

## **The Influence of Uncertainty in Air Temperature and Albedo on Snowmelt**

**G. Blöschl**

Institut für Hydraulik, Gewässerkunde und Wasserwirtschaft,  
Technische Universität Wien

Extrapolating meteorological data to the basin scale represents a major problem of spatial snowmelt modelling in alpine terrain. Within this study errors in air temperature introduced by regionalization are analyzed for the Sellrain region in the Austrian Alps. Albedo is simulated using a range of model parameters representing different snow cover conditions. The influence on snowmelt is assessed by simulating water equivalent at the site scale using estimated air temperatures and albedoes. Simulation results indicate that a bias in measured temperatures as produced by local effects may be significantly more important than interpolation errors. Uncertainty in albedo appears to affect snowmelt to a higher degree than air temperature.

### **Introduction**

Accounting for areal variations of meteorological variables represents a major problem of distributed snowmelt modelling in rugged terrain (Lang 1986; Leavesley 1989). The approach to extrapolating point values to the basin scale may be even more important than the selection of hydrological models (Charbonneau *et al.* 1981). In the literature air temperature and albedo generally have been identified to be the most crucial variables for estimating snowmelt (Zuzel and Cox 1975; Lang 1981; Blöschl *et al.* 1988). Some authors emphasize the importance of air temperature, whereas others find albedo to be more significant. Clearly, this discrepancy derives from differences in climate. Advection melt situations early in the season are typical of lowlands (Moore and Owens 1984b; Bauwens 1988). In alpine regions, however, melt is most intense in early summer when solar radiation

reaches a maximum and the reflectivity of snow is low (Obled and Harder 1979).

Little work has been devoted to the accuracy of spatial estimates of air temperature and albedo and its implications on melt. Anderson (1973a) presented interpolation algorithms for air temperature as a function of elevation and distance, and found root mean square errors ranging from 1.2 to 4.7K. Anderson noted that the thermal gradient up the side of a mountain may significantly differ from the lapse rate in the free atmosphere. Charbonneau *et al.* (1981) correlated maximum and minimum daily air temperatures with elevation and found a best fit of data in May. Charbonneau *et al.* showed that inaccurate air temperatures may have a critical effect on simulations when discriminating rain from snow. Jensen (1989) applied Kriging techniques to hourly air temperature readings and analyzed residuals as related to weather situations.

Figures of the range of albedo in a 20 km<sup>2</sup> alpine basin were presented by Anderson (1973b). Anderson pointed out that the spatial variability of albedo increases as the season progresses being in the order of magnitude of 0.6 to 0.8 in the late ablation period. Based on a sensitivity analysis in a high relief catchment Blöschl *et al.* (1990) investigated the influence of albedo on snowmelt averaged over the whole basin. A reduction in albedo from 0.75 to 0.65 was found to yield an average increase in melt of 30 % over a six-day period.

The objective of this study is to analyze the effect on point snowmelt simulations of uncertainty introduced by regionalizing air temperature and albedo.

## Methods

### Area and Instrumentation

The Sellrain region in the Stubai Alps, Austria (Fig. 1) is characterized by a high relief and complex topography. Elevations range from 600 m (Inn valley) to about 3,500 m a.s.l.. Precipitation rates are low (*e.g.* 1,100 mm/yr at Kühtai, 1,930 m a.s.l.) and the snow cover period typically lasts from November until mid-May (Kuhn and Pellet 1989). Stations used in the analysis are shown in Fig. 1. Air temperatures were measured as listed below: Horlachbach and Finstertal: ventilated resistance probes; Niederthai, St. Sigmund and Kühtai: unventilated resistors shielded by ÖNORM standard screens (ÖNORM 1988); Innsbruck: ventilated NTC resistor (Mohnl and Rudel 1984). At Innsbruck hourly readings were used, whereas for the other stations mean hourly values were available. Wind speeds were derived from wind travel readings three times per day at St. Sigmund. At Kühtai a more comprehensive set of meteorological data was measured including short wave snow albedo. Incoming and reflected solar radiation were measured using Schenk and Eppley pyranometers, respectively. Water equivalent at Kühtai was monitored using a 10 m<sup>2</sup> rubber snow pillow. More detailed information on the instrumental equipment of the site is contained in Kirnbauer and Blöschl (1990).

