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# Applying a time-lapse camera network to observe snow processes in mountainous catchments

**J. Garvelmann, S. Pohl, and M. Weiler**

Institute of Hydrology, Freiburg, Germany

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Correspondence to: J. Garvelmann (jakob.garvelmann@hydrology.uni-freiburg.de)

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## Abstract

A network of 45 spatially distributed time-lapse cameras was used to carry out a continuous observation of snow processes and snow cover properties throughout three mid-latitude medium elevation mountain catchments in hourly intervals. A simple technical modification was conducted to enable the deployment of the standard digital cameras in any location. Image analysis software was applied to extract information about snow depth, surface albedo, and canopy interception from the digital images. Furthermore, the distributed design of the camera network made it possible to identify the elevation of the snow rain interface for any precipitation event for the interpretation of winter flooding events resulting from snow melt. Study results prove that the application of digital time-lapse photography is an appropriate technique to observe the spatial distribution and temporal evolution of seasonal snow covers in a mountainous environment.

## 1 Introduction

Snow is an important component of the hydrological system in many mountainous environments. Vegetation and topography have a crucial influence on the spatial distribution and temporal evolution of snow covers and the relation of all factors influencing the distribution have not been well understood (e.g. Jost et al., 2007, 2009). A continuous monitoring of the snow cover at the catchment scale is valuable to improve the understanding of the processes driving the spatio-temporal variability of seasonal snow covers. Furthermore, it yields important information for water resource applications and the prediction of snow melt runoff events. The interception of snow in the forest canopy is a major factor contributing to the difference in snow accumulation between open and forested areas (Hedstrom and Pomeroy, 1998; Storck et al., 2002). Different processes (mass unload, sublimation, and melt water drip) are involved in the unloading of snow from the canopy (Pomeroy et al., 1998). Incoming global radiation is often the most important component of the snowmelt energy balance. The albedo of the snow surface

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view, respectively. An overview of studies using time-lapse photography in glaciology and snow research can be found in Parajka et al. (2012).

In this study we further extend these approaches by modifying standard digital cameras to run independently of any outside stationary power source. This allowed us to set up an experimental design consisting of a network of numerous standard standalone digital time-lapse cameras distributed throughout the study watersheds and covering a wide variety of topographical and vegetational situations. In addition, we automated and extended the information that can be derived from the time-lapse images to derive time series of snow depth, albedo, snow interception, and the state of precipitation.

## 2 Methodology

### 2.1 Study area and camera network

The study was conducted in the Black Forest, a typical mid latitude medium elevation mountain range in the southwest of Germany. In order to accomplish a continuous observation of the quantity and the status of the snow cover, a network of 15 standalone digital time-lapse cameras was established over the winter season 2010/2011 in a meso scale catchment. The network was extended to 45 cameras spread over three watersheds of different sizes and topographic characteristics for the 2011/2012 winter (Fig. 1).

Within the study catchments, a stratified sampling design was used to cover a wide range of altitudes and exposures. To specifically investigate the influence of the vegetation cover on the accumulation and ablation processes of the snowpack beneath, generally pairs of cameras were installed in close proximity to each other with one being located underneath the forest canopy while the other was situated on an adjacent open field site.

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## 2.2 Camera design

We used a standard “Pentax Optio W90” digital camera, which is a waterproof outdoor camera. The camera is equipped with a 12 megapixel 1/2.3” RGB-CCD-sensor chip and allows to electronically set-up a time-lapse routine. Hourly pictures were stored on a camera internal 2 GB SD-card. The time-lapse mode of the camera allows for a maximum of 1000 images. Therefore the cameras had to be read-out and restarted after a maximum duration of 41 days. To ensure a continuous power-supply for the digital camera, we used a 3.7V external rechargeable Lithium-Polymer battery. Rechargeable Lithium-Polymer batteries are known to provide reliable power supply even for low temperatures. Cables were soldered to the camera internal battery terminals which we connected with gold plated plugs to the rechargeable Lithium-Polymer batteries (Fig. 2). With this modification we were able to install and run the digital cameras independently of any additional power source at any location in the field. This gave us complete freedom to choose adequate locations to suit our research questions. It also made the installation comparably easy and time efficient, which was essential for setting up the high density camera network used in this study. To protect the cameras from severe weather conditions and minimize drops on the camera lens, they were mounted within wooden birdhouses, which were then mounted to trees and other suitable objects in the field (Fig. 2). The birdhouses also helped us to reduce vandalism of the equipment in the watersheds.

## 2.3 Image analysis

We used IDL image processing software to extract information about snow depth, albedo and the interception of snow in the forest canopy from the digital images. A wooden measurement stake with alternating 10 cm black and red bars was installed in camera view at every location to accommodate the snow depth estimation. On top of the stake a black/white plastic board was attached to provide a control surface of a “perfect white and black” area for each picture. Having these boards in the pictures

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allows the direct determination of the references for black and white for differing illumination conditions in the image analysis. A white balance was used for the albedo estimation and a black/white balance for the calculation of canopy interception. Polygon masks, called regions of interest (ROI), were defined within each image to define the areas within the pictures for which snow surface albedo and canopy interception calculations were carried out (Fig. 3). Several ROIs for albedo or interception analysis can be defined within the pictures providing more representative average values for a location but also allowing an analysis of the potential variability of those values at a location.

