USING SATELLITE SNOW DATA IN HYDROLOGICAL FORECASTING

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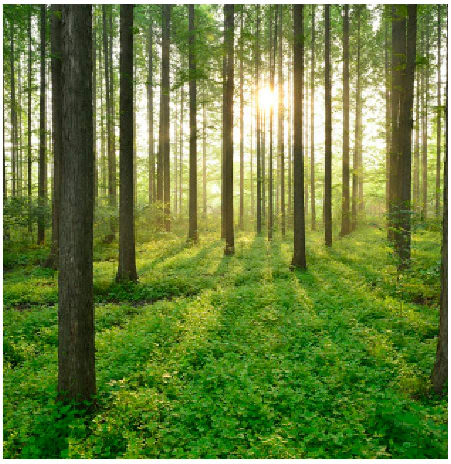

HYDROLOGICAL
DEVELOPMENT WORK

Energiforsk

Using satellite snow data in hydrological forecasting

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Foreword

Within the research programme Hydrological Development in the Hydropower Industry (HUVA), continuous efforts are made to improve the precision of inflow forecasting. Throughout 2021 to 2023, one focus area has been to explore how satellite-based snow data can enhance the quality of hydrological models, particularly in regions with limited access to ground-based observations.

The project "*Using satellite snow data in hydrological forecasting*" was initiated by Energiforsks R&D programme HUVA to evaluate the usability of satellite-derived snow water equivalent (SWE) and snow-covered area (SCA) products in operational forecasting. The study was conducted in the Klarälven catchment in Värmland, Sweden, where traditional observations are insufficient for accurate model calibration. By integrating data from GlobSnow and CryoLand into the WSFS model, the project demonstrated that satellite data can improve snow simulations and spring flood forecasts under certain conditions.

The project was carried out by Panu Juntunen, Juho Jakkila and Kalle Sippel at the Finnish Environment Institute (Syke) in collaboration with Energiforsk and representatives from the HUVA programme board. The results provide valuable insights into the potential of remote sensing as a complement to traditional methods and highlight the relevance of further development in upcoming R&D projects.

The financiers of this research project where Vattenfall Vattenkraft AB, Fortum Sverige AB, Sydkraft Hydropower AB, Statkraft Sverige AB, Skellefteå Kraft AB, Holmen Energi AB, Tekniska Verken i Linköping AB, Mälarenergi Vattenkraft AB och Sollefteåforsen AB.

The authors are responsible for the conclusions and results of this report.

Summary

Snow accumulated during winter has a significant effect on spring flood volumes. The snow water equivalent (SWE) has conventionally been measured in in-situ surveys. However, this method is labour-consuming and provides a limited estimation of the areal variation of SWE.

Satellite data is becoming a more commonly used source to estimate various hydrological variables. More specifically, satellite-based earth observation (EO) snow-covered area (SCA) and SWE products can be used as input data for hydrological model calibration and data assimilation processes in operational forecasting settings, providing more extensive information about snow than what is feasible with direct observations.

This project tested the usability of SWE and SCA satellite products for hydrological forecasting in the Klarälven River in Värmland, Sweden using the Watershed Simulation and Forecasting System (WSFS) developed at the Finnish Environment Institute (Syke).

The results show that EO-based snow data can improve snow simulations to some degree in basins lacking good quality water level and discharge observations. The usability of satellite data was, however, limited to the lower sections of the Klarälven River because the satellite SWE product is non-applicable in the more mountainous upper section of the river.

Keywords

Hydrological forecasting, satellite data, snow water equivalent, fractional snow cover, remote sensing

Sammanfattning

Den ackumulerade snön under vintern har en betydande effekt på vårflodens volym. Snöns vattenekvivalent (SWE) har traditionellt mätts i in-situ-undersökningar. Denna metod är dock arbetskrävande och ger en begränsad uppskattning av den areella variationen av SWE. Nya satellitbaserade jordobservationsprodukter (EO) av snötäckt område (SCA) och SWE ger ytterligare och mer omfattande information för hydrologiska prognoser.

Satellitdata blir allt vanligare som källa för att uppskatta olika hydrologiska variabler. De EO-baserade SCA- och SWE-produkterna kan användas som indata för hydrologiska modeller i modellkalibrering och dataassimileringsprocesser i operativa prognoser.

Detta projekt testade användbarheten av SWE- och SCA-satellitprodukter för hydrologiska prognoser. I projektet användes Finlands miljöcentrals (Syke) Watershed Simulation and Forecasting System (WSFS). Testområdet var Klarälven i Värmland, i Sverige.

Resultaten visar att EO-baserade snödata kan förbättra modellsimuleringen i avrinningsområden som saknar observationer av vattennivåer och flöden av god kvalitet. Användbarheten av satellitdata begränsades till att endast täcka de nedre delarna av Klarälven, eftersom den testade SWE-produkten från satellit inte är tillämplig i bergsområden.

Nyckelord

Hydrologiska prognoser, satellitdata, snöns vattenekvivalent, fraktionerad snötäcke, fjärranalys

List of content

1 Introduction

Snow is an important part of the water cycle at northern latitudes, being the main driver of spring flood. Consequently, the accuracy of hydrological forecasting models to simulate snow water equivalent (SWE) plays a key part in the accuracy of spring flood forecasts, which are crucial for flood risk mitigation and optimization of hydropower production. Hydrological models used for flood forecasting have significant uncertainties related to snow accumulation and melting, and therefore data assimilation of SWE measurements can significantly improve the spring-flood forecasts (Arheimer et al. 2011, Pechlivanidis et al. 2020).

Conventionally, data assimilation of in-situ snow depth and SWE measurements have been used to improve the spring flood forecast quality (Vehviläinen et al. 2005, Griessinger et al. 2016, Huang et al. 2017). However, the availability, extent, and quality of such observations are highly region dependent. For instance, in Finland, there has been a long tradition of snow surveying. The average areal SWE is typically estimated by measuring the variation of snow depth, snow density and SWE in four-kilometre-long snow courses covering various land-use and vegetation types (Kuusisto 1984, Lundberg and Koivusalo 2003). This extensive snow course observation network has been used in the Watershed Simulation and Forecasting System (WSFS) for model calibration and data assimilation (Vehviläinen and Huttunen, 2002).

