HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 3327–3337 (2012)
DOI: 10.1002/hyp.8389

Potential of time-lapse photography of snow for hydrological purposes at the small catchment scale

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Abstract:

Time-lapse photography provides an attractive source of information about snow cover characteristics, especially at the small catchment scale. The objective of this study was to design and test a monitoring system, which allows multi-resolution observations of snow cover characteristics. The main aim was to simultaneously investigate the spatio-temporal patterns of snow cover, snow depth and snowfall interception in the area very close to the camera, and the spatio-temporal patterns of snow cover in the far range. The multi-resolution design was tested at three sites in the eastern part of the Austrian Alps (Hochschwab-Rax region). Digital photographs were taken at hourly time steps between 6:00 and 18:00 in the period November, 2004 to December, 2006. The results showed that the time-lapse photography allows effective mapping of the snow depths at high temporal resolution in the region close to the digital camera at many snow stake locations. It is possible to process a large number of photos by using an automatic procedure for accurate snow depth readings. The digital photographs can also be used to infer the settling characteristics of the snow pack and snow interception during the day. Although it is not possible to directly estimate the snow interception mass, the photos may indeed give very useful information on the snow processes on and beneath the forest canopy. The main advantage of using time-lapse photography in the far range of the digital camera is to observe the spatio-temporal patterns of snow cover over different landscape configurations. The results illustrate that digital photographs can be very useful for parameterising processes such as sloughing on steep slopes, snow deposition in gullies and snow erosion on mountain ridges in a distributed snow model. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS time-lapse photography; snow; multi-resolution observations; small catchment scale

Received 13 May 2011; Accepted 12 October 2011

INTRODUCTION

Water stored as snow is an important component of the hydrological cycle in many regions around the world. Monitoring the accumulation and melt of snow provides detailed insight into the governing hydrological processes and valuable up-to-date information for water resources managers. Snow cover characteristics have traditionally been observed either at climate stations or by snow course campaigns at irregular intervals in space and time. These measurements are essential for many hydrologic applications (Holko *et al.*, 2011). However, because of the immense spatial variability of snow processes, it is difficult to collect snow data that are representative of the spatial distribution of snow (Blöschl, 1999).

An alternative to ground observations are remote sensing methods. These include global satellite monitoring, radar-based observations, aerial photography and laser scanning altimetry (e.g. Blyth and Painter, 1974, König and Sturm, 1998, Cline, 1993, Déry *et al.*, 2005, Trujillo *et al.*, 2009, among others). These techniques provide a large amount of spatially distributed information. However, there is a trade-off between the spatial and temporal resolution of remotely sensed data, costs and limitations of snow mapping algorithms due to vegetation, cloud obscuration and/or strong topographical variability (Parajka and Blöschl 2008; Parajka *et al.*, 2010).

At the small catchment scale, time-lapse photography is an attractive monitoring method. Originally, it has been a cinematography technique used to capture film frames at slower rates than they are replayed. Thus, the events appear to be lapsing faster than observed. The benefits of time-lapse photography have been investigated in several studies, covering different disciplines in geophysics. In atmospheric sciences, for example, Holle *et al.* (1979) studied cloudiness changes during the day using whole-sky cameras, mounted aboard four research ships and compared cloud cover to satellite and radar observations. In fluvial geomorphology, Dexter and Cluer (1999) used time-lapse photography to detect lateral erosion rates along the Colorado River. They showed that this technique was very successful in detecting rapid erosional events at the daily time scale. Blaschke *et al.* (2003) used video techniques to analyse stream–aquifer interactions caused by riverbed clogging in the Freudenau reservoir of the Danube at Vienna. Time-lapse photography helped them to identify different types and the variability of clogged layers and also allowed observations of macro-zoobenthos organism activities in the hyporheic zone.

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Table I. Examples of using time-lapse photography of snow

