An analysis of snow cover patterns as derived from oblique aerial photographs

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ABSTRACT Snow cover patterns in a 9.4 km² basin in the Austrian Alps were examined during the 1989 ablation period. Nine aerial surveys were conducted at intervals of about two weeks. The oblique aerial photographs were printed and snow boundary lines were identified. The metric restitution of the images was performed by digital monoplotting, making use of a digital terrain model with 25 m grid spacing. The depletion process is documented and snow cover is analyzed as a function of elevation, slope and aspect. The snow cover is found to be better related to elevation and slope during winter conditions than during the late ablation period. Differences in snow cover associated with aspect are more pronounced later in the year.

INTRODUCTION

Evaluation of distributed hydrological models has received considerable attention in the literature (e.g. Loague & Freeze, 1985; Obled, 1990; Moore & Grayson, 1991). It is evident that distributed snowmelt models require distributed snow cover data to form the basis of model calibration and evaluation. Runoff observations at the outlet of a catchment alone are clearly not adequate for the assessment of model performance because the numerous components of the snowmelt-runoff-process cannot be disentangled from observations of their collective effect (Blöschl et al., 1991b).

Recently, Leavesley and Stannard (1990) reported on verifying a distributed snowmelt model by comparing the spatial and temporal variations of simulated and measured snow covered areas. The latter data were derived from satellite measurements. In alpine terrain, however, satellite data do not meet the requirements for modelling with respect to resolution in space and time (Rott, 1987). Snow cover mapping on the basis of terrestrial photogrammetry (e.g. Rychetnik, 1984) is particularly suited for small scale investigations and requires the position of the camera to be accessible and free of avalanche hazard.

In this paper the technique of mapping snow cover patterns from oblique aerial photographs is described. Snow cover patterns are analyzed statistically and by visual inspection, and relations between snow cover and terrain features are examined. An application of these patterns for evaluating a distributed snowmelt model is reported in Blöschl et al. (1991a).

STUDY SITE AND PERIOD

The study was conducted in the Längental catchment near Kühtai, Tirol at 47° 12'N,
11°E in the Austrian Alps (for a map see Fig. 1 in Blöschl et al., 1991a, this volume). The basin is 9.4 km$^2$ in area and elevations range from 1900 to 3050 m a.s.l.

The topography is typical of crystalline bedrock (gneiss and micaschist) formed by glaciers as an U-shaped valley with whaleback-forms and partly covered by glacial sediments. The lower part of the valley consists of slopes, partly covered by talus-fans with inclinations of 30-40° (Blöschl & Kirnbauer, 1991). The valley head faces east, and three prominent cirques form the southeast corner of the basin.

Nearly the whole catchment lies above the timber line. Vegetation is characterized by a few cembra-pines and larches, by Alpine roses and by Alpine meadows in the flat areas. Fig. 1 gives an impression of the ruggedness of the terrain. This aerial photograph was taken on 4 May 1989 and shows the east-facing slope in the middle of the Längental.

Despite the lower-than-normal winter precipitation the depletion period in 1989 lasted from late April until late July. This was a consequence of frequent snowfalls throughout spring and temperatures well below the long-term seasonal average.

FIG. 1 Aerial photograph of the east-facing slopes and the valley floor of the central part of the Längental, 4 May 1989. By permission of BMLV, 13088/502-1.6/89.
MAPPING OF SNOW COVER PATTERNS

During spring and early summer of 1989 nine aerial surveys were conducted at intervals of about two weeks depending on weather conditions. Due to the rugged topography of the Längental there is no single camera position covering the entire basin. Therefore, each survey consisted of nine photographs. For ease of interpretation a fixed flying route at an altitude of 3500 m a.s.l. was adhered to. The camera was a non-metric Hasselblad 500 C/M, the interior orientation of which was determined by off-line calibration.

All photographs were printed, the boundary lines of snow cover were identified and marked manually. Manual identification was preferred to an automatic procedure because of the potential inaccuracies of the latter method (Good & Martinec, 1987). Under the specific weather conditions of spring 1989, these inaccuracies were deemed to be large. Varying lighting conditions would have impeded assigning fixed grey levels to snow covered or snow free areas and caused misclassifications. Moreover, manual identification allows to discriminate areas covered with a shallow layer of new snow from deep winter packs.

Ground control points were taken from 1 : 40 000 topographic aerial photography. Subsequently, ground control and tie points were identified on the oblique photographs. Together with their coordinates they formed the basis for bundle triangulation (Kager, 1980), which allowed to determine the exterior orientation elements for all camera positions.

The boundary lines of snow covered patches were digitized counterclockwise. The transformation of these lines from the photographs to the map scale was made on the basis of digital monoplotting (Waldhäuser et al., 1986; Hochstöger, 1989). In this method, the image-rays from the camera to the snow cover boundary lines are intersected point by point with a digital terrain model (DTM) to find the XYZ-coordinates of the snow lines (Fig. 2). The inaccuracies of the monoplotting technology due to intersection angle and DTM spacings were estimated to be in the order of 5 m thus being negligible for the purposes of this study. In the map scale individual pictures derived from single photographs were linked in a graphic

![Diagram](image)

FIG. 2 As soon as the centre of projection (PRC) in the coordinate system of the digital terrain model (DTM) and the orientation of the bundle of rays are known, any ray \( S' \rightarrow PRC \) can be intersected with the terrain (\( S \)) (Waldhäuser et al., 1986).
Fig. 3 shows a map view of snow boundaries in the Längental basin on 4 May 1989. These vector data were rasterized to yield 25 x 25 m square ground elements matching the grid of the digital terrain model. An element should be classified as snow covered if more than 50% of its area were snow covered. This was accomplished by first overlying the vector data by a 5 x 5 m grid. Each of these elements was classified according to the relative position of its centres to the boundary lines. A final ground element, consisting of 25 elements of the finer mesh type, was deemed to be snow covered if it contained 13 or more snow covered elements.

