ABSTRACT: The snow cover in lower mountain areas is often a very dynamic matter. For flood forecast, but also for continuous water balance modelling, a detailed knowledge of the snow cover, its temporal dynamics and current snow properties is essential.

According to this, modelling of the snow cover is a constituent part of applied water balance models. To drive and calibrate the models, spatial measurements of the land-surface parameters are necessary. Reliable information on snow conditions for catchments is not operationally available. Remote sensing methodologies, brought to an operational level, can fill this gap by providing spatial information for hydrologic modelling.

Within this paper, the obtained results from operational multisensoral remote sensing of snow in Southern Germany for the Neckar area, the results from spatial snow modelling on an hourly basis and the improvements through data assimilation for improvements will be presented.

1 INTRODUCTION

Approaches of monitoring and snowmelt modelling for hydrology are applied for different regions of the globe, mainly providing information on expected runoff for power generation and water supply. The object of these investigations are mainly persisting snow coverages, outlasting several weeks or months. Lower mountain areas in Central Europe are characterised by the fact that the snow pack accumulates and melts off several times during a winter season due to frequent temperature changes. Especially the temporary snow cover is often a factor to drive floods. Especially rainfall in combination with snow melt is the most critical situation for the origin of floods. Small snow packs (< 25 cm) are of special interest, because they can melt rapidly and completely and the stored snow water equivalent (SWE) (< 50 mm) will be added to the precipitation. For example, in February 2005, a storm event providing intense precipitation in Southern Germany, together with snow coverage led to local floods within the catchments of rivers Main and Neckar. Using the modelled spatial availability of water (comprising rainfall and snowmelt), local runoff peaks could be forecasted and finally observed. This event emphasizes the need of detailed knowledge of snow cover and snow properties, essential for reliable modelling and forecasting results. A frequent spatial observation is necessary to provide secure information on highly dynamic parameters like snow. Remote sensing applications, brought to an operational service, can provide helpful information for driving and controlling/supervising models, representing the actual and prospective state of the snow cover. Operational remote sensing is confronted with a number of challenges affecting the steady and automatic processing of reliable results.

The presented monitoring and modelling is carried out on a section (200 km × 200 km) of
Southern Germany, covering the entire Neckar catchment, the neighbouring elevated parts of the mid-mountains ‘Black Forest’ and ‘Swabian Alb’ and parts of the Upper Danube valley. (cf. Figure 1)

The Neckar Area:

Location:
- 47°50′–49°40′/10°35′E

Elevation:
- Neckar Catchment (14,000 km²): 100 - 500m
- Swabian Alb: 700 - 900m
- Black Forest: 500 - 1450m
- Upper Danube 400 - 600m

Mean annual precipitation:
- Stuttgart (314 m): ~ 700 mm
- Feldberg (1473 m): ~ 1700 mm

Average snow season:
- Mid December to early March
- Stuttgart: ~ 34 days of snow
- Feldberg: ~ 117 days of snow (high yearly variations)

Figure 1. Characteristics of the observed and modelled ‘Neckar area’, comprising the Neckar catchment (14,000 km²), surrounding mid-mountains and parts of Rhine and Danube watersheds.

2 REMOTE SENSING METHODOLOGIES

For an operational retrieval of information on snow properties all available approaches of remote sensing, permitting a high spatial and temporal resolution, were reasonable. To obtain frequent data on the actual state of the snow-covered area (SCA), daily observations from medium-resolution optical sensors (e.g. AVHRR and MODIS) show the best capabilities. Unfortunately, this information is only available in case of cloud-free conditions and limited to simple discrimination of snow and snow-free areas. This data provides no further parameters on the snow cover, like snow height or water equivalent, essential for hydrological applications. Observations from SAR systems, independent of illumination and weather conditions, are able to determine additive important information on snow properties like melting snow. For a continuous monitoring of the highly variable snow cover at the Neckar area, a joint observation from both physically different approaches are essential.

3 OPERATIONAL OPTICAL REMOTE SENSING

Snow cover mapping from optical imagery is based on a fully automatic processing chain for NOAA-AVHRR, developed within the Inferno-project (Appel et al. 2004a). The basic background of geometric processing and spectral classification are described in (Appel et al. 2002) and (Appel & Bach 2003). Main components of the processing are a trisection of geometric pre-processing, geometric and spectral processing and post-classification operations (see Figure 2). During the processing pass an accurate geocoding using individual correction terms and terrain information, a sensor depending classification scheme and land-use dependent thresholds are considered. For reliable results, the section of post-classification and exporting algorithms was further improved in close cooperation with the users (Flood Forecast Centre ‘HVZ’ and German Weather Service ‘DWD’). Particularly the information on the snow line and snow-free areas is an important parameter for adjusting operational water balance models (Bach et al. 2004). For these requirements the products must be reliable in all cases, impeding any negative affection of the running model. The high portion of forest areas gives a serious impact. Although they were regarded in spectral classification, an additional test will prevent misclassification of snow beneath the trees.
For the past winter seasons (since 2001) snow cover maps from automatic NOAA-AVHRR processing were generated operationally. Maps of the snow and cloud distribution are provided daily. In case of little cloud coverage (sufficient ground control areas allow geometric fine correction), datasets of 'virtual' snow measurements for snow-free and snow line areas were transferred for model integrations. The snow-covered area (SCA) derived from NOAA-AVHRR, was tested to correspond to 95% with station measurements (Appel & Bach 2003). Geometric accuracy of all products was ascertained to fit within +/- 1 pixel (= 1 km).