Author	Study objective	Time resolution	Camera
Tennyson *et al.* (1974)	The rate of snowfall accumulation and interception, Apache National Forest, Arizona, U.S.	5-min during day-light, 5 discrete snowfall events December–March 1972/73	Super-8-mm time-lapse camera with Kodachrome II film
Harrison *et al.* (1986)	Temporal and spatial patterns of glacier velocity change, Variegated Glacier, Alaska	1–2 times a day, summer period, 1979–81	10 automatic Olympus 35-mm cameras
Krimmel and Rasmussen (1986)	Determination of glacier velocity, Columbia Glacier, Alaska	3 times a day (8:00, 12:00, 16:00), 226 days in 1983	35 mm Hulcher camera (model 112)
Haefner and Laager (1988)	Map the transient snow line on glacier, Aletsch-Glacier, Switzerland	Daily images, May–October, 1985.	
Blöschl and Kirnbauer (1992)	Model testing and snow cover mapping, Längental catchment (9.4 km^2), Austria	14-day interval, April–July 1989	non-metric Hasselblad 500 C/M
Harrison *et al.* (1992)	Determination of glacier speed, West Fork Glacier, Alaska	Daily images, 1988	Off-shell 35-mm camera
Pomeroy *et al.* (1998)	Estimation of the fractal dimension of intercepted snow, Waskesiu Lake, central Canada	Daily images, three events of 5–10 days in 1995 and four events of 1–4 days in 1996	Logitech Fotoman digital camera
Bründl *et al.* (1999)	Interception estimation by analysis of branch motion during an event, Davos-Seehornwald, Switzerland	Image each 3.2 s., 3 events: k 9–14 April, 1994, 11–13 Jan., 1995, 25–27 Feb, 1995	
Aschenwald *et al.* (2001) and Tappeiner *et al.* (2001)	Mapping the number of days with snow, Passeier Valley (2 km^2), Italy	Daily images, 1997–1998	Pentax A-3 with Takumar 28–80 mm objective, with Kodak Elite Chrome 100 color slide films
Hinkler *et al.* (2002)	Snow cover mapping, Zackenbergdalen valley, Greenland	Daily images, 63 images during 1998–1999	Kodak DC50 digital camera
Matheussen and Thorolfsson (2003) and Matheussen (2004)	Snow cover mapping in urban areas, Risvollan catchment (20 ha), Norway	Daily images, March–April 2001	Digital AXIS 2120 Network Camera
Floyd and Weiler (2008)	Monitoring of the precipitation state (rain *vs.* snow) and the rate of snow accumulation, melt and interception, Russell Creek, Canada	~1–2 h (daytime), February 20 to March 12, 2007	Canon PowerShot A430
Schmidt *et al.* (2009)	Monitoring of snow cover disappearance on the meso-scale, Loetschental (SwissAlps)	Daily, ablation period 2003–2004	
Ahn and Box (2010)	Quantification of glacier velocity, West Greenland glaciers	Hourly interval (sunlit period), May–June 2007	10.2 megapixels Nikon D200 camera
Farinotti *et al.* (2010)	Validation of simple snow accumulation and melt model, Dammagletscher (9.1 km^2), Switzerland	Daily, May–September 2008	Olympus OM-2 N with Kodak Kodachrome ISO 64/19°

Time-lapse photography was also successfully applied in the past to map the spatial and temporal patterns of snow characteristics (Table 1). The summary in Table 1 indicates that its major applications include the determination of glacier velocity, mapping of daily/weekly snow cover changes over small regions and a detailed monitoring of snowfall interception processes (e.g. loading/unloading rates) during a few events on the scale of single trees or small stands.

The main objective of this study is to further investigate the potential and benefits of time-lapse photography of snow at the small catchment scale. The idea was to design and test a monitoring system, which allows multi-resolution observations of snow cover characteristics. In contrast to previous studies, our interest was to simultaneously investigate the spatio-temporal patterns of snow cover, snow depth and snowfall interception in the area very close to the camera, and the spatio-temporal patterns of snow cover in the far range.

METHODS

Time-lapse photography of snow

Time-lapse photography of snow has a number of advantages over alternative observation techniques. First, it is a non-destructive method, e.g. in comparison to snow courses. Second, the images are usually not obstructed by cloud cover, which is an advantage over optical remote sensing. Third, the temporal sampling is very attractive for hydrological applications, as it allows detailed diurnal monitoring of snow cover changes. Fourth, the spatial resolution is very high, particularly in regions close to the camera. In this paper, we describe the use of digital camera as a multi-resolution tool, where the foreground is monitored at very high spatial resolution and the background at a lower resolution.

In this study, two ranges of time-lapse photography were implemented. In the near range (100–300 m from the camera), snow cover patterns as well as snow depths and qualitative information about snowfall interception were monitored (Figure 1). In the far range (around 1000–2000 m from the camera), snow cover patterns were monitored over an area of about 2 km^2 (Figure 2). The advantage of described system is that both ranges are monitored by using only one single photograph.

Camera selection and calibration

The system for automatic time-lapse photography of snow requires a digital camera with high pixel resolution, industry PC with a hard disk and an interface to the camera, network interface for remote control and a case with heating. In this study, we used an off-the-shelf 3 megapixel (2048 × 1536) Canon A70 camera (Table 2), an industry PC (18 GB hard disk drive, Windows operating system) equipped with RS232 and USB interface, GSM and ISDN modem and TCPIP network card. A special software running on the industrial PC was used for remote control of the camera. This software provided setting of the time interval, several shooting parameters and the target directory on the hard drive for storing of the images. The system was installed in a specially air-conditioned compartment (steel housing with forced ventilation), heated and equipped with an electric fan (80 W). The camera was mounted in the front of the

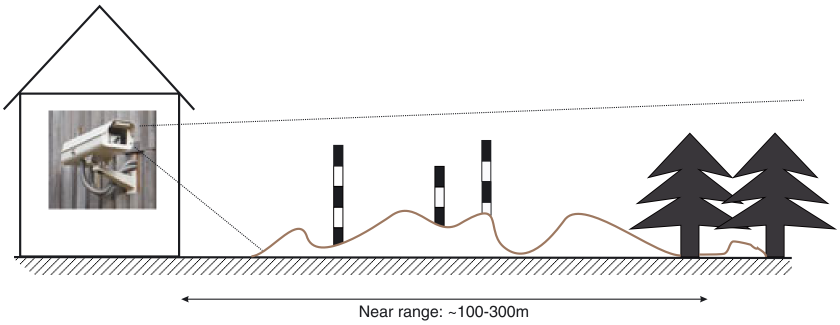

Figure 1. Monitoring of snow cover patterns, snow interception and readings of snow depth in the near distance range (Design 1)