Conversely, in Sweden, while the snow depth observation network has been tested for updating the HBV-model with promising results (Lindström et al. 2002), the availability of manual measurements of SWE is more limited. The SWE data is more relevant for flood forecasting models, and several studies with various ground-truth observation methods have been carried out to try to capture the accumulation and areal variation of SWE (e.g. snow pillows and ground-penetrating radars) (e.g. Lundberg et al. 2010, Clemenzi et al. 2023). However, the estimation of areal SWE is still challenging, especially in mountainous areas where SWE has a higher spatial variability.

The development of remotely sensed earth observation (EO) techniques has provided an alternative to in-situ observations of SWE. Visible light and infrared satellite sensors can provide reasonable estimates of snow-covered area (SCA) (Warren, 1982), and more recently developed satellite products based on passive microwave sensors have shown promising results for estimating SWE (Luojus et al. 2021).

These EO-based SWE products cover large areas, and near-real-time data is available during the snow accumulation season (Luojus et al. 2014). The advantage of the microwave radiometer compared to optical satellite products is that the signal is independent of the visible light. Therefore, daily data is available throughout the whole winter, which is especially important in northern Europe, as the high latitude limits the amount of sunlight during the winter months. An important disadvantage of this technique is that under deep snow and wet snow conditions the microwave scattering response is not feasible (Luojus et al. 2014, Luojus et al. 2021). The GlobSnow SWE product used in this study also incorporates in-situ snow depth observations and snowpack modelling with passive microwave radiometer retrievals, which can be beneficial compared to other EO-based SWE-products (Frei et al. 2012, Luojus et al. 2021).

EO-based SCA products are available during cloudless days in the spring melting period and can be used for estimating the timing of the snowmelt (Metsämäki et al. 2005). These products can produce reliable values for snow-covered areas under boreal forest canopy (Metsämäki et a. 2005), which is important in Scandinavia due to the slower melting rates in forested areas compared to open areas (Vehviläinen, 1992, Koivusalo and Kokkonen 2002).

The assimilation of EO-based SCA data to the WSFS hydrological model has the potential to improve its forecasting accuracy, particularly at the end of the melting season (Metsämäki et al. 2004), whereas the assimilation of SWE data is more challenging in locations with complex terrain and occasionally wet snow conditions (Musuuza et al. 2020). However, the potential to improve the forecasting accuracy through data assimilation of EO-based products is remarkable especially in data scarce regions (Sheffield et al. 2018). In this study both EO-based SWE and SCA was used in the calibration and updating routines of the WSFS model in the lower sections of the Klarälven watershed, in western Sweden.

2 Objective

The aim of this work was to test the degree of improvement of hydrological model forecasting by using EO-based SWE and SCA products, in the lower sections of the Klarälven watershed (Sweden), where model calibration and data assimilation are limited due to lack of good quality discharge and water level observations. More specifically, this general aim was achieved by focusing on the following partial objectives:

- To improve the calibration performance of the inflow model
- To study the quality and utility of the SCA and SWE products for hydrological modelling and forecasting
- To improve the snow data assimilation process of the WSFS for hydrological forecasting.

Improving the hydrological forecasting accuracy is connected to a more realistic simulation of the SWE in the hydrological model before the snow melting period and an improvement in the timing of the snowmelt. To achieve this, a combined use of EO-based SWE and SCA products in the data assimilation process of the WSFS hydrological model provided additional criteria to correct SWE simulations, in addition to the traditionally used water level and discharge observations.

3 Materials and methods

3.1 STUDY AREA AND DATA AVAILABILITY

The test sites for this study were local sub-catchments in the lower part of the Klarälven River located in Värmland, western Sweden, which has poor coverage of ground-based SWE observations. Local sub-catchments are here defined as the contributing area between a lower and an upper discharge observation station. The local sub-catchments contain several sub-basins, for which water balance is simulated separately in WSFS. The few point SWE measurements available in this area are not representative of the snow distribution in these local sub-catchments.

In total, six local sub-catchments were used as test sites in this study. Of these, located in lower reaches of Klarälven river, Skoga (255 km^2), Skymnäs (160 km^2) and Dejefors (250 km^2) (Figure 1) lack good quality discharge and/or water level observations, which makes calibration of hydrological models challenging, thus causing unrealistically large SWE estimates in WSFS simulations. Therefore, previous modelling efforts in these areas have been of poor quality. Conversely, other three local sub-catchments, located along Uvån River, a tributary of the Klarälven River (Figure 2), Mussjön (93 km^2), Nain (201 km^2) and Kvien (216 km^2) have better quality water level and discharge observations.