A batch analysis routine was used to load and analyze each image. RGB values for every pixel within the defined polygon masks and the control surfaces (black/white board) are used for the calculations. The calculated output was written to a text file which could be used for further analysis. Images taken at night and during poor visibility conditions (fog, intense snowfall events) were discarded and could not be used for the image analysis resulting in data gaps.

The established camera network allowed a continuous observation of snow depths at different locations throughout the catchments. These snow depth time series and accompanying snow surveys which determined snow densities can be used to calculate snow water equivalents (SWE). Snow depth can be calculated automatically with image analysis software from the images by counting the number of snow stake pixels not covered with snow (Floyd and Weiler, 2008; Parajka et al., 2012). Such a computer routine was applied to calculate the snow depth at the camera locations. To check the accuracy of this automated process we also determined the snow depths “manually” by opening each picture and determining the snow depth by counting the visible red and black bars by eye. Figure 4 shows the comparison of the two methods for one location ( $R^2 = 0.98$ , RMSE = 7.1 cm). The comparison shows that the overall evolution of the snow depth over the winter is reproduced well by the automated method. However, there seems to be a constant slight underestimation of snow depths at higher values.

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We therefore chose to “manually” determine the snow depths from the digital images for this study.

The snow surface albedo estimation from the images is limited by the fact, that the CCD-sensor used in the digital cameras is only able to detect the visible range of the electromagnetic spectrum. Therefore we can only estimate the snow surface albedo within the visible range. Nevertheless, Corripio (2004) has shown that terrestrial photography is a suitable and useful approach to estimate snow surface albedo. He used an algorithm for georeferencing the images in order to correct the reflectance values of the images with respect to the topographic position. In this study we used an even simpler approach by Gorski (2011) to estimate albedo values directly from digital images. The calculated albedo value is the ratio of the mean RGB pixel values of a control surface (white board in the focus of the camera) and the mean RGB pixel value of defined polygon masks on the snow surface within the digital image. The computed ratio is adjusted with a correction factor of 0.6 which Gorski (2011) suggest is suitable for CCD-sensor cameras. The albedo is therefore calculated as follows:

$$\text{Albedo} = 0.6 \times (\overline{\text{RGB}}_{\text{snow}} / \overline{\text{RGB}}_{\text{reference}}) \quad (1)$$

$\overline{\text{RGB}}_{\text{snow}}$  = mean of the RGB pixel values in the ROI on the snow surface

$\overline{\text{RGB}}_{\text{reference}}$  = mean of the RGB pixel values of the reference area

For the calculation of snow interception in the forest canopy we first performed a black/white balance using the control surfaces mounted on top of the snow stakes in the images. Based on this balance white (snow) pixels could then be distinguished from non-white (non-snow) pixels within the polygon masks and a fraction of snow (white pixels) could be calculated. A fraction of zero would therefore indicate no snow in the canopy and a fraction of one would indicate a completely snow covered canopy, respectively. It is important to note that the fraction of white pixels within the defined ROI depends on the camera position, view angle and distance of the camera to the

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canopy. Therefore, this method initially only provides relative values for the total snow load within the forest canopy.

The images could also be used to identify the state of precipitation at the camera locations. Since the digital time-lapse cameras were deployed at different altitudes, the images could therefore be used to determine elevation ranges for the snow line during different winter precipitation events.

### 3 Results

#### 3.1 Snow depth

Figure 5a shows the snow depth at three open and one forest location of similar ex-  
position but different elevation. As expected the snow depths increase with increasing  
elevation at the open locations. It is interesting to note that the snow depths at the  
peak of the snowpack differ by as much as 53 cm (150 mm SWE) between the highest  
and lowest location. Furthermore, the analysis shows that the snow cover duration was  
about 16 days shorter for the 2011/2012 winter for the 900 m a.s.l. location compared  
to the 1200 m a.s.l. location. A comparison with the fourth location, which was situated  
underneath a dense forest canopy at an elevation of 1195 m a.s.l. highlights the strong  
effect a forest canopy has on the snow cover distribution in watersheds. A difference of  
55 cm (155 mm SWE) was observed for peak snow depth (around 22 February 2012),  
while in the spring the ground underneath the forest first became snow free 27 days  
before the snow on the adjacent open meadow disappeared.

Figure 5b presents the snow depths during the winter 2011/2012 at four different  
locations at similar elevation but different expositions and land cover. The influence of  
the exposition can be clearly seen for the two open locations with a significantly deeper  
snowpack on the north-facing slope. The overall maximum difference in snow depth  
between the two open locations is about 30 cm (or about 90 mm SWE). The observed  
snow depths at the two forest locations are nearly identical suggesting that exposition

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does not play an important role for snow accumulation under forest canopies. The results, however, once again shows the great importance the forest cover has on the snow cover as there are large differences in snow depth between open and forest locations. Figure 5 also shows the great potential of the camera pairs (open vs. forest locations) used in the current study to investigate the influence of a vegetation cover on the snowpack beneath in considerable detail. Overall, the presented results demonstrate the crucial importance of determining the small scale snow cover variability even in a medium elevation mountain range for a wide variety of hydrologic and ecologic aspects.