FIG. 3 Map of snow boundaries (thin lines) 4 May 1989. The coverage of the aerial photograph (Fig. 1) is marked by thick lines (redrawn from Hochstöger, 1989).
RESULTS OF SNOW COVER ANALYSIS

In Fig. 4 the map views of the snow cover patterns for the nine surveys during the ablation period are presented. Fig. 4 indicates that the maximum extent of the snow cover (86%) occurred on 4 May 1989. Even on this day a relatively large portion of the steep east-facing slopes on the left hand side of the Längental remained bare. Another prominent feature remained constant throughout the ablation period: ridges, especially those between the cirques in the south-east of the catchment, were generally bare, whereas in the cirques themselves the snow cover did not disappear until late July.

A statistical analysis of the snow cover may be used for quantifying the impressions gained from visual inspection and a-priori-knowledge. Fig. 5

FIG. 4 Snow cover patterns as mapped from nine surveys from March to July 1989. White areas are snow covered, black areas are bare.
summarizes results of such an analysis performed for 20 March and 5 July, 1989. The late winter distribution of snow (20 March, Fig. 5a,b) is characterized by nearly 100% snow cover on areas inclined less than 35°, irrespective of aspect or elevation. West and east-facing slopes exhibit a similar decrease in snow cover above that limit. North and south-facing slopes, however, show a slight asymmetry, particularly in the lower portion of the basin: the former ones are completely covered up to an inclination of about 30°, whereas the percentage of snow cover of the latter ones sharply decreases from 20° on. Slopes steeper than 60° were virtually never snow covered.

On 5 July (Fig. 5c,d) there were significant differences between areas below and above 2400 m a.s.l. The lower portion of the basin was nearly bare whereas the upper part was heavily snow covered. Again, west and east-facing slopes yield similar results whereas south-facing slopes were significantly less snow covered than north-facing slopes. These differences in aspect are more pronounced than those on 20 March and apply to both the lower and the upper portion of the basin.

In Fig. 6 the joint distribution of snow cover as a function of slope and elevation is presented for 4 May and 5 July. Fig. 6a shows an example of late winter conditions. During this survey the snow cover appears to be closely related to terrain features. This relation is represented by a snow cover near unity at elevations lower than 2700 m and inclined less than 35° and an abrupt decrease above these limits. Fig. 6b gives an example of the late ablation period. As expected from Fig. 5c,d, the snow cover increased with increasing elevation and decreasing slope. However, the relationship to terrain parameters is less
pronounced than during late winter conditions.

DISCUSSION

It may be stated that steep slopes are generally snow free in the Längental catchment. Obviously, this may be attributed to sloughing, avalanching and the combined effect of gravitation and wind. Differences in snow cover on slopes of different aspects may be easily interpreted: during late winter conditions snow distribution was basically controlled by accumulation. Only on the south facing slopes in the lower portion of the basin some melt had occurred reducing the snow covered area slightly. This may be explained by the combined effects of short wave radiation and turbulent heat fluxes which, in lower elevations led to melting shallow layers of new snow adhering to steep rocks. The cumulative effect of short wave radiation during the ablation period clearly becomes more important in July producing strikingly contrasting patterns on north and south-facing slopes. Many authors have reported on this effect (e.g. Buttle & McDonnell, 1987; Elder et al., 1989).

Similarly as with steep slopes, areas at high elevations were generally snow free. This is probably due to the enhanced exposure to wind compared to lower elevations.

In contrast to the winter conditions, a weak relationship of snow cover to terrain features was found for the ablation period. This may be due to both variations in snow depths and the cumulative effects of melting and redistribution processes (Blöschl & Kirnbauer, 1991). Similarly, Rychetnik (1987) only explained a small portion of the spatial variations in the date of disappearance of the snow cover by terrain features. He found maximum seasonal snow depths to be a better index. For a small lower alpine catchment Meier & Schädler (1979) found variations in global radiation to control depletion patterns.
CONCLUSIONS

The use of a non-metric medium format camera for periodical aerial photography together with expert photogrammetric bundle adjustment, DTM-data base and monoplotting technology proved to be an economic alternative to classical terrestrial or aerial photogrammetry. Snow cover patterns mapped by these methods were found to be quite complex. However, some basic structures remained constant during the ablation period due to topographic effects. During winter conditions the snow cover is found to be closely related to terrain features. This relation is represented by a snow cover near unity at elevations lower than 2700 m and slopes inclined less than 35° and an abrupt decrease above these limits being a consequence of redistribution processes. During the early summer the cumulative effect of melting becomes more dominant. This results in a less pronounced relation of snow cover to terrain features and in significantly less snow cover on south facing slopes. Though attempts at correlating snow cover and terrain features appear to be encouraging it is important to realize that terrain features do not influence snow cover per se. They provide no more than a means for indexing the highly complex redistribution and snowmelt processes. This fact will limit the accuracy of predicting the snow cover distribution.

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REFERENCES

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