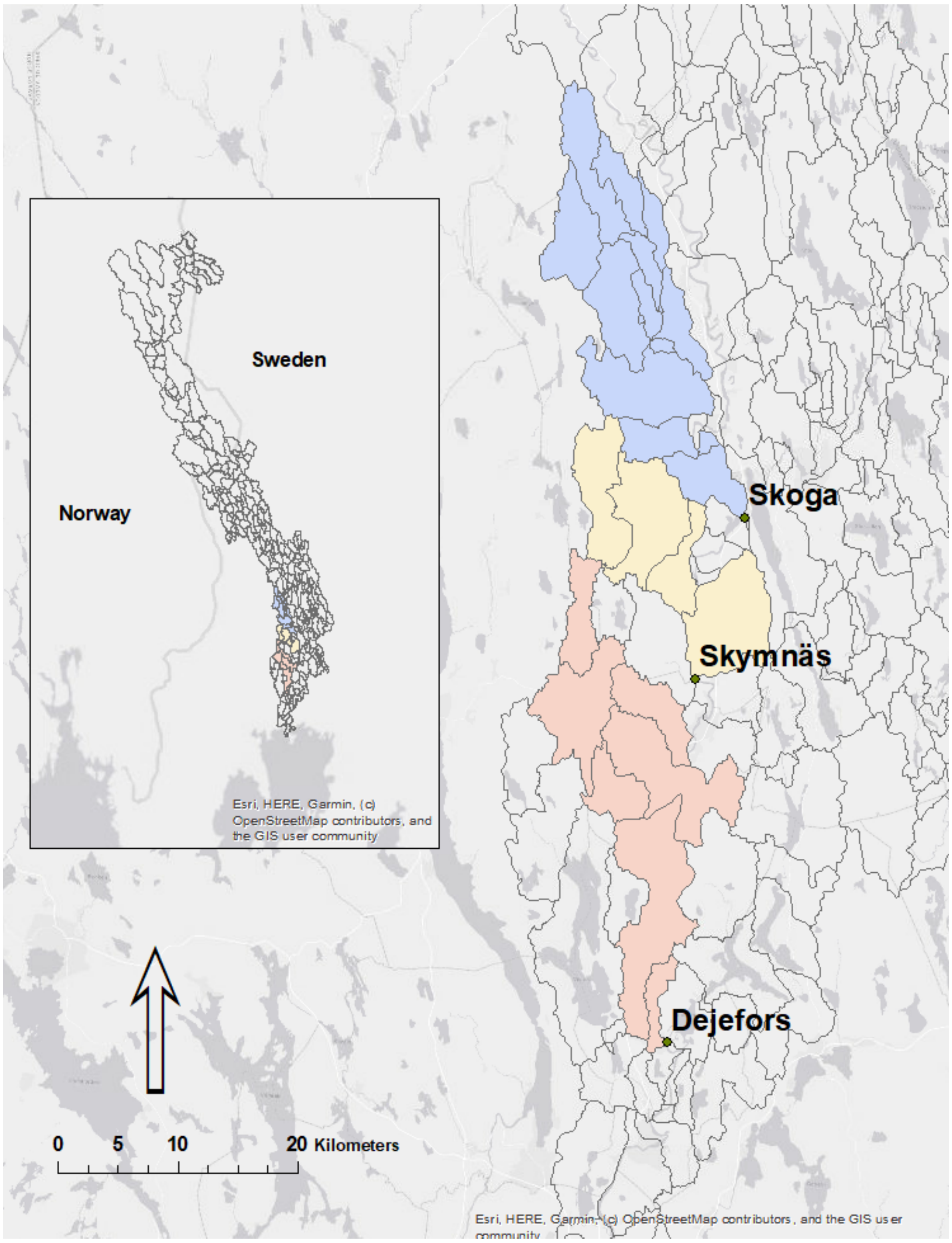


Figure 1 The map shows sub-catchments of Skoga (highlighted in blue), Skymnäs (highlighted in yellow) and Dejefors (highlighted in red) and the sub-basins they consist of in the lower part of the Klarälven watershed. "Snow calibration 1", described in chapter 3.5, was tested for these sub-catchments. The map shows also other sub-basins of Klarälven watershed in grey lines.

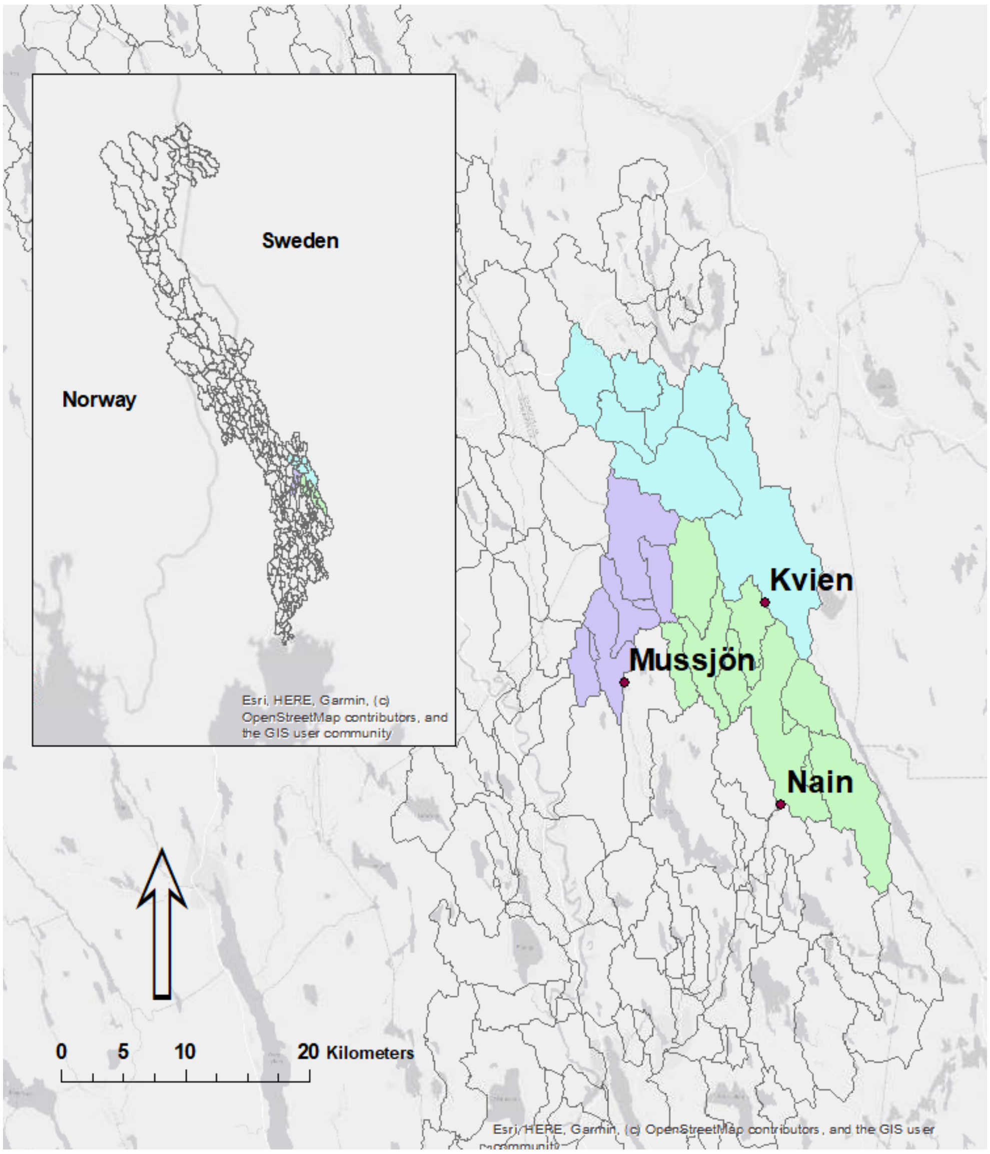


Figure 2 The map shows sub-catchments of Nain (highlighted in green), Mussjön (highlighted in purple) and Kvien (highlighted in blue) and the sub-basins they consist of in the middle part of the Klarälven watershed. "Snow calibration 2", described in chapter 3.5, was tested for these sub-catchments. The map shows also other surrounding sub-basins of Klarälven watershed in grey lines.