Based on the snow depth observations at the 19 camera locations throughout the Brugga watershed and snow density measurements from manual snow surveys, the spatial distribution of the SWE in the Brugga catchment prior to and after a rain-on-snow event on 2 January 2012 was determined using a simple linear regression model (Fig. 6). Elevation was related to snow depth separately for open and forested for each time, respectively. Subsequently, SWE was calculated for each 10 × 10 m grid square in the catchment using elevation and land cover data. The flood peak observed on 2 January 2012 (see Fig. 7) was categorized as a 2-yr flood event at the basin outlet. More extreme flood discharges were measured in some of the tributaries. The flood was generated by both liquid precipitation and snow melt water. There was a snow cover present throughout the catchment prior to the event ranging from a few cm in the lowest parts to more than 50 cm in the highest parts of the catchment. Snow depths and consequently SWE decreased significantly at all altitudes during this ROS event. With the linear regression model a basin wide mean SWE of 56 mm was calculated for the snow cover prior to the event, whereas a mean SWE of 13 mm was determined for the snow cover after the event. Therefore, a total of 43 mm of SWE melted during the event. Total precipitation was 44 mm during this event. Assuming a negligible change in storage within the catchment these input values (43 mm + 44 mm = 87 mm) match the observed total runoff of 83 mm very well. The numbers also show the importance of

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the snowmelt for this flood event as about half of the available flood peak input resulted from the rain-on-snow melt of the pre-existing snow cover.

Subsequently, the time-lapse images from different locations throughout the catchment were used for a further detailed interpretation of the hydrograph for this and a subsequent runoff event 2 days later (Fig. 7). Despite higher precipitation intensity and amount the flood peak was slightly lower. The pictures show that most snow in the catchment had disappeared during the rain-on-snow event on 2 January 2012. Therefore the water available for runoff during this event was virtually limited to rainwater and, as a result, discharge did not rise as high. Another precipitation event (6 January 2012) caused nearly no runoff increase, because as the pictures indicate, precipitation fell as snow in most parts of the catchment.

### 3.2 Snow canopy interception

The experimental setup presented in this study allows a continuous observation of the forest canopy and the temporal evolution of the snow interception in the canopy at different topographic situations and during various climatic conditions. Figure 8 shows the snow interception results obtained from images taken by a camera installed at 900 m a.s.l. altitude and a viewing direction of north-east. Daily interception values from the beginning of December 2011 through end of February 2012 are shown. Several snowfall events could be observed during this period. Events of particular interest are labeled with red arrows and the corresponding pictures after the snowfall events are shown. It is interesting to note, that more snow was intercepted in the canopy on 20 December 2011 compared to 15 February 2012 even though more snow fell on 15 February. The reason is most likely the difference in air temperatures during the events. Average daily temperature on the 19 and 20 December 2011 were much higher at 1.5°C compared to -5.5°C in February 2012. Previous studies have suggested that interception efficiency increases with decreasing density of the falling snow, increasing temperature and decreasing wind speed (Pomeroy and Gray, 1995; Marsh, 1999). The warmer temperatures result in more flexible tree limbs and lead to the building of ice bridges

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between the individual needles and snow crystals therefore allowing more snow to be intercepted. The results of this study clearly support this assumption.

The event around 3 February 2012 is special in terms of the snow removal from the canopy. The sublimation or unloading of snow from the canopy was much slower compared to the other events observed. This behavior can most likely be attributed to the meteorological conditions a nearby weather station observed at the time of the event. Air temperatures were consistently below freezing and incoming solar radiation was high during the entire period after the 3 February 2012 event. For the other events shown in Fig. 8, observed air temperature was higher and the radiation energy input was lower. This analysis indicates that sublimation of intercepted snow directly back to the atmosphere dominated this event. This is a much slower process than the mass unload and melt water drip processes, that were most likely responsible for the quick disappearance of the intercepted snow after the other events.

Figure 9 shows the comparison of the snow interception of similar forests on a north-facing versus a south-facing slope for a snowfall event in February 2012 in the Breg catchment. The snowfall event was followed by an overcast day with freezing temperatures where the snow remained in the canopy at both expositions. The following sunny day with moderate temperatures close to 0°C caused an abrupt decrease in intercepted snow. The comparison shows that the release of the snow interception storage progressed much faster at the southfacing canopy. As a result the forest canopy on the southfacing slope was snow free two days earlier compared to the canopy on the northfacing slope probably due to a more intense input of solar radiation to the south facing slope.

These results indicate the difficulties in modeling the unloading of snow with simple interception models (e.g. Hedstrom and Pomeroy, 1998) in this environment as compared to colder environments where these kinds of studies have so far often been conducted. It also further highlights the importance of having continuous observations in various topographical situations to better understand the relative importance of the involved processes in relation to topography and meteorological conditions.

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### 3.3 Albedo

The albedo of a snow cover provides important information about the status of the snow and its temporal evolution is a crucial factor for the energy balance of the snow. Visible albedo was calculated from the digital images. In the visible range measured albedo values of fresh snow are generally high.

Hourly derived albedo values using Eq. (1) are plotted against measured albedo values from a weather station for eight days showing a high correlation of  $R^2 = 0.89$  (Fig. 10). The resulting regression equation of this correlation was used to calibrate the albedo values calculated with Eq. (1) from the digital images in the catchment to receive useful data.

Figure 11 shows the temporal evolution of the albedo obtained from the time lapse images compared to the albedo measured by a weather station at the same location during a rain-on-snow event followed by fresh snow. The decreasing surface albedo during the melting of the snowpack and a subsequent increase of the albedo caused by new snow can be clearly seen in the graph. The obtained results are in very good agreement with the measured albedo values of the on-site weather station ( $R^2 = 0.89$ , RMSE = 0.08, NS-Efficiency = 0.88). This comparison proves the validity of the presented method to obtain meaningful albedo values using the visible range.