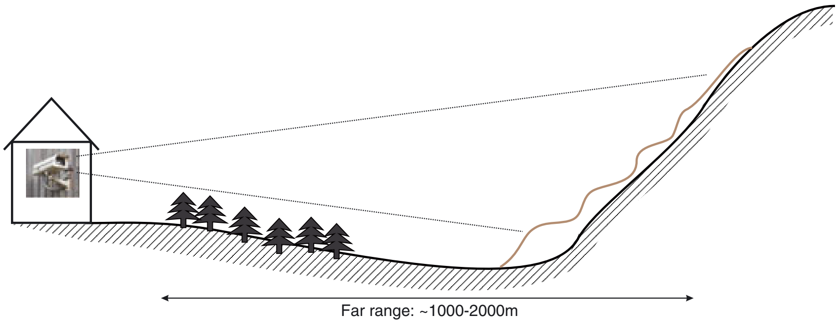

Figure 2. Monitoring of snow cover patterns in the far distance range (Design 2)

Table II. Canon camera specification

Model	Canon A70 camera
CCD effective pixels	3.2 million
CCD size	1/2.7" (5.3 x 4.0 mm)
CCD Colour Filter Array	G - R - G - B
Max resolution	2048 x 1536 (3.14 million)
Image ratio w:h	4:3
File format	JPEG (EXIF 2.2)
Zoom	35–105 mm
Lens Aperture	F2.8–F4.8
Autofocus type	5-point AiAF (auto area selection)
Normal Focus Range	46 cm to Infinity
Sensitivity equivalent	Auto, ISO 50/100/200/400
Exposure compensation	±2 EV (at 1/3 EV steps)
Storage	Compact Flash Type I
Battery	4 x AA

case and was protected from outside weather by a glass window (Figure 3).

Photogrammetric interpretation of the snow cover position in the far range requires the determination of the internal geometry of the digital camera (camera calibration). The calibration, i.e. the reconstruction of the perspective imaging process, consisted of the determination of the principal distance, the location of the principle point on the sensor plate and the lens distortion. In addition, in order to position the camera at the right place with respect to the object, the exterior orientation had to be calculated, i.e. the three-dimensional coordinates of the projection centre and the viewing direction. The calibration was carried out with the help of a calibration test field in the court yard of the Vienna University of Technology, consisting of retro-reflecting targets (Figure 4). All cameras were focused to infinite, and zoom setting was fixed to wide angle. The achieved accuracy of the principal distance was about ±4 μm (equivalent to a mapping accuracy of some 0.7 m at a distance of 1 km). The achieved accuracy of the principal point was about ±0.7 pixels. Since the calibration values will be valid only for the aforementioned camera settings, they must not be changed during the acquisition period.

In order to determine the position and viewing direction of the cameras (i.e. the exterior orientation), several GPS control objects were measured in the eventual field of view of the cameras. The achieved accuracy of the exterior orientation turned out to be rather low due to the poor definition of the control objects in the image. Still, the values could serve as a first approximation so that in a later stage with the help of the digital terrain model and the superimposed model-derived snow patterns, a virtual image can be generated, whose perspective geometry comes very close to that of the real image. By geometrically matching these two images the shortcomings of the poor quality of the exterior orientation can be eliminated to a great extent, especially in the far ranges. Remaining mapping errors are influenced by the accuracy of the digital terrain model rather than by the low accuracy of the exterior orientation.

Figure 3. Camera CANON Powershot A70 camera (left) and its implementation inside the outdoor case (right)

Figure 4. Part of the calibration test field with retro-reflecting targets mounted on the wall of the I.P.F building of the Vienna University of Technology

TEST SITE

The study was performed in the Hochschwab-Rax region situated in the eastern part of the Austrian Alps, approximately 100 km south-west from Vienna. Many of the fresh water springs for the Vienna water supply system are located in this region, thus snow cover provides a very important natural source of water storage. The selection of monitoring locations within the region was based on the following criteria: (1) the camera view should capture a representative landscape configuration in the study region, (2) no obstruction by trees in the near range of the camera, (3) power supply should be available, (4) the slope in the far range of the image should, ideally, be perpendicularly to the line of sight of the camera. Based on these criteria, three sites were selected: the Edelbodenalm, Waxriegelhaus and Damböckhaus sites (Figure 5). These were used to observe the spatial and temporal patterns of snow characteristics at hourly time step between 6:00 and 18:00 in the period November, 2004 to December, 2006. At all three sites, a multi-resolution design was chosen that allows snow monitoring both in the near range and the far range. At the Edelbodenalm, additionally, five graduated snow stakes were positioned on an open meadow in front of the camera (see Figure 6). Initially, each of them had a height between 1.45 and 1.50 m, but one stake was extended to 3.35 m on January, 26, 2005 because of the high snow depths in that winter. The snow stakes were painted black and yellow at 10-cm intervals. The viewing areas of the cameras at the Edelbodenalm, Waxriegelhaus and Damböckhaus sites are approximately 3.3, 0.5 and 1.1 km², respectively (Figure 5).