3.2 SATELLITE DATA

3.2.1 Snow water equivalent

The GlobSnow-2 SWE product (Luojus et al. 2014) used in this study has been developed at the Finnish Meteorological Institute (FMI) and is based on remotely sensed microwave radiometer signals of snow cover brightness temperature, combined with direct snow depth observations at meteorological stations. The brightness temperature and snow depth observations are used to model the effective snow grain size for grid cells, which is then used for estimating the SWE using the HUT snow emission model (Pulliainen et al. 1999, Luojus et al. 2021). The GlobSnow-2 product has been validated against independent in-situ SWE data collected from 517 snow courses distributed across Russia and the former Soviet Union from 1979 until 2009. In comparison to this reference dataset, the GlobSnow-2 average root-mean-square-deviation (RMSD) was 32.5 mm and bias 9.8 mm (Luojus et al. 2014).

The GlobSnow-2 SWE product has spatial resolution of 25 kilometres (Kärnä et al. 2007) and it is most accurate during the snow accumulation period. However, under deep snow (SWE > 150 mm) and wet snow conditions the microwave scattering response is not feasible (Luojus et al. 2014, Luojus et al. 2021). Thus, SWE data produced with this methodology is not informative during the melting period. Additionally, snowmelt during winter months may also reduce the accuracy of the product. The test area was limited to covering only the lower parts of the Klarälven River due to unreliable data arising from deep snow in the upper, more mountainous parts of the watershed.

3.2.2 Snow covered area

The EO-based SCA product used in this study is based on a CryoLand product, which uses visible and infrared reflectance measured by the MODIS instrument, providing daily fractional snow cover estimates for the Pan-European area at 500-meter spatial resolution. The SCA product was developed by the Finnish Environment Institute (Syke) (Metsämäki et al. 2005).

The main limitations of this EO-based SCA product are the lack of light during the winter months in the high latitudes and cloud cover, which can obstruct the view from orbit and thus limit data collection. However, this EO-based SCA product may provide valuable information about the onset and end of the snow melting period in spring, which can effectively improve the timing of the spring flood peaks in hydrological forecasts.

3.3 MODELLING SETUP

The hydrological model used in this work is Syke's own WSFS model, applied in this project to Swedish rivers. The WSFS model is typically calibrated and updated using discharge and water level observations (Vehviläinen et al. 2005) and has been successfully applied to provide operational inflow forecasts for hydropower production planning for rivers located in Central and Northern Sweden, namely Faxälven, Indalsälven, Ljungan, Ljusnan, Dalälven, Klarälven, Gullspångsälven, Norsälven and Byälven.

The WSFS model is a conceptual, semi-distributed hydrological model, originally based on the Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Bergström, 1995), which simulates runoff using precipitation and temperature as input variables. In this framework, the modelled watersheds are divided into sub-basins, forming a hierarchy for the simulations. The sub-basins are on average a few dozen square kilometres in size, and they are connected to each other in a way that forms a structure representing the actual stream network. The model calculates elevation corrected areal estimates from precipitation and temperature data observed at and forecasted for meteorological stations. The relevant hydrological variables such as snow, soil moisture, groundwater, evapotranspiration, runoff and water levels, as well as inflow to water reservoirs and discharges of rivers and lakes (Figure 3) are simulated at a daily time-step.

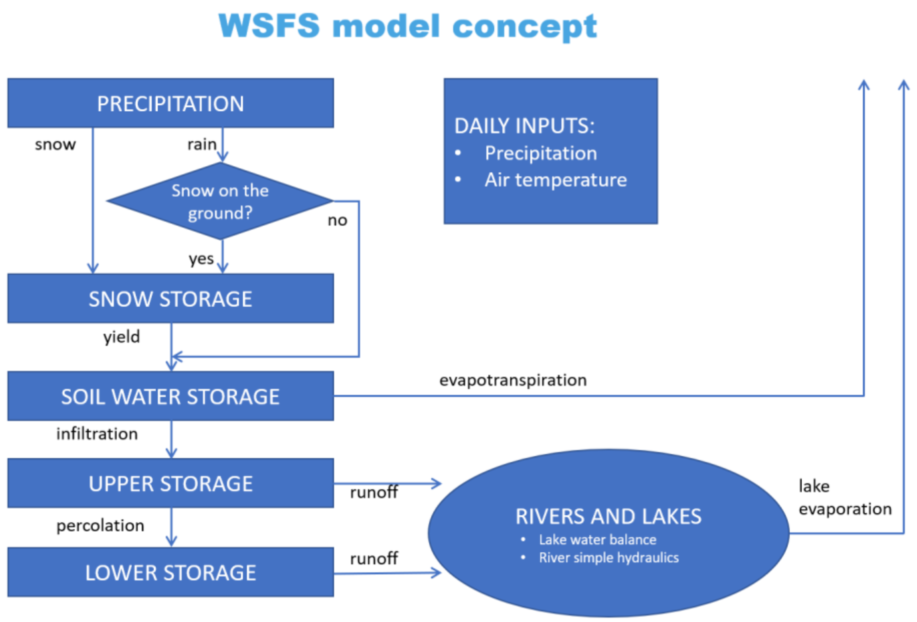


Figure 3 Flow diagram representing the WSFS model concept.

The operational version of the WSFS model for Finnish rivers is calibrated using a multicriteria approach based on the weighted sum of the square differences between the observed and simulated discharge, water levels, realized inflows and SWE (Vehviläinen and Huttunen, 2002) and the Hooke-Jeeves routine is used for minimising the total model error (Hooke and Jeeves, 1960). In addition, individual error weights are used for different hydrological variables and observation sites to find a good balance of fit with varying hydrological conditions.

The same optimization routine is also used for data assimilation of real-time hydrological observations for flood forecasting purposes (Vehviläinen and Huttunen, 2002). In this case, the model optimizes the hydrological simulations by adjusting the areal temperature and precipitation to match real-time observations and, in this way, improves the estimation of the initial conditions of the simulated hydrological variables before the forecast is initialised.

In this project the model was primarily calibrated against water level and discharge observations and secondly against EO-based snow products together with water level and discharge observations. Thereafter, the same EO-based snow products were also tested in the data assimilation routine for real-time inflow forecasting.

3.4 USE OF SWE AND SCA DATA IN WSFS

Near-real-time SWE data was transferred to the WSFS model on a daily basis. Values for each sub-basin were calculated as an average of overlapping grid values from each product. The SCA data was postprocessed in an automated production chain to calculate the daily average SCA value for each sub-basin.