Subsequently, the albedo image analysis was applied to images taken at other field sites in the study area. Figure 12 shows calibrated albedo values of the snow surface under a conifer forest canopy for the entire winter 2011/2012. The data clearly shows the expected increase in albedo after snowfall events. Frequently, a further slight increase in the days following a big snowfall event can also be seen. This phenomenon can be attributed to initially intercepted snow falling out of the canopy and onto the snow cover. The subsequent albedo decrease due to snow metamorphism as well as needles, small branches and other debris deposited on the snow cover underneath the canopy is also well reproduced by the data. Such observations are very valuable for the improvement of snowmelt models as many of these models use open field albedo

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values to calculate the snow cover energy balance underneath a forest canopy. This assumption has to be tested as it could potentially lead to significant errors in the simulation of forest snowmelt rates. Data collected with the presented method can be used for such testing and, if necessary, for the formulation of a new model algorithm.

### 3.4 State of precipitation

Time-lapse images were also used to identify the state of precipitation during precipitation events. Due to the high number of digital cameras installed at different elevations in the study catchments, the pictures could be used to identify the elevation of the snow line and its changes over time during precipitation events. Since the study also included the installation of a high density meteorological observation network we were able to compare measured temperature profiles to the snow line determined from the images (Fig. 13). For the 13 December 2011 event the snow line determined from the images was between 890 m a.s.l. and 1010 m a.s.l. (red box). For the 27 January 2012 event the snow line was fairly close to the 780 m a.s.l. since we observed a mix of rain and snow in the pictures at this altitude and snowfall was evident in the pictures of the next higher camera station 890 m a.s.l. (green box). For the third event shown here the snow line was lower than the altitude of the lowest digital camera. Therefore we can assume that the precipitation fell as snow in virtually the entire catchment during this event. When comparing the estimated snow lines from the digital images to the observed temperature profiles we can see that the snow line was at an elevation with an air temperature (2 m above ground) of around 3°C–4°C for the 13 December 2011 event and around 2°C for the 27 January 2012 event, respectively. These temperature values are relative high compared to the frequently used threshold temperatures in many hydrological models.

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## 4 Discussion

With a simple technical modification to a standard digital camera, it was possible to establish a cost and time efficient network of time-laps cameras in several meso-scale mountain catchments to perform a very detailed continuous observation of the snow cover and snow processes. However, there are some limitations concerning this technique. Gaps in the data are caused by: (1) photographs taken during night time which are useless for the analysis; (2) strong snow fall events causing frost or snow to accumulate on the lens of the camera; (3) reduced visibility due to fog and (4) images showing snow rime build up or snow sticking to the measurement scale and the black/white reference scale. These images had to be discarded from the image analysis. Furthermore, the camera locations had to be accessible to download the images three to four times during the winter season. Unfortunately, it is not possible to switch off the camera during night time, which would increase the period between having to download the images significantly. It is also not possible to increase the number of pictures taken by the camera (1000) despite the SD card could store many more pictures.

A fully automated analysis of the digital images was not always possible, since the cameras are moving slightly due to wind or snow on the camera housing and after downloading the images. Further improvements of the image analysis software could account for these limitations for example with an automatic identification of the measurement scales needed for image analysis and an automatic determination and discarding of useless images.

The determination of snow depths for the camera locations was very successful. The collected data is extremely useful to investigate snow accumulation and ablation processes at different time scales (hourly, daily) and for different locations. Furthermore, the data could be used to interpolate the spatial distribution and temporal evolution of a snow cover throughout a mountainous catchment in forested and open areas.

Interception in the forest canopy was calculated qualitatively as a fraction of white pixel within a defined polygon mask in the canopy. In a next step, a method to calculate

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quantitative total snow loads from this data will be developed. Another limitation is that the results are dependent on the camera position (angle, distance to the forest). However, the continuous and spatially distributed nature of the observations allows a detailed study of the canopy interception process and snow exposure times for different altitudes and exposures, canopy densities, and meteorological conditions.

Despite some simplifications compared to other approaches (Corripio, 2004; Gorski, 2011) we were able to extract useful data to compare snow surface albedo at different locations by calibrating the data with measured albedo values. The data show realistic values of a high albedo values after a new snowfall, a subsequent decrease in albedo due to snow metamorphism and especially for a melting snow pack with an increasing snow free area.

For the daylight photographs it was possible to identify the state of precipitation and thus the snow line by using the information from the cameras at different altitudes. The information from time-lapse images can also be used to verify snow cover patterns or snow processes simulated from hydrological models (e.g. Farinotti, 2010; Parajka et al., 2012). The spatial and temporal high resolution data collected from a camera network such as the one presented in this study provides a very useful data set which could be used to test assumptions in existing hydrological models and to improve the simulation of the spatio-temporal variability of seasonal snow covers and the related processes at the plot and catchment scale.