4 MICROWAVE REMOTE SENSING

For the observation of medium and large-scale watersheds, the use of ENVISAT ASAR Wide Swath data offers several advantages. In contrast to high resolution SAR systems, like ERS, major
parts of the Neckar catchment can be covered within one single overflight. The reduced resolution of WSM datasets (150 m) is adequate for the final products with 1km spatial resolution (corresponding to NOAA-AVHRR and model resolution). However, the main advantages of WSM data for the application in snow monitoring are the high temporal repetitions using different image geometries. This enables an observation rate of up to 3 scenes a week.

For an automatic geometric and radiometric processing of all available ASAR datasets an operational methodology and software were developed. The challenge for the derivation of products from heterogenous image geometries is caused by the large spatial extent of WideSwath data and the related diversity of incidence angles. The derivation of snow properties from ASAR imagery for large-scale areas firstly necessitates practicable and automated methods for data homogenisation. Relevant parts of the developed methodology are the geocoding and radiometric correction of the WSM_1P datasets using orbit information, automatic fine correction based on ground control areas, and the correction of incidence angle influences. Detailed information on the processing chain and the single algorithms can be found in (Löw & Mauser 2003).

Following the basic processing (used for the derivation of surface soil moisture as well (Löw et al. 2004), wet snow (melting snow) is detected using an algorithm based on the image ratio technique (see Figure 3) introduced by (Rott et al. 2000).

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**Figure 3. Methodologies of automatic geometric and radiometric processing of ASAR WSM data.**
The detection of the wet snow, which can be distinguished by a reduced backscatter comparing to the reference, is applied using a synthetic reference scene. This dataset, also used for the fine geocoding, was calculated from several autumn datasets of the year 2003 using subpixel land-use fractions. Limitations for the suitability of wet snow detection were given by the large extent of forest areas and settlements in the Neckar area (e.g. Black Forest and the city of Stuttgart).

By upscaling of the primary 150 m resolution to the final 1 km product, with regard to land-use, a large number of unclassified single pixels can be avoided. From the existing more than 10% of valid pixels, the fraction of wet snow will be assumed for the entire 1 km pixel area.

During the melting period (mid-February to early March 2003) a strong coherence between the detected snow covered area (from optical NOAA) and the reduced backscatter values in the SAR images was observed (several ASAR and ERS datasets). This characteristic comprises the definite wet snow area (threshold – 3dB) and a heterogenous transition zone. The boundary area towards the snow-free area represents a mixture of (wet) snow and snow-free parts of the surface. For this zone an overlap of reduced (from wet snow) and increased backscatter (from high soil moisture and increased snow roughness) within one pixel can be assumed (see Figure 4). Due to the slight relief gradient of the observed area a spatial extent of several pixels (several kilometres) for this boundary area seems to be realistic.

For the mapping of the snow-covered area from this dataset a two-step approach was deduced. Starting from strongly detected wet snow areas, an extension towards the snow line (using a ‘growing’ approach on lower thresholds) (Appel et al. 2004b) and an extension for the elevated dry snow is applied (Malnes et al. 2004). This methodology of snow cover mapping from ASAR is linked with an explicit snow melt. In case of slight snow melt no larger areas of unique wet snow (< – 2.5 dB) can be detected.

5 DISCUSSION ON MULTISENSORAL SNOW MONITORING

Snow cover mapping from optical imagery is a proved method to get important spatial information on current snow conditions. Using operational processing this information can be provided within less than one hour for model comparisons and integrations. The product-derived NOAA-AVHRR observations agree very well (95%) with station measurements. But this approach is limited to
largely cloud-free conditions. Based on different physical methodologies the SAR observations can help to overcome this limitation on parameter acquisition. The presented approach looks promising for an estimation of the snow cover and the snow line from SAR data for lower mountain areas in case of a melting snow cover. By extension of the detected wet snow area with the presented ‘growing’ methodology and the subsequent mapping of the higher dry snow parts, an approximation towards the observed snow cover from optical data could be achieved. Any significant misclassification of snow-free areas was not observed (Appel et al. 2004b). For the presented dates (see Figure 5) only 1.5% of the snow cover from ASAR did not agree with NOAA-AVHRR observations.

Figure 5. Results from multisensoral snow cover monitoring early in March 2003 for 1.3.2003 (left) and 4.3.2003 (right). Observations from ENVISAT ASAR (upper row) and NOAA-AVHRR (lower row) were processed to similar products, including information on the snow line. Information loss is caused by geometry, forest cover (ASAR) and cloud coverage (NOAA).