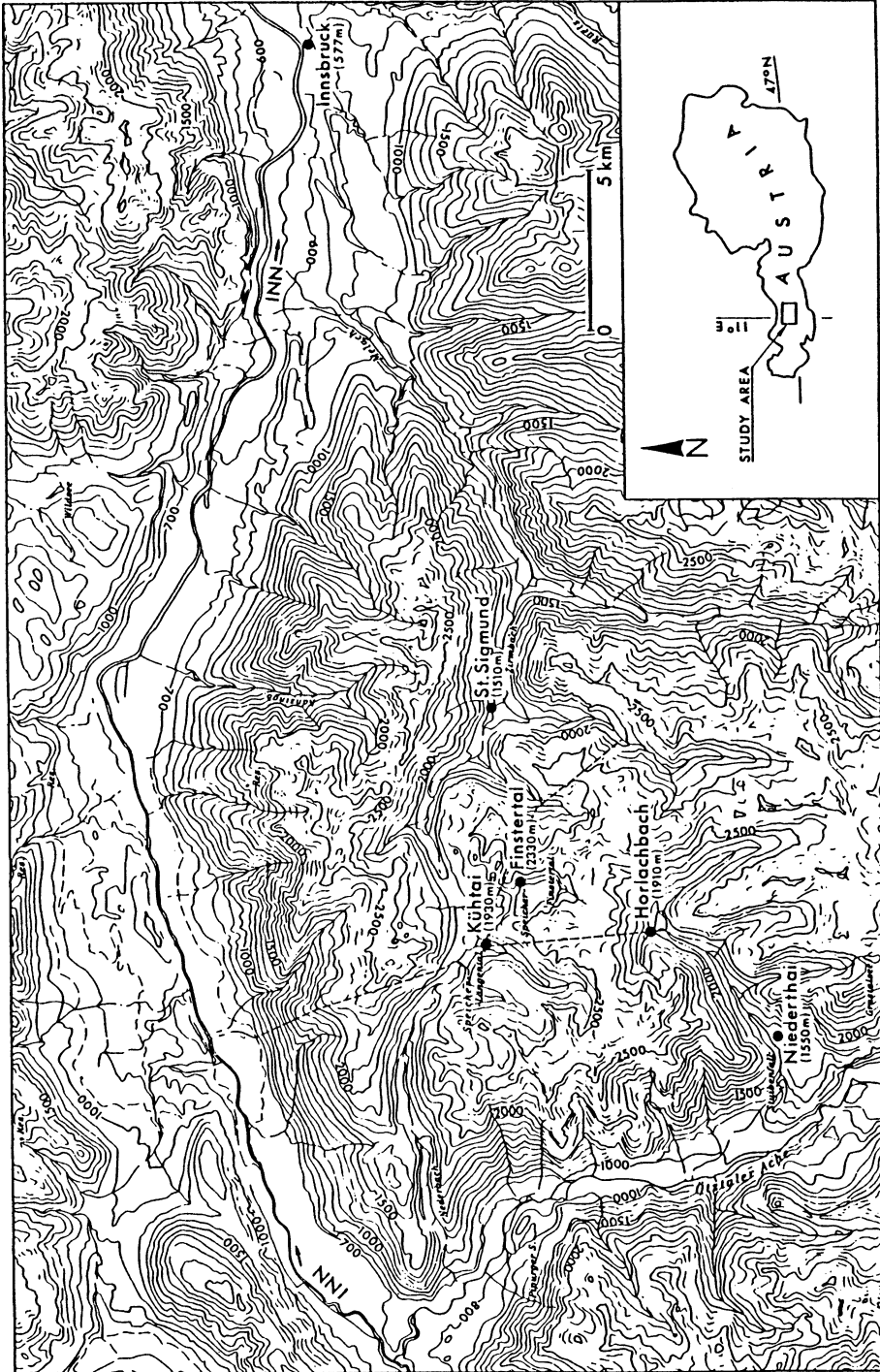


Fig. 1. Station location map with elevations in parentheses. By permission of BEV, ZI.L71283/90.

**Approach to Sensitivity Analysis**

A study on effects of regionalizing data should comprise three steps:

- analyzing data variability,
- analyzing estimation errors and
- evaluating effects of above errors on snowmelt.