## 5 Conclusions

The study highlighted the usefulness of a distributed network of standard digital time-lapse cameras for snow observations in mesoscale mountain catchments. A simple technical modification related to the power supply of the cameras is needed to run the standard digital cameras autonomous at any location in the field. The presented experimental design is an appropriate technique to realize a continuous observation of the spatial distribution and temporal evolution of key aspects of a seasonal snow cover

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throughout a mesoscale catchment. The method is easy to accomplish, low-cost and provides useful data about snow depth and snow albedo as well as important snow processes such as snow interception and state of precipitation. Furthermore, the spatially distributed design of the camera network provides reliable continuous information for the identification of the snow line during winter precipitation events and the interpretation of snowmelt runoff hydrographs. The time-lapse cameras could also be used for other application where visible information could provide useful information of its own or together with additional observations.

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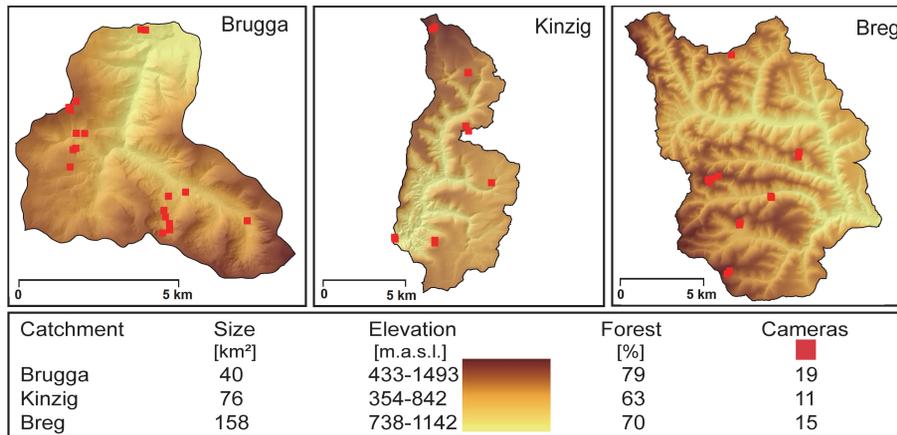
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**Fig. 1.** Study catchments in the Black Forest, South-West Germany.

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**Fig. 2.** Camera setup used in the presented study.

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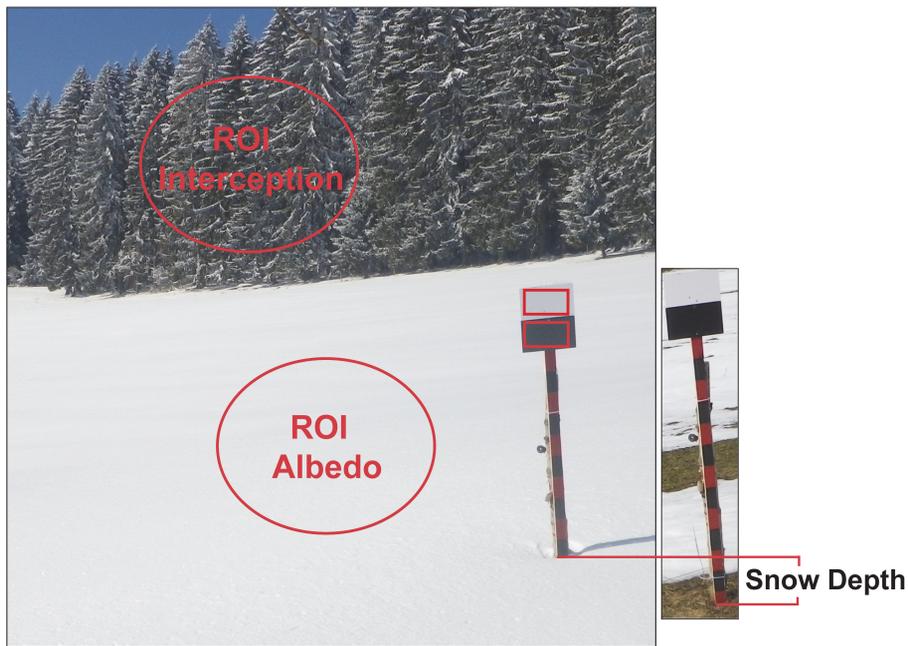
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**Fig. 3.** Methodology used for the image processing.

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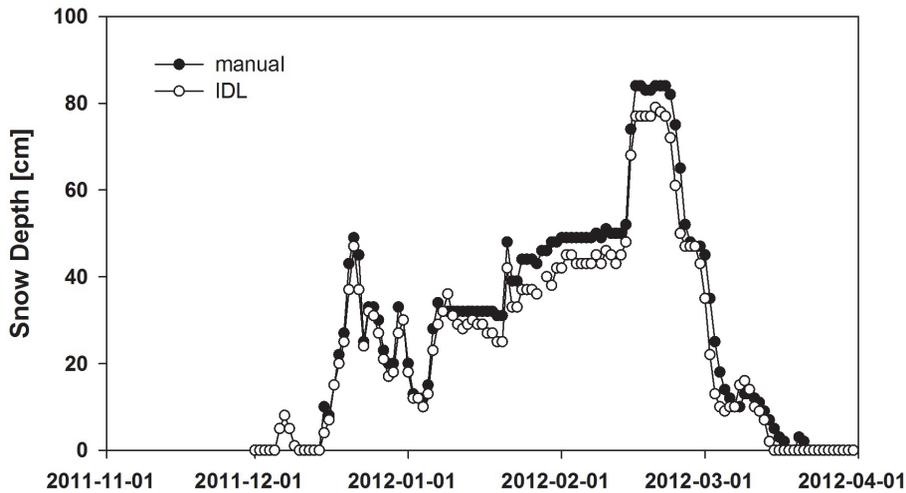
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**Fig. 4.** Comparison between manually derived snow depths and the results from an automated IDL routine.

