Hence the AVHRR-derived SCA is less reliable for Vinde-Elv than for the other two, which probably explains the poor calibration results of the SCA-Q models for this catchment.

When several models, calibrated against runoff and SCA, are run operationally, the models that simulate both runoff and SCA reasonably will be trusted in the forecast period. Nevertheless, in the examined simulations (Figure 5) neither the SCA-Q models nor the Q models perform noticeably better than the other models during the first 2-3 days after an updating. For a longer forecast period the Q models tend to be slightly better. However, on special occasions as in 1995, some of the SCA-Q models simulate the start of the flood better than the Q models both for Vinde-elv and Akslen. This indicates that SCA-Q models can be used in addition to the traditional Q models. The precision of the utilised method of deriving SCA from AVHRR images is probably too low for most catchments. Updating of the SCA in the simulations will therefore only be of interest when there are obvious errors in the simulations. Such errors could be simulations of snow free catchments when snow covered areas are derived from AVHRR data. Situations like that are not included in the data sets in this work. Another implication of the simulation results is that the model calibration should be weighted more against the flooding situations. At least for Sjodalvatn, other model calibrations should be used in flooding situations than in a normal forecast situation.

Figure 5: Simulated and observed runoff compared for two of the test years 1995 and 2000.

CONCLUSIONS

When HBV models are calibrated traditionally, against runoff alone, the simulated SCA tends to be clearly over-estimated compared to the AVHRR-derived SCA. Calibrations against AVHRR-derived SCA, in addition to runoff, show that models can be calibrated to simulate SCA more consistently with these data, without major reduction in the precision of the runoff simulations. Models calibrated against SCA and runoff do not prove to simulate runoff better, nor worse, than the traditionally calibrated models during the first days following an updating of SCA and runoff. As the precision of the utilised method of deriving SCA from AVHRR images probably is too low for most catchments, updating of the SCA in the simulations will only be of interest when there are obvious errors in the simulations.

Future work will integrate satellite-derived snow parameters in ten operational HBV models representing different regions and catchment scales in Norway. The model will be adapted to use earth observation data for updating the snow variables, snow covered area, snow water equivalent, snow liquid water, surface reflectance and temperature, and model performance and uncertainty will be assessed. A new description of the snow distribution in the HBV model will be developed and tested.

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