However, slight differences between optical and SAR observation can still be found. For this circumstance all the uncertainties of the detection of small snow packs using low resolution imagery must be considered. The systematic differences between the different observation methodologies (and the real existing snow coverage) have to be further analysed and considered during application of the monitoring results. Accordingly, operationally processed products of mean spatial resolution (1 km) were limited in accuracy relating to high resolution and supervised classification datasets.

Nevertheless, these products provide a striking possibility of periodic, spatial and reliable observations of the snow cover. As a further task, these obtained datasets can be used to improve snow and water balance modelling.

6 MODELLING OF THE SNOW COVER

Since the direct spatial retrieval of snow properties from remote sensing is limited to its extent and in certain cases to wet snow distribution, relevant parameters for hydrologic applications (snow
water equivalent) have to be obtained from station measurements. For the Neckar area, a dense station network (operated by the DWD) is existing, but only few measurements are available online. Therefore, water balance and snow models were operated. The precise simulation of the snow cover, together with forecasting, helps to improve the operational flood forecast and water management.

To further investigate the potential of remote sensing for snow and water balance modelling using assimilation strategies, the calculation of the snow pack is carried out with the process-oriented multi-scale evaporation transpiration model (PROMET) of the University of Munich (Mauser & Strasser 1997). Adaptations of the model made it possible to compare and integrate the remotely sensed snow properties (snow cover and wet snow distribution) directly. The snow sub-model (single layer) is physically based on the simulation of the energy balance, the water equivalent and the melting rate of a snow pack. This basic model concept, driven by synoptic meteo data (temp. / humidity / precipitation / wind / cloud coverage) and basic GIS data (terrain, soil, land-use), has been successfully applied on different scales, with a spatial resolution of 1km² and temporal resolution of 1 hour (Strasser et al. 2002).

Results from the revised model version for the Neckar area from 1998/99 and 2002/03 show a good agreement between modelled and measured SWE, but illustrate also the chance for improvements by assimilating remote sensing products. In particular for the snow season 2002/03, a significant deviation appears. Possible reasons may be the reduced availability of input station datasets for the year 2003. Appearing differences between measured and modelled SWE (see Figure 6, right) are also identifiable in spatial comparisons between SCA from remote sensing (e.g. from NOAA-AVHRR) and model output (see Figure 7).

![Figure 6. Comparison of modelled (line) and measured (bars) snow water equivalent [mm] for one example station at the Black Forest for the season 1998/99 (left) and 2002/03 (right).](image)

7 METHODS OF DATA ASSIMILATION

Improvement of snow modelling using spatial information from remote sensing is breaking new ground. Particularly the adaptation of a continuously running model is a major challenge. In this case remote sensing products (e.g. SCA) do not only serve as input data. They should affect internal or external parameters to adjust the current and future state of the snow pack.

For the dynamic assimilation of snow data to the PROMET model two strategies have been found. By an occasional adaptation of ‘critical temperature’ (Tcrt) (separating precipitation into snow and rain), and the ‘energy impact parameter’ (biasing the affection of energy to the snow pack), broad modulations of the modelled SWE values can be performed. While the physical ‘Tcrt’ value (ranging from –4°C to +4°C), the most influential parameter driving accumulation, strongly affects the absolute value of the SWE, the ‘energy impact’ affects the energy flux into the snow pack (see Figure 8). This has wide effects on melting processes and liquid water content.

Both parameters are under investigation to be automatically determined from remote sensing datasets. A derivation of the ‘Tcrt’ correction was successfully applied using the ASAR observations
on 1.3.2003 in comparison with the modelled snow coverage. From the spatial difference between modelled and observed snow, spatially distributed correction parameters for 'Tcrit' were derived and applied for a new model run, starting from the last significant accumulation event. The results of the recalculation showed improvements on large areas. Remaining differences were based on the limitations of available precipitation measurements. By an adaptation of 'Tcrit' not all lacking SWE can be compensated, if no sufficient rainfall was measured or forecasted???.

Figure 7. Spatial comparisons of modelled (PROMET) and observed (NOAA-A VHRR) snow-covered area for the 1.3.2003 (left) and 4.3.2003 (right) in the Neckar area. The lack of modelled snow during this period is quite obvious. This difference can be caused by insufficient snow accumulation or accelerated melting processes.

Figure 8. Impact of ‘Tcrit’ and the ‘energy impact parameter’ for improvement of the snow model performance.
8 CONCLUSIONS

Operational products of the snow-covered area, both from optical and SAR observations, provide very helpful information on the current snow situation. The lack of detailed hydrologic information can be compensated applying detailed water and snow balance modelling. By integrating snow cover observations obvious improvements in model performance can be achieved. A further step towards the assimilation of remote sensing data will be the analysis of observed wet snow for the adaptation of the “energy impact parameter”. Preliminary results show close coherences between calculated and observed liquid water distribution of the snow cover (see Figure 9). Assimilation strategies for the context of observed and modelled snow melt are under investigation.

Figure 9. Spatial comparison and close coherences between calculated (left) and observed (right) wet snow for 01.03.2003 (09 UTC). The wet snow distribution is totalized from the liquid water content for the last 24 hours. The model results obtained from improved model run after SCA assimilation.

REFERENCES