RESULTS

Monitoring of snow characteristics close to the camera

As a first analysis step, the photographs at the Edelbodenalm site were used to read off the snow depths from the snow stakes. Because of the large number of photos, an automatic procedure was developed based on image processing. The routine first checks each image for its usability. Photographs before sunrise and after sunset with insufficient exposure were discarded. For each of the stakes, a frame was defined manually. As the position of the photos varied little between the shots, the same frames could be used for all the photos. The routine then counts the number of visible black and yellow blocks from the top of the snow stakes which gives the snow

Figure 5. Positions and views of the digital cameras at the three sites: Edelbodenalm (top), Waxriegelhaus (middle) and Damböckhaus (bottom panels)

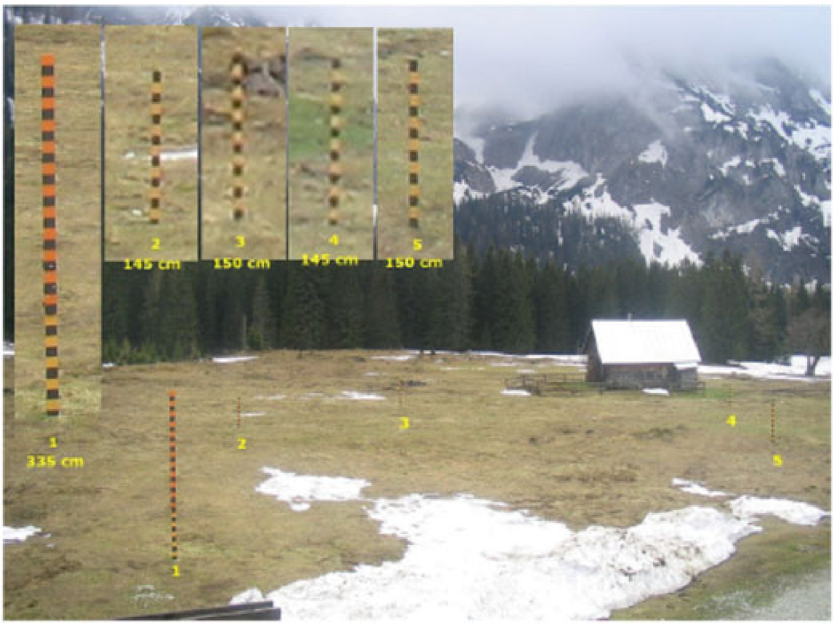

Figure 6. Five graduated snow stakes installed at the Edelbodenalm site. Digital photograph from November 2004

depth. Problems may occur during fog and precipitation when the images are not clear. The accuracy may also be affected by melt around the stake (due to radiation from the stake) as is always the case with snow stakes. As there was a small number of misreading, a robust estimate of the snow depth in the near range was obtained by omitting the largest and smallest readings. As can be seen from Figure 7, the readings nicely trace the evolution of the snow pack. Also, the readings give an indication of the spatial variability of the snow depth with the test field which was about 10–20 cm during snow accumulation and 20–40 cm during snowmelt. The advantage of using the digital photographs is that it is straightforward to check the accuracy of the automated procedure. Inaccuracies mostly occurred during reduced visibility conditions, i.e. in the early morning, late afternoon and during snowfall events. Overall, however, the comparisons suggest that the accuracy of the automatic readings was very similar to the manual readings from the photographs. The measurement setup and analyses can be easily extended to a larger number of stakes to provide more detailed information on the spatial patterns of snow depths in the near field area.

The digital photographs can also be used to infer the settling characteristics of the snow pack during the day. As an example, Figure 8 shows the settling characteristics of the snow pack at the Edelbodenalm site on 8 March, 2006. There were approximately 20 cm of new snow the day before. During 8 March, the air temperatures varied between -5 and $-12\,^{\circ}$C. The photographs indicate that the snow pack settled by more than 10 cm within 12 h. Settling was largest in the early afternoon. Snow settling rate is used by different snow models to describe the snow depth evolution (see, e.g. Brun *et al.*, 1989, Brown *et al.*, 2003), thus its monitoring is very useful for snow model parameterisation or validation.

Another interesting piece of information that can be inferred from the time-lapse photography is snow interception. Although it is not possible to estimate the snow interception mass, the photos may indeed be a very useful indication of the snow processes on and beneath the forest canopy. Most importantly, they can be used to assess whether snow is intercepted in the canopy or not, at any point in time. As an example, Figure 9 presents the evaluation of a simple interception model (Hedstrom and Pomeroy, 1998) by time-lapse photography for the Edelbodenalm site. The model parameters were chosen according to Hedstrom and Pomeroy (1998), and the model was driven by meteorological data near the Edelbodenalm site. The zoom-in to the forest area in the centre of the images allows us to identify the temporal dynamics of snow interception. On 6 November, the canopies were snow free. There was about 10 mm of snowfall on 7 November which led to about 6 mm of snow storage at the end of the day according to the model. There was additional snow-fall on 8 November and 9 November. The increase in canopy snow storage during this three-day period can be clearly seen in the photos. Because of the temperature increase on 10 November, no snow was left in the canopy on 11 November in the morning. This is fully consistent with the photos. While the information on snow interception is qualitative, it is considered very useful for parameterising and validating snow interception models, particularly if one is interested in the spatial variability of snow interception in an area.