Initially, qualitative and quantitative comparisons of EO-based SWE values were made against modelled SWE. Thereafter, SWE data was included as an error criterion in the model's calibration and data assimilation routines. Due to the aforementioned limitations related to wet snow, EO-based SWE values calculated for each sub-basin needed to fulfil a series of predetermined conditions for ensuring their reliability. In this study, we introduced a method for detecting wet snow conditions based on the EO-based SCA product and the mean air temperature of the previous five days. If EO-based SCA values are below 80% or the five-day mean air temperature is above zero, the snowmelt season is considered to have started, and EO-based SWE data is thereafter considered to be unreliable. As a result, EO-based SWE data was used in calibration and data assimilation routines only during the snow accumulation phase and with dry snow conditions.

SCA data was also used to detect the end of the snow season. The instances of SCA data indicating zero snow coverage were considered as a sign of no snow remaining. This was used as an additional error criteria of model calibration and updating to improve the timing of the snowmelt in the hydrological model.

3.5 MODEL CALIBRATION

The satellite snow observations were initially tested to improve snow simulation in selected local areas (Figure 1), where snow simulation had been unrealistic due to the lack of accurate hydrological observations (named “snow calibration 1” hereafter). Then, these observations were included in the model calibration as an additional error criterion. The calibration period was 2011-2020.

The EO-based satellite data was also used as error criteria for the calibration process in areas with reasonable model accuracy and better discharge observations (Figure 2). In this case, satellite snow data was used together with the existing time series of discharge and water level observations to investigate the potential for using the SWE data for updating the model. Contrary to the previous calibration runs, in which the optimization routine was only allowed to modify snow parameters, here the optimization routine was allowed to change all model parameters in these calibration runs (named “snow calibration 2” from now on). Error weights were set based on trial-and-error for each local sub-catchment and data type to get a suitable initial error balance for the optimization routine.

The simulations of runoff and inflow to the lakes were calibrated against water level observations and actual local inflows which, in their turn, are based on water level and discharge observations. The Nash–Sutcliffe model efficiency coefficient (R^2) was used to indicate the model accuracy with respect to actual inflows based on measurements.

3.6 MODEL UPDATING FOR SPRING FLOOD FORECASTING

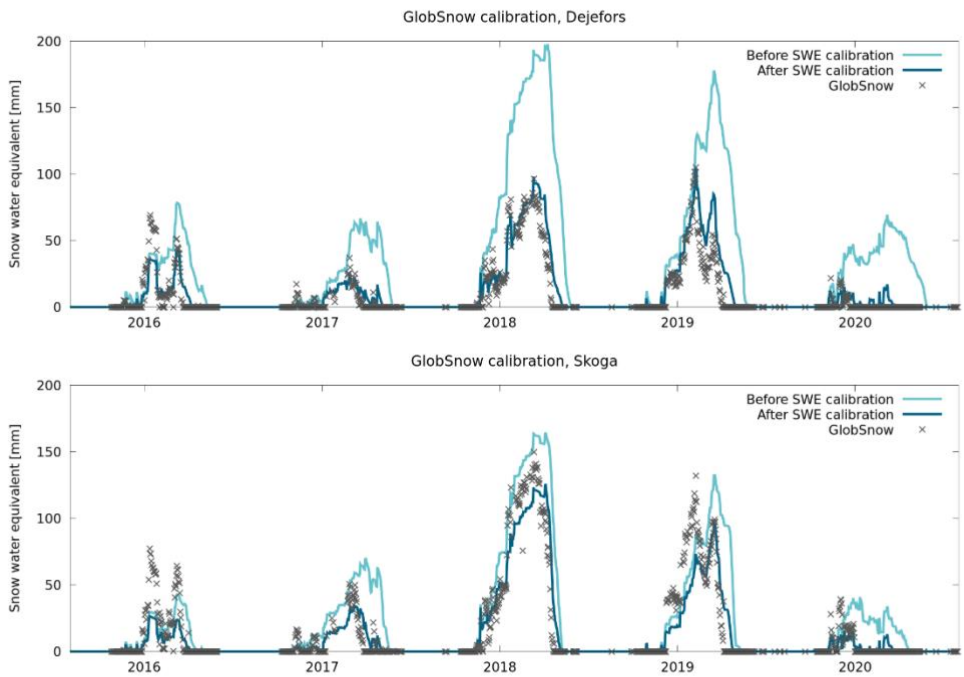
EO-based snow product applicability was tested in model updating for spring flood forecasts with two forecasting setups which were run side by side, producing daily forecasts throughout the spring season of year 2022. The forecast setup 1 produced daily ensemble of inflow forecasts based on medium-range (14 days) ensemble weather forecasts from European Centre for Medium Range Weather Forecasts (ECMWF), which includes 51 forecast members. This forecast was then prolonged with climatological data. In this setup, model inputs are only corrected against available water level and discharge observations to update the initial state of the model.

The forecasting setup 2 is similar to the forecasting setup 1 but the precipitation and temperature corrections are made not only against water level and discharge observation but also against EO-based SWE data. Satellite observations were used as an additional error criterion in the model updating routine with the purpose of driving modelled SWE values closer to those obtained from GlobSnow-2 data.

4 Results

4.1 MODEL CALIBRATION

Using EO-based SWE and SCA data as additional error criteria for calibration of the model's snow parameters notably improved the calibration results of snow simulation. Figure 4 shows the results of the areal snow simulation for the period between 2016 and 2020 based on a calibration using only discharge observations (cyan line). The second simulation is based on parameter values calibrated by utilising satellite snow data (blue line). The snow calibration 1 process improved SWE simulation to match with satellite observations more closely, as shown in its smaller RMSD and bias metrics (Table 1). The simulation of SWE improved most notably in the Skymnäs and Dejefors local sub-catchments, where SWE values used to become unrealistically high due to the model calibration algorithm trying to compensate for inaccuracies in discharge observations. The Skoga local sub-catchment was less affected by these issues and the simulated SWE was thus closer to GlobSnow-2 observations even before the snow calibration 1 process was implemented. This process also reduced the areal variability of SWE between Dejefors, Skoga and Skymnäs.