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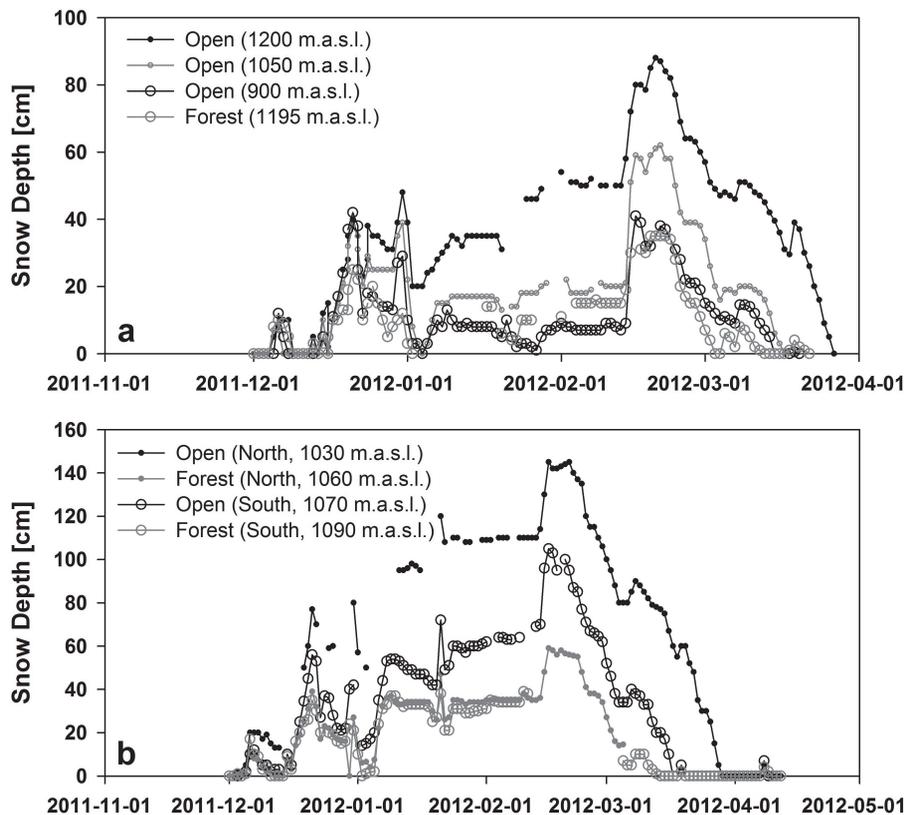
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**Fig. 5.** Snow depths dynamics in the winter season 2011/2012 derived from the digital images.

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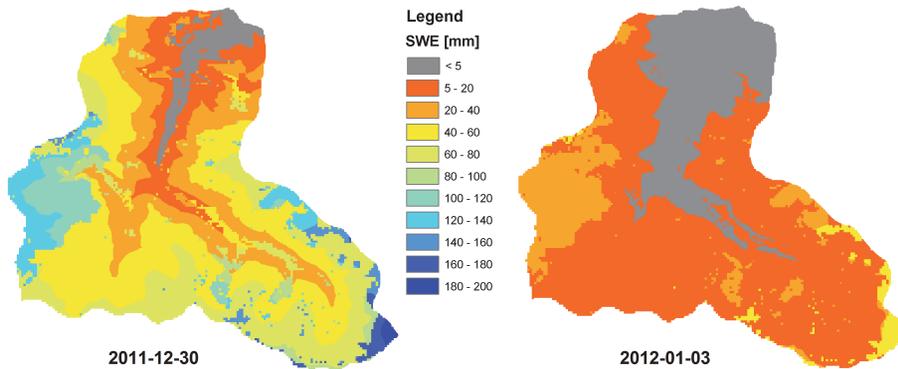
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**Fig. 6.** SWE distribution in the Brugga catchment based on the snow depths derived from 19 camera locations and a simple linear regression model for forested and open areas before and after a rain-on-snow flood event on 2 January 2012.

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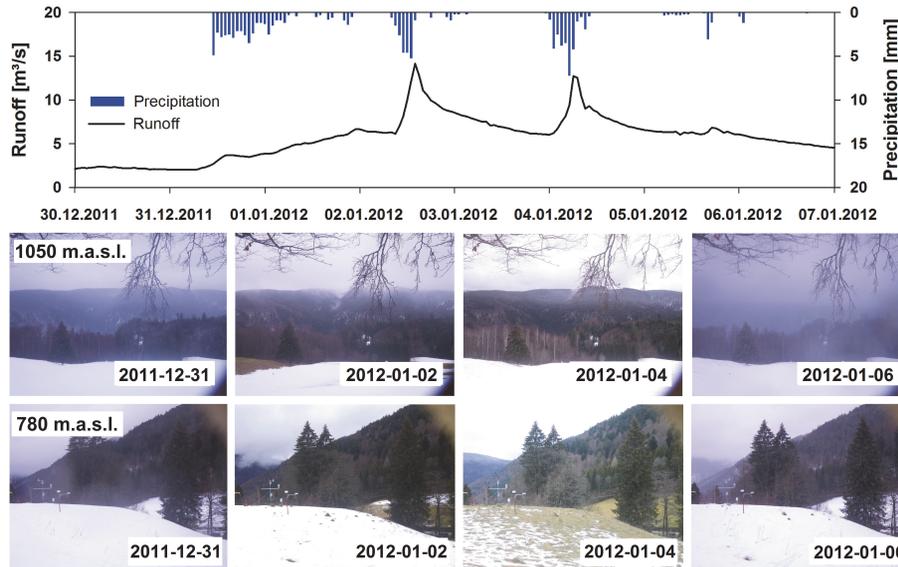
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**Fig. 7.** Hydrograph, precipitation and time lapse photographs for the Brugga basin for three runoff events at the beginning of January 2012.