Monitoring of snow cover patterns in the far range

The main purpose of using time-lapse photography in the far range of the digital camera is to observe the spatio-temporal patterns of snow cover over different landscape configurations. Such information can be very useful for

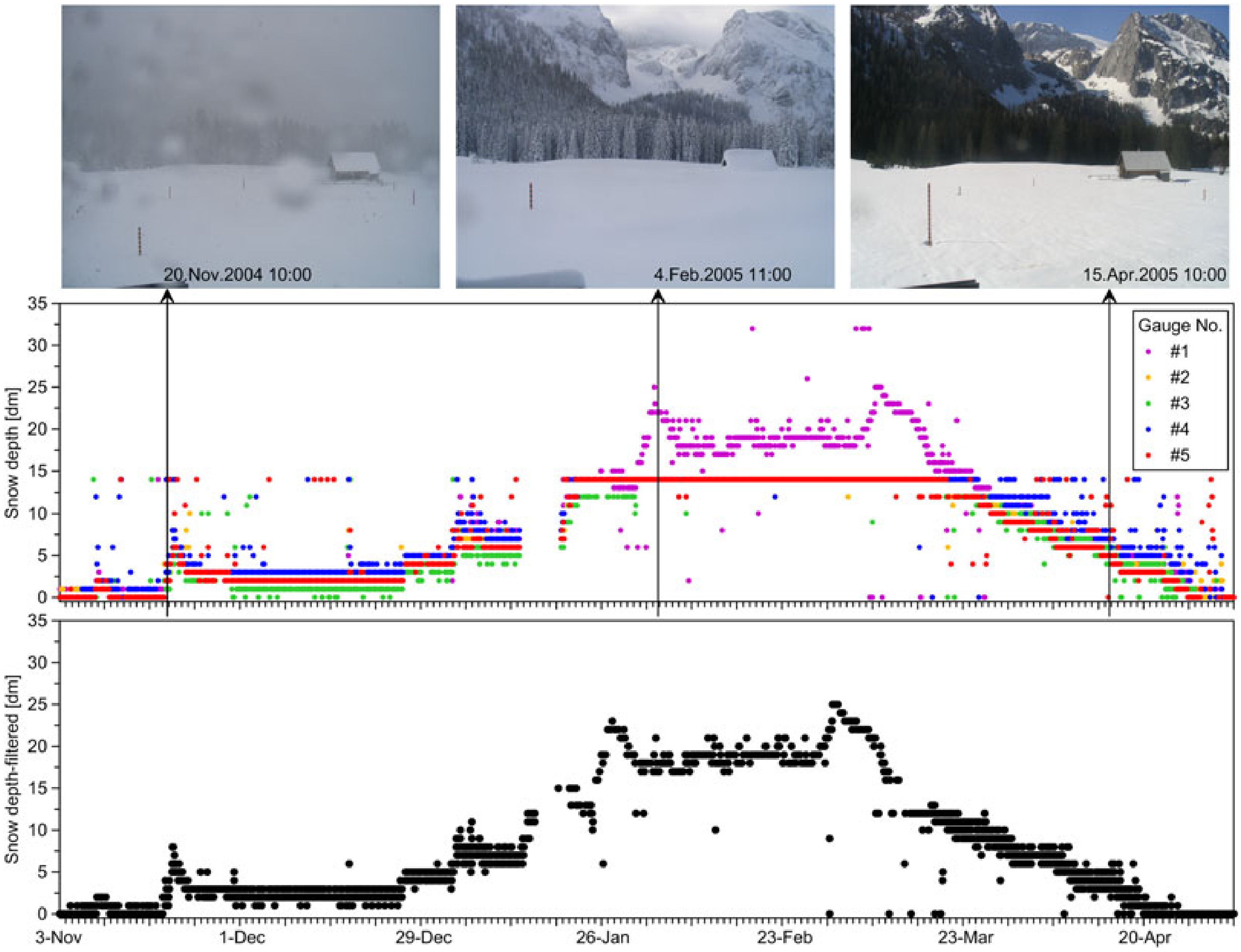

Figure 7. Snow depth (in decimetres) observed at five stakes in the period 3 November 2004 – 4 May, 2005. Snow depth was extracted from digital photographs using an automatic procedure. Middle and bottom panels show snow depth in the near range obtained from all and by omitting the largest and smallest readings, respectively

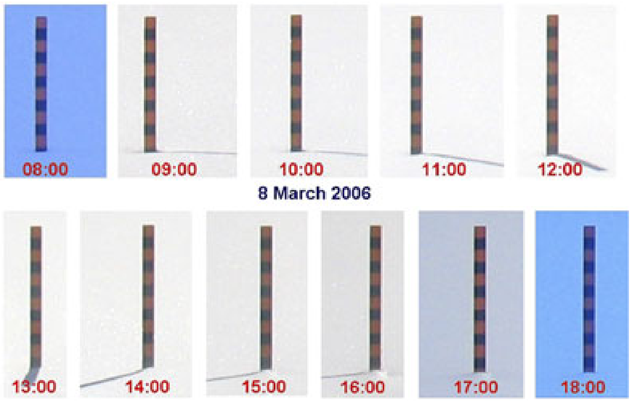

Figure 8. Illustration of snow cover settling. Hourly photos of snow stake #1 (Fig.6) at the Edelbodenalm site on 8 March 2006

parameterising processes such as sloughing on steep slopes, snow deposition in gullies and snow erosion on mountain ridges in a distributed snow model (Blöschl *et al*., 1991a, 1991b). The patterns can be similarly useful for validating these snow models for an independent observation period. Figure 10 shows an example of comparisons of the time-lapse photography with simulations of a distributed snow model for the Edelbodenalm, Waxriegelhaus and Damböckhaus sites. The snow model simulates snow interception in the canopy (Hedstrom and Pomeroy, 1998), snow accumulation and melt on the ground based on the energy balance approach (Blöschl and Kirnbauer, 1991) as well as snow redistribution by gravity and wind drift based on an index approach (Blöschl *et al*., 1991a, 1991b). The model was driven by meteorological data near the observation sites. In order to effectively evaluate the terrain effects on snow cover patterns, the snow model simulations were draped over