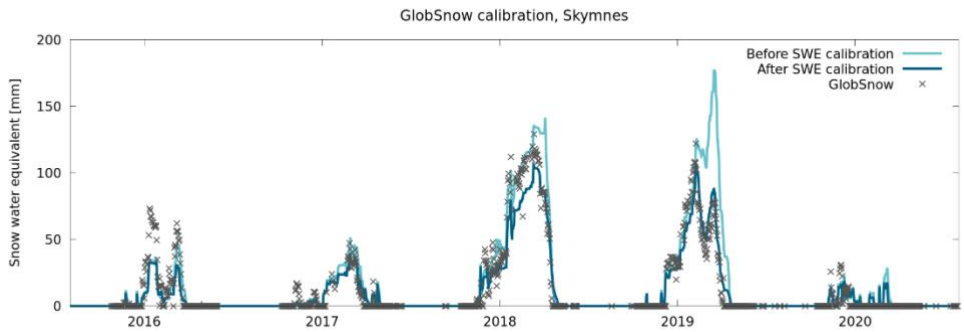


Figure 4 Snow simulation for Dejefors, Skoga and Skymnäs before and after calibration using GlobSnow-2 SWE values as error criteria for the period 2016-2020.

Study Area	Snow RMSD		Snow bias	
	before calibration	after calibration	before calibration	after calibration
Skymnäs	49.9	15.9	34.9	-0.6
Skoga	37.5	29.1	21.9	12.5
Dejefors	54.9	19.6	43.5	9.6

Table 1 RMSD and bias between satellite SWE estimates and model simulation before and after SWE calibration for the period 2011-2020.

The snow calibration 1 process, using EO-based SWE and SCA products, also improves the runoff simulations in the local sub-catchments included in this study. This can be seen in a long time series of simulated runoff from 1961 to 2011. For example, the re-calibrated Skoga local area had lower maximum SWE values for winter and an earlier onset of the snowmelt period, resulting in smaller and earlier spring flood events (Figure 5). After the calibration, the model does not longer produce unrealistically large runoff peaks (>20 mm).

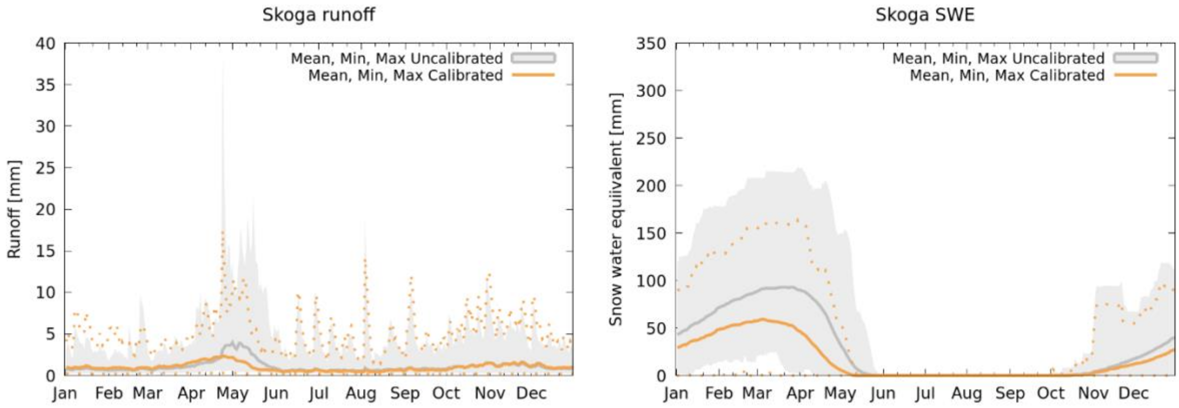


Figure 5 Changes in Runoff and Snow simulation in Skoga area, presented with daily minimum, average, maximum during the period 1961- 2011. The grey line corresponds to a reference simulation, and the orange line corresponds to the situation after calibration.

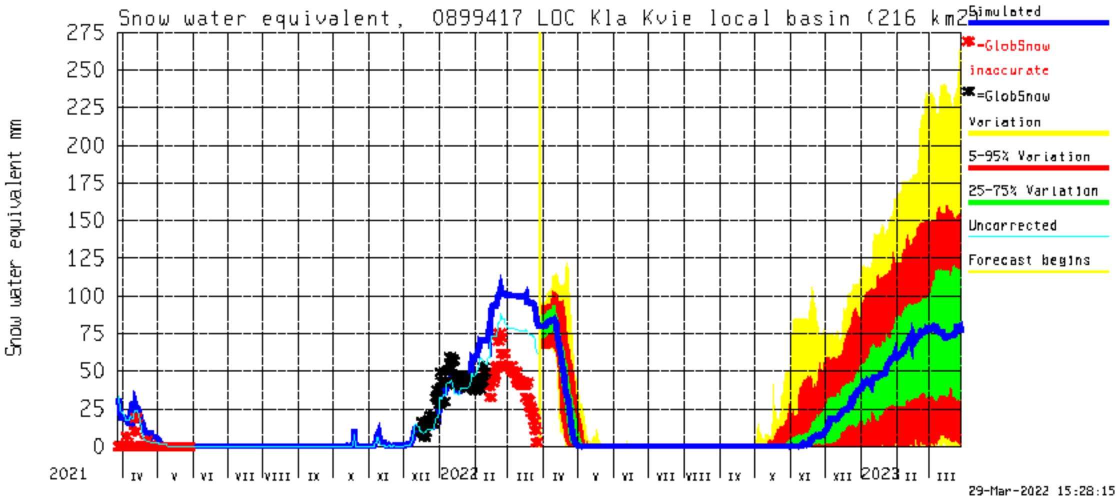
The snow calibration 2 process brought simulated SWE values closer to GlobSnow-2 data, mainly by reducing snow accumulation, but without significantly deteriorating local inflow simulations, which indicates that this EO-based SWE product could also improve the spring flood forecasts, when used for data assimilation. The inflow R^2 value decreased only at Lake Mussjön, signalling a lower model performance when the model was calibrated with this setup. This can be attributed to the challenges related to setting up suitable error weights for discharge observations and satellite data that would allow the optimization routine to improve the snow simulation whilst also improving the inflow simulation at this location.

Study area	Snow RMSD		Snow bias		Qin R^2	
	before calibration	after calibration	before calibration	after calibration	before calibration	after calibration
Kvien	26.1	16.4	7.7	-3.2	0.80	0.79
Nain	47.1	20.2	-35.6	-13.4	0.36	0.38
Mussjön	34.6	24.1	19.5	8.9	0.82	0.79

Table 2 RMSD and bias between satellite SWE estimates and model simulation before and after SWE calibration for the period 2011-2020. For these points, there is also the Nash–Sutcliffe model efficiency coefficient of local inflow measuring the model performance.