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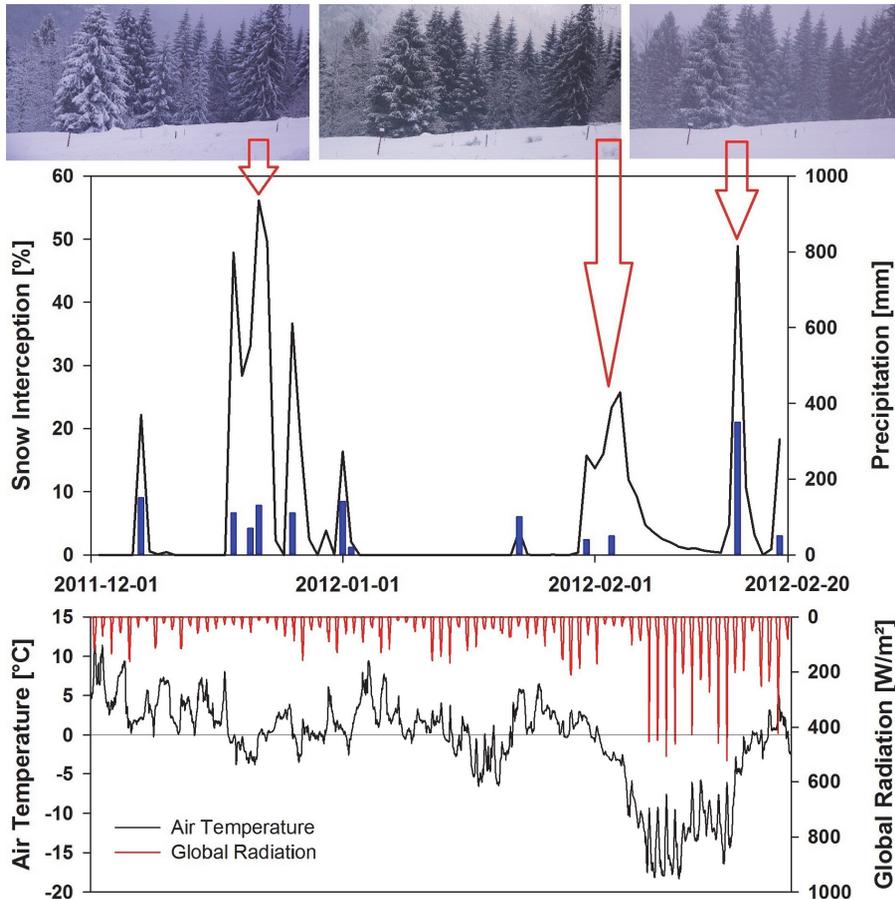
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**Fig. 8.** Interception of snow in a conifer forest canopy observed during different snow fall events in winter 2011/2012 with measured air temperature and incoming solar radiation.

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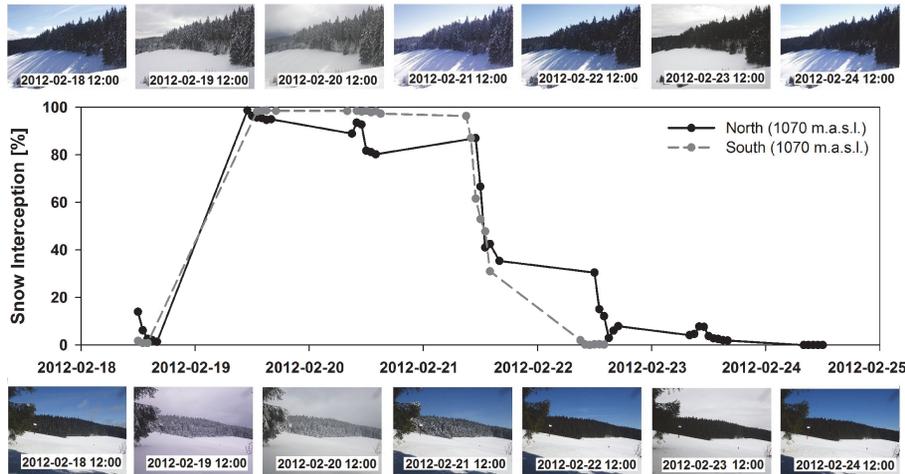
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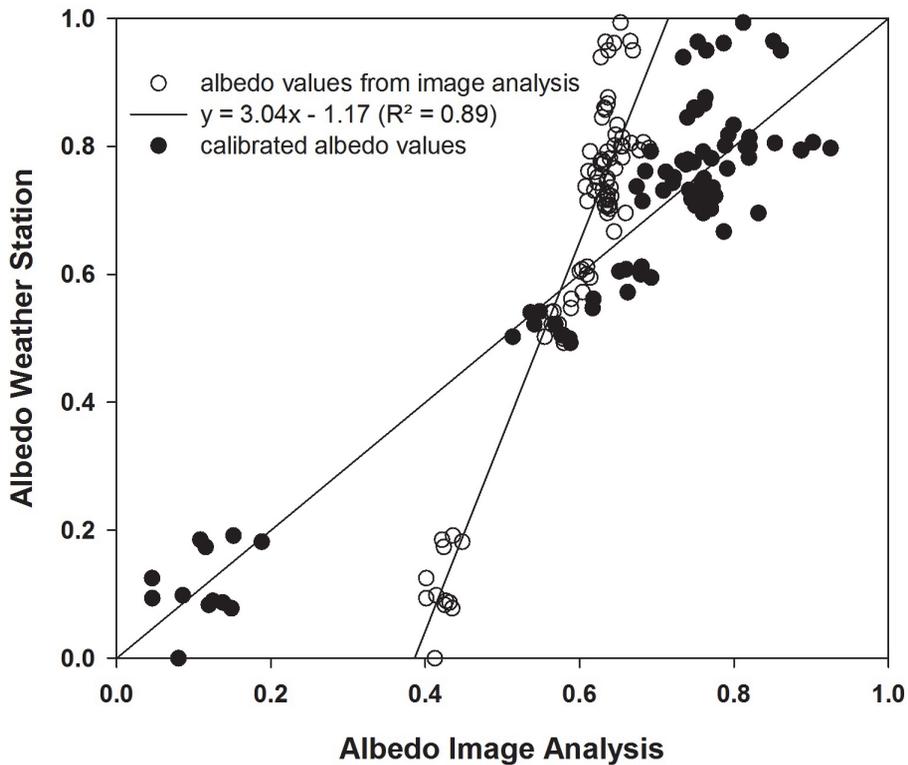
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**Fig. 9.** Snow interception in the conifer forest canopy of a north facing and a south facing slope, respectively.