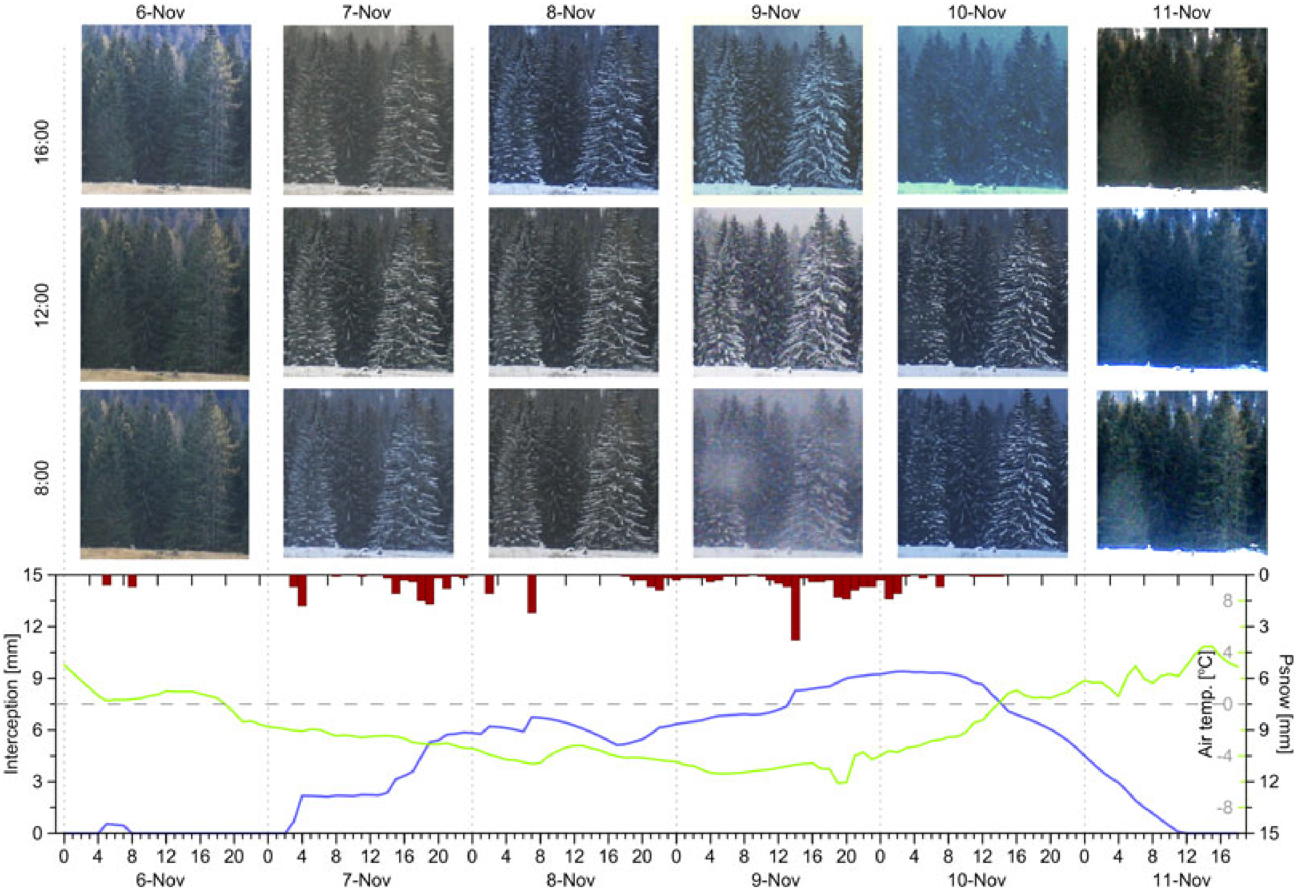

Figure 9. Snow interception as observed by time-lapse photography and snow interception simulated by a simple interception model (blue line) at the Edelbodenalm site during 6-11 November, 2004. Air temperature (green line) and precipitation (red bars) are shown for comparison

the digital elevation model and plotted as perspective views using the SCOP software (I.P.F, 2007). Two colour scales were used (Figure 10). The first one is applied in forested areas, visualises snow interception and ranges from dark green (no snow storage) to yellow (12-mm snow storage). The second scale is used for open areas, visualises the snow water equivalent and ranges from brown (no snow) to white (80-mm snow water equivalent) and turquoise blue (500-mm snow water equivalent).