4.2 MODEL UPDATING FOR SPRING FLOOD FORECASTING

Using EO-based SWE and SCA data in model updating for spring flood forecasting kept snow simulations close to GlobSnow-2 values roughly until early February, as long as GlobSnow-2 accuracy criteria was fulfilled. The reliability of satellite SWE data after mid-February was deemed to be inaccurate due to the occurrence of occasional melting periods, as detected by the temperature and SCA criteria. Daily average temperatures increased above zero on several occasions, leading to snowmelt, which was also observed from decreased satellite SCA values. Simulated SWE values were notably different in the modified setup with respect to the main forecasting system (Figure 6).



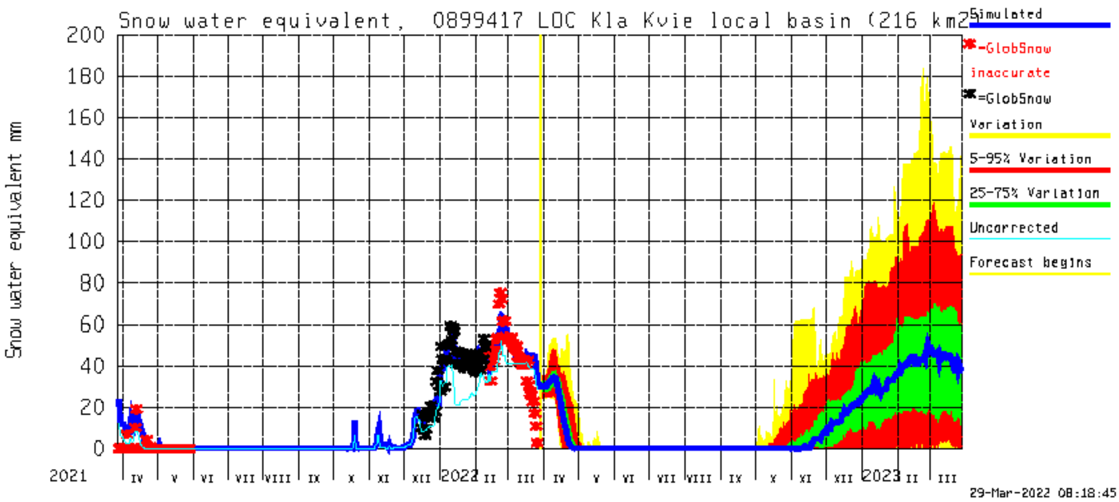
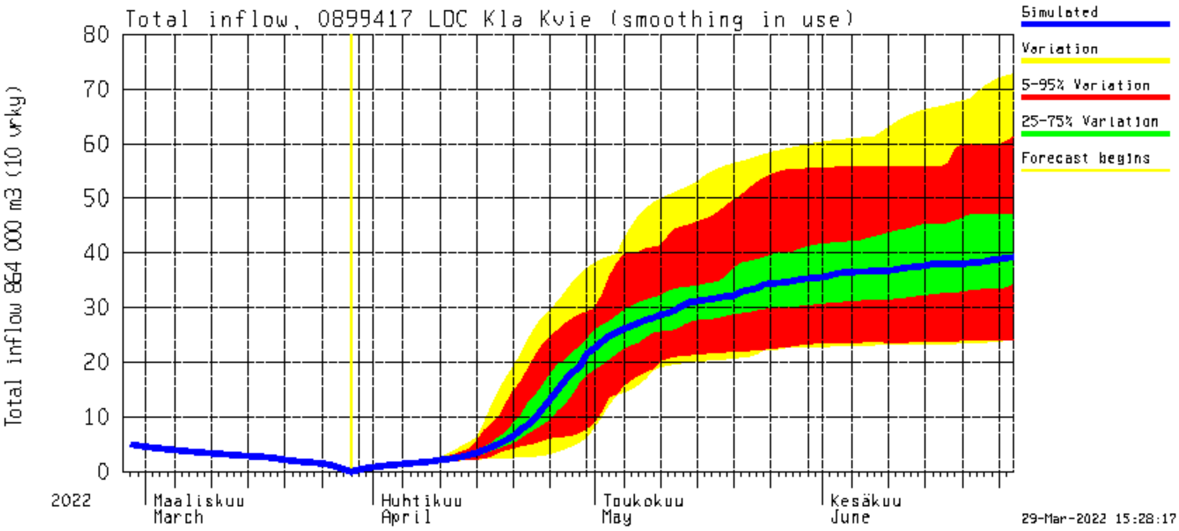


Figure 6 The SWE simulation with the forecast setup 1 in the upper figure. SWE simulation of forecast setup 2 in the lower figure using the additional error criteria. The forecasts were prepared on 29 March.

The model updating used in the forecast setup 2 process showed a significant impact to inflow volume forecasts during the spring flood period. For instance, the larger maximum SWE values in forecast setup 1 led to a larger forecasted spring inflow volume in the local sub-catchment of Lake Kvien compared to that from forecast setup 2. The median inflow volume sum until 18 May was estimated to be roughly 240 day units (1 day unit = 86400 m^3) when using the forecast setup 2, and about 300 day units when using the forecast setup 1 (Figure 7). The actual inflow sum based on water level and discharge observations was about 320 day units. Consequently, the actual inflow sum was better estimated by forecast setup 1 (being close to its ensemble median value) than by forecast setup 2 (being closer to the 75^{th} percentile of the ensemble). However, the observed precipitation sum was closer to the median of the ensemble weather forecast, which indicates that the forecast setup 1 was closer to the actual inflow sum.

Nevertheless, the results presented here are drawn based on a single season and may therefore not be entirely representative of the larger dynamics of the study areas. A more comprehensive evaluation of the performance of these two forecast setups would require several years of follow-up in various catchments or using reanalysis data over a longer and more representative time period, which was out of the scope of the present project.