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**Fig. 10.** Albedo values measured at the weather station versus albedo values derived from the image analysis.

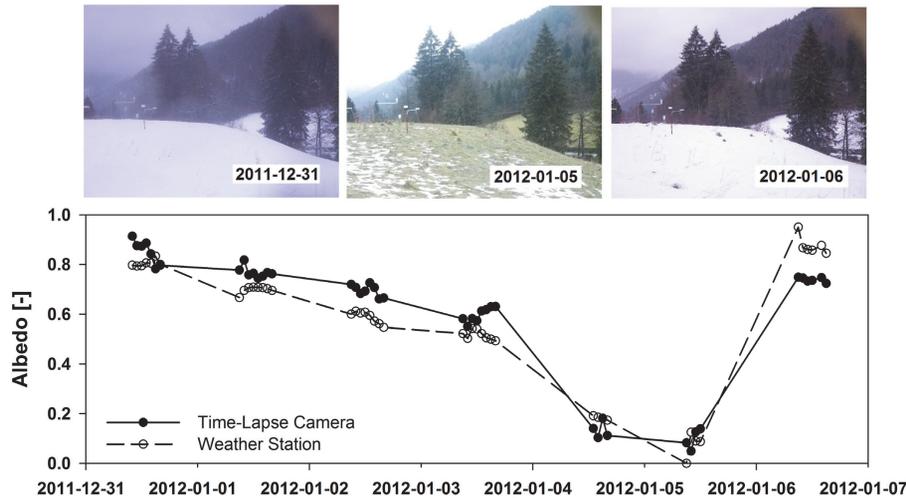
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**Fig. 11.** Comparison of calibrated albedo values derived from the image analysis compared to measured albedo values.

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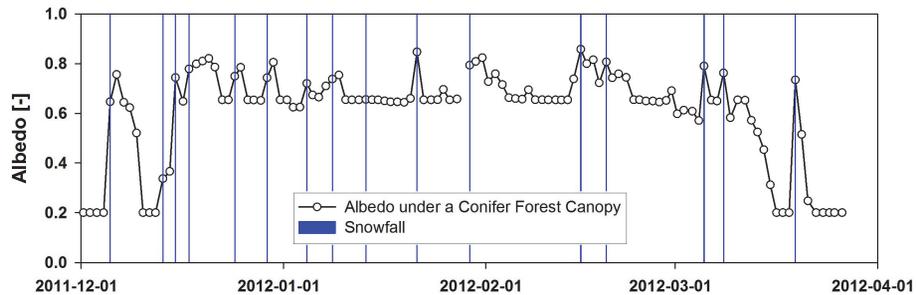
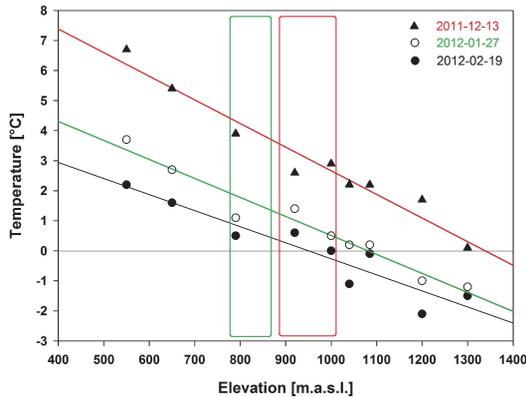


Fig. 12. Snow cover albedo under a conifer forest canopy during the winter 2011/2012.



**Fig. 13.** Temperature profiles for different precipitation events in the Brugga catchment. Time-lapse images could be used to determine the state of precipitation.

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