Figure 10 shows that the model simulations are consistent with the patterns visible on the digital photographs. Using time-lapse photography allowed us to compare the snow cover dynamics during the snowmelt season (i.e. patchy snow cover patterns), snow interception over the forest canopy and the snow cover dynamics on the steep rock slopes, mountain ridges and in the valleys. Importantly, the differences between the simulated and observed patterns allowed us to pinpoint deficiencies of the individual model components in a spatially distributed way. The snow drift component of the model relates the falling snow at any time step to topographic features (terrain curvature and slope) by the empirical parameters. These depend on the snow characteristics, the wind field and the terrain roughness and have been determined in Blöschl *et al.* (1991a) by calibration against snow pattern data in a different catchment. The comparisons such as those in Figure 10 allowed us to test the snow drift module for this catchment and indicated that the parameters slightly differ from those found in Längental, Tirol (Blöschl *et al.*, 1991a). These differences were likely due to different terrain model resolution and also consistency of the falling snow.

The resolution of the photographs mapped back to the landscape characteristics obviously depends on the distance of the camera and the slope of the terrain relative to the image rays. For the Edelbodenalm site (Figure 10, top), the areas in the far range are at a distance of about 2.3 km. This corresponds to horizontal and vertical resolutions in the real landscape of about 1 and 2 m, respectively. This is much smaller than the pixel size of the model of 50 m. At the Waxriegelhaus site (Figure10, middle), the distance of the far range is about 1 km with the associated horizontal and vertical resolutions of 0.5 and 1 m, respectively. At the Damböckhaus (Figure10, bottom), the far range is at a distance of 2 km, and horizontal and vertical resolutions do not exceed 0.6 and 5 m, respectively. In the case of Damböckhaus, the image rays in the far range are quite flat relative to the terrain, so the resolution becomes gradually poorer as one approaches the horizon. It would be possible to classify the snow patterns in the photographs and map them back into the landscape as was done in Blöschl and Kirnbauer (1991), which allows a direct comparison with the model. However, this was beyond the scope of this study.

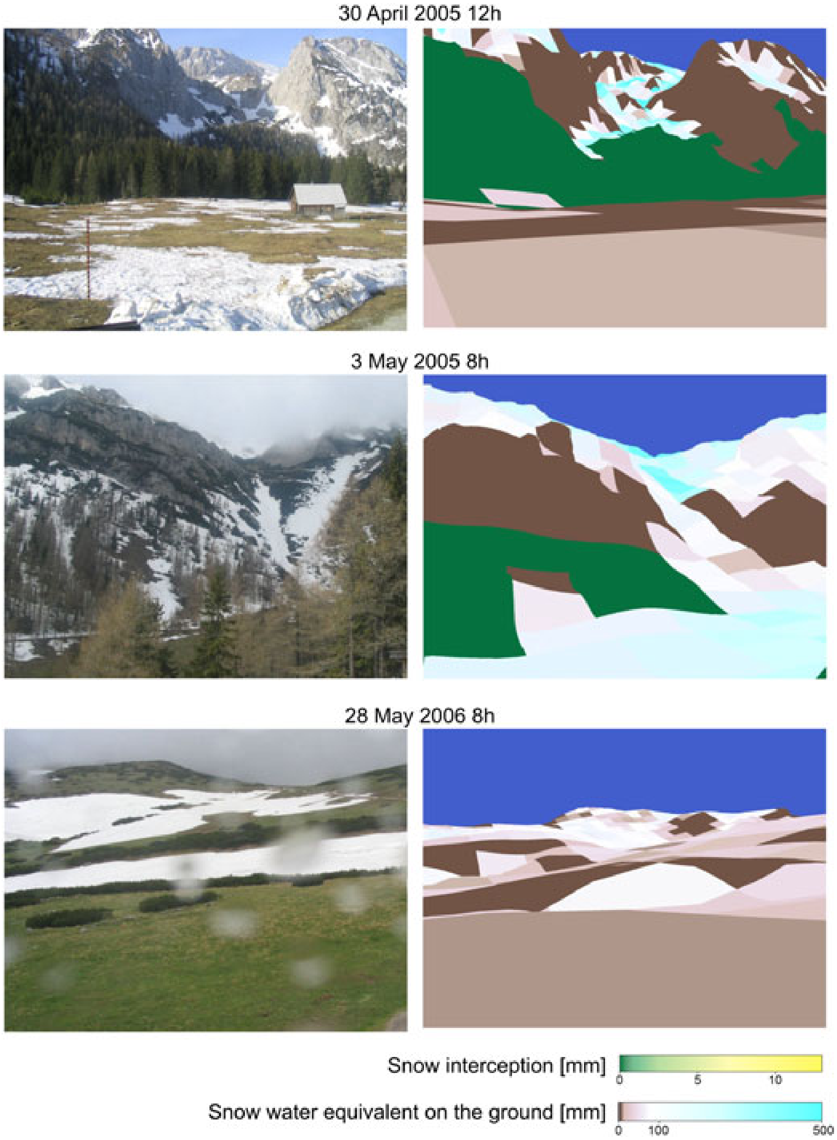

Figure 10. Comparison of time-lapse photographs at the Edelbodenalm (top), Waxriegelhaus (middle) and Damböckhaus (bottom panels) with the distributed snow simulations. Legends at the bottom show the amount of snow on the ground and in the forest canopy, respectively

DISCUSSION AND LESSONS LEARNED

Overall approach and setup: This study illustrated that the multi-resolution approach to time time-lapse photography is indeed a very effective method of mapping snow for hydrological purposes. It has clear advantages over a single resolution setup in that it provides snow information at two different scales. In the near range, it provides information on the snow depths, while in the far range, it provides information on the spatial snow cover patterns.