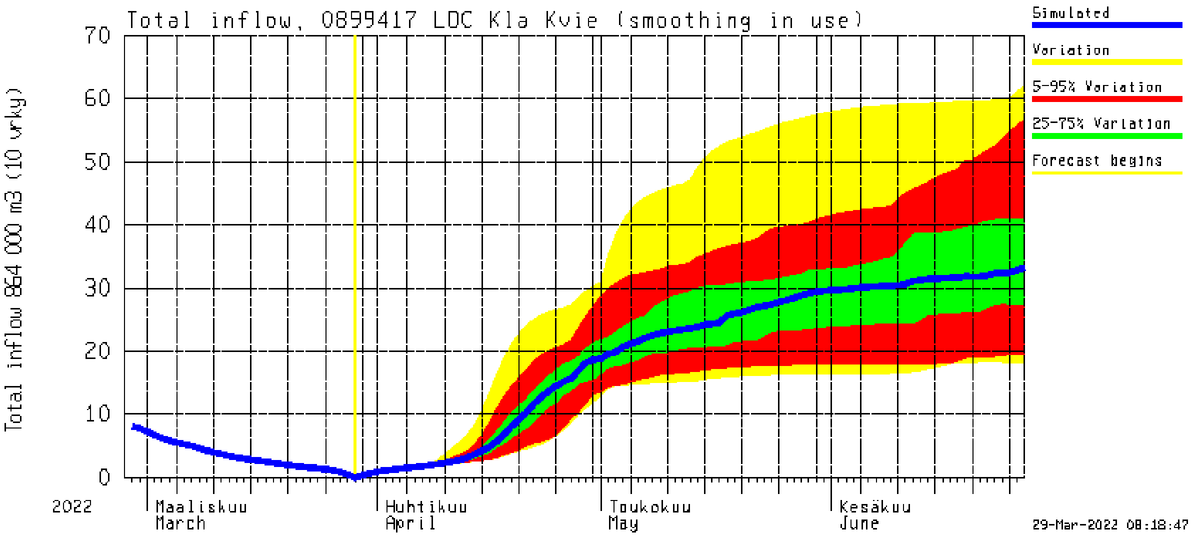


Figure 7 Inflow forecast of setup 1 in the upper figure. The inflow forecast of setup 2 with additional SWE error criteria is in the lower figure. The forecasts were prepared on 29 March.

5 Discussion and conclusions

EO-based passive microwave SWE and optical SCA products were used for WSFS model calibration and data assimilation for operational hydrological forecasts in several local sub-catchments of the lower part of the Klarälven watershed. The aim was to explore the potential for improving hydrological forecasting accuracy and model performance in such a data-scarce area. The results show that the EO-based SWE and SCA products are a valuable addition for hydrological model calibration in the study area, while their use for model updating still requires further research. Musuuza et al. (2020) found that, while the assimilation of EO-based optical SCA products improve the hydrological model predictions in Umeälven catchment located in Northern Sweden, such passive microwave SWE products cannot be used without addressing their limitations in mountainous and coastal regions. In this study, EO-based SCA product and temperature observations were used to detect wet snow conditions, and the study area was limited to low-land areas, acknowledging the unreliability of microwave SWE data in deep snow and/or wet snow conditions.

In this study, the GlobSnow-2 SWE data, based on passive microwave sensors, was found to improve snow simulations, especially in areas which lack accurate water level and discharge observations. Before using this dataset for model calibration, the RMSD and bias between the WSFS model simulation and Globsnow-2 data were larger than the average values of GlobSnow-2 validation against independent in-situ snow course data collected from Russia (Luojus et al. 2014) in all study sites except for in the local sub-catchment of Lake Kvien. After the model calibration with this dataset, both RMSD and bias were smaller or close to the validation results. The model calibration with EO-based SWE data was also shown to improve the unrealistically large variability in the WSFS snow simulations between the study catchments. The improved estimations of the areal maximum SWE before snow melting are of especial relevance for hydropower companies as they may improve forecasts for spring flood volumes.

The model updating against EO-based SWE and SCA products did not show any improvement in the skill of ensemble forecasts for the study period, which was limited to only one year. At least 10 to 15 years of reanalysis data (or real-time testing) would be required for a robust analysis of the performance of hydrological forecasts, which was out of scope for the present project. Additionally, a more comprehensive study of ensemble forecasts with two different model updating setups (with and without EO-based snow products) would have required the use of ERA-Interim reanalysis data (Dee et al. 2011). In a future study this reanalysis data could be used for comparing different forecast setups across a range of winter seasons with different snow and weather conditions by using multiple verification metrics (e.g. Verkade et al. 2013, Troin et al. 2021).

Good quality water level and discharge observations are the most important inputs for hydrological model calibration and updating. EO-based SWE products can be used alongside these data sources for model calibration and data assimilation during the snow accumulation period in lowland areas, and EO-based SCA can be used as an indicator for snowmelt. The EO-based snow products tested here have the potential to improve hydrological model simulations of snow and spring flood volumes, but the estimation of the timing and magnitude of spring flood peaks require anyway good quality water level and discharge observations, which might not be always available.

The EO-based SWE and SCA products used in this study are especially useful in data scarce regions lacking accurate discharge and water level observations (Sheffield et al. 2008). In the areas with good quality in-situ SWE observations, the EO-based SWE products can instead be used as a reference material, while the data assimilation of EO-based SCA product may even be used to improve the hydrological forecast quality (Musuuza et al. 2020). The most recent developments of the GlobSnow product, including spatially and temporally varying snow density and an enhanced algorithm for dry snow detection have further improved the accuracy of SWE estimations (Venäläinen et al. 2023, Zschenderlein et al. 2023). This could improve the accuracy of maximum SWE estimation. However, these improvements on the GlobSnow product were not available during the realization of this study.

Nevertheless, satellite-based estimations of SWE remain challenging in mountainous areas, due to its large spatial variability, deep snowpack and complex topography (Largeron et al. 2020). These challenges could be tackled in a short-term perspective by assimilation of multiple remote sensing observations with distributed snowpack models and in the future by upcoming Earth observation missions focusing on remote sensing of SWE in complex terrain (Gascoin et al. 2024).

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USING SATELLITE SNOW DATA IN HYDROLOGICAL FORECASTING

Snow has an important role for hydrology in the northern hemisphere and, the snow layer accumulated during winter can significantly affect spring flood volume. The snow component in hydrological models always has some uncertainty, and snow observation data can be used to estimate snow water equivalent more accurately. Adequate ground-based observations are rarely available, but satellite-based snow estimates can cover the area of interest even at daily intervals.

In this project study, satellite-based snow water equivalent and snow-covered area data was used to calibrate the WSFS model's coverage of the lower part of the Klarälven River. Satellite data was also used to update snow simulation in spring flood forecasts during the snow-covered season of 2022. The study shows that satellite data can improve simulation accuracy under certain conditions. However, using satellite observation requires careful consideration of data reliability.

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