Near range: We positioned five graduated snow stakes in the near range of the Edelbodenalm site. In the first season, we underestimated the maximum snow depths to be expected so had to extend the stakes in the second season. The 10-cm graduation on the stakes and yellow-black contrasting colours proved to be clearly discernible in the photographs. The camera resolution was just sufficient to resolve the stripe pattern of the graduation of the most distant stakes. The snow depths were therefore digitised by counting the stripe intervals (i.e. in units of dm) for all stakes, although for the close ones, the resolution of the snow depths could have been increased to a few centimetres. The camera used had a resolution of 3 megapixels. If we had to repeat the study today, we would probably chose a camera with a resolution of 10 megapixel or higher which would allow us to resolve the snow depths at all stakes to about 2 cm. Also, in hindsight, increasing the number of snow stakes would be a small extra effort and allow a better spatial coverage of the near range.

The canopy interception inferred from the photos in the near range proved to be very useful. Although we did not test the interception information in a quantitative way against mass measurements, we used it to constrain the parameters of a simple canopy interception model. The photo also allows to visually assess the plausibility of the snow model in terms of simulating the state of precipitation.

Far range: We observed the snow patterns in the far range at three sites which was at a distance of about 2 km from the camera. At this distance, the camera resolution did not limit the snow cover information. The pixel size mapped back to the landscape was about 1 m. Although, one would select a higher resolution camera today, this will not affect significantly the information in the far range. However, it is essential that the angle between the image rays and the terrain is not too flat. At one of the sites (the Damböckhaus), this was the case, and the information in the most distant part of the viewing area could not be used. The snow patterns of the photo could be directly mapped back to the landscape (Blöschl and Kirnbauer, 1992), but this was not pursued in this study. In this case, the mapping accuracy will depend on the accuracy of the digital terrain model and the intersection angle of the terrain and the image rays. The viewing direction of the camera could not be determined effectively by the available GPS ground control measurements. Therefore, for each camera, the horizon and structural terrain elements of a virtual perspective, calculated from the viewing direction and the terrain model, were matched with the shape of the horizon and the respective structural terrain elements on the photograph. By this relative matching, the effects of existing inaccuracies of the viewing direction could be reduced so that they did not affect the mapping accuracy. However, more accurate results would be achieved by more extensive GPS ground control measurements.

Site selection: Selecting the site has two main challenges. The first is to obtain representative views of the catchment of interest and with steep slopes where the angle between the image rays and the terrain is not too flat. For two of the sites (Edelbodenalm, Waxriegelhaus), this worked well in this study. For the Damböckhaus, the angles were flat, so part of the photos could not be used for interpreting the snow cover patterns. Clearly, prudent selection of the sites based on a field knowledge of the catchment and the snow distribution is essential. The second challenge is related to power supply. Power supply is often very limited in alpine regions, but essential for heating the protective case and for capturing and transferring the images. As was discussed in Floyd and Weiler (2008), during very humid conditions, condensation and frost tend to build up on the outside of the digital camera, which reduces the availability and quality of the images. In our study, we selected all three sites where grid power was available. The 80-W heater and fan worked very well. There were only a few images affected by thawed snowflakes or frost on the glass of the protective case. Conditions with reduced visibility did occur during heavy snowfall and fog, and in the early or late hours of the days. However, it was relatively easy to filter these images out. At the Damböckhaus site, there were power blackouts causing the loss of data in the 2004/2005 winter season. An alternative to connecting the camera and casing to the power grid would be a battery setup supported by solar panels and/or a wind turbine. Importantly, this would give more flexibility in site selection. This option was considered at the beginning of this project, however, for cost reasons, sites with power grid supply were preferred. As electronic equipment gets less expensive, stand alone systems for snow cover monitoring based on time-lapse photography may become more attractive. Future systems may be smaller and therefore require less heating energy. Also, protective gas systems may avoid inside fogging of the glass. However, it remains to be seen whether stand alone systems are more reliable and cost effective than systems connected to the power grid.

Applications: The multi-resolution approach allowed us to acquire both snow depth information in the near range and snow cover patterns in the far range. We used this information to set up and validate a spatio-temporal snow simulation model. While, often, only point data of snow characteristics are available, e.g. through snow courses, the patterns provided additional spatial information which helped us assess the snow redistribution module of the simulation model. The snow pattern observations over different seasons will allow to determine also the temporal stability of snow cover patterns, which is perfectly in line with recent investigations on how to compare physically based snow models across different catchments (Sturm and Wagner, 2010). As compared to daily photographs that are sometimes used, the hourly sampling provided additional, very useful information about the snow settling, snow drift and snow interception dynamics.

ACKNOWLEDGEMENTS

We would like to thank the Vienna Waterworks (Municipal Department 31) for financial support and Gerhard Kuschnig for his excellent collaboration at various stages of the project. We would also like to thank the ÖAW project "Predictability of Runoff in a Changing Environment" for financial support.

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