Within the constraints of data availability the following approach was chosen: air temperatures at one station were estimated using data from the surroundings only. The estimates were compared with the measurements and the errors were analyzed. By examining various combinations of stations a range of possible errors expected in a catchment was produced. Water equivalent at the site scale was simulated using estimated temperatures and measurements for other meteorological variables yielding a variety of snowpack evolutions. Finally, the simulated water equivalent was compared with the pertaining errors in air temperature in order to assess sensitivity.

Since no reliable spatially distributed data for albedo were available an alternative approach was chosen. Albedo was simulated at the site scale. A range of model parameters derived from the literature was used representing different snow cover conditions expected within a basin. These estimates were used to show the effect of albedo on simulated water equivalent.

**Models**

In many snowmelt models (*e.g.* Charbonneau *et al.* 1981; Blöschl *et al.* 1990) air temperatures at an arbitrary point within a basin are found by linear regression of data with elevation. In this study air temperatures are estimated using data from two neighbouring stations. The three cases being considered are: 1) linear interpolation (temperatures estimated from stations above and below the reference); 2) linear extrapolation (from two low-elevation stations) and 3) substitution of

Table 1 - Estimator stations, elevations and distances to the station being estimated (Kühtai) for determining air temperature

method of determining air temperature	station(s)	elevation (m a.s.l.)	distance to Kühtai (km)
reference	Kühtai	1,930	0
substituted	Horlachbach	1,910	5.7
extrapolated	St. Sigmund	1,520	7.1
	Innsbruck	577	30.5
interpolated	Finstertal	2,330	1.7
	St. Sigmund	1,520	7.1

data from a station at the same altitude. The stations used and their characteristics are given in Table 1.

Numerous albedo models, with different degrees of complexity, based on snow surface characteristics and meteorological conditions have been suggested in the literature (*e.g.* Petzold 1977; Choudhury and Chang 1981; Marshall and Warren 1987).

Here, for the sake of clarity, a simple model is used. Albedo is assumed to decrease solely with the age of the snow surface (U.S. Army Corps of Engineers 1956). Specifically, the relation is an exponential decrease to a minimum value allowed. This is a widely used approach in operational models (WMO 1986). Three parameter sets were chosen and values were fixed according to U.S. Army Corps of Engineers (1956):

- a) accumulation period (5 % decrease on the first day and a minimum of 0.5),
- b) ablation period (15 % decrease on the first day and a minimum of 0.5) and
- c) same as b) but a minimum of 0.4.

In case of snowfall the albedo is set to 0.9. Fig. 2 shows albedoes calculated with these parameters.

Simulation of water equivalent at the site scale is based on the energy balance approach. Counter radiation is parameterized as a function of air temperature, humidity and cloudiness. Turbulent fluxes are estimated using a wind function. Snow temperatures are simulated according to Anderson's (1976) model and water percolation is based on the kinematic wave approach (Colbeck and Davidson 1973). More details on the snowpack model are furnished in Siemer (1988) and Blöschl and Kirnbauer (1991).

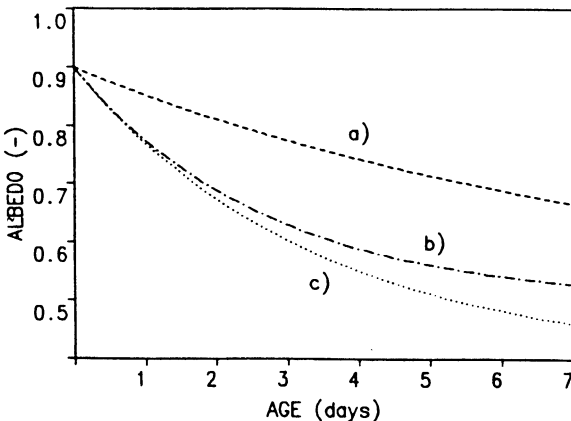


Fig. 2. Albedo as calculated with three parameter sets versus snow surface age: a) accumulation period (5 % decrease on the first day and a minimum of 0.5), b) ablation period (15 % decrease, minimum 0.5), c) ablation period (15 % decrease, minimum 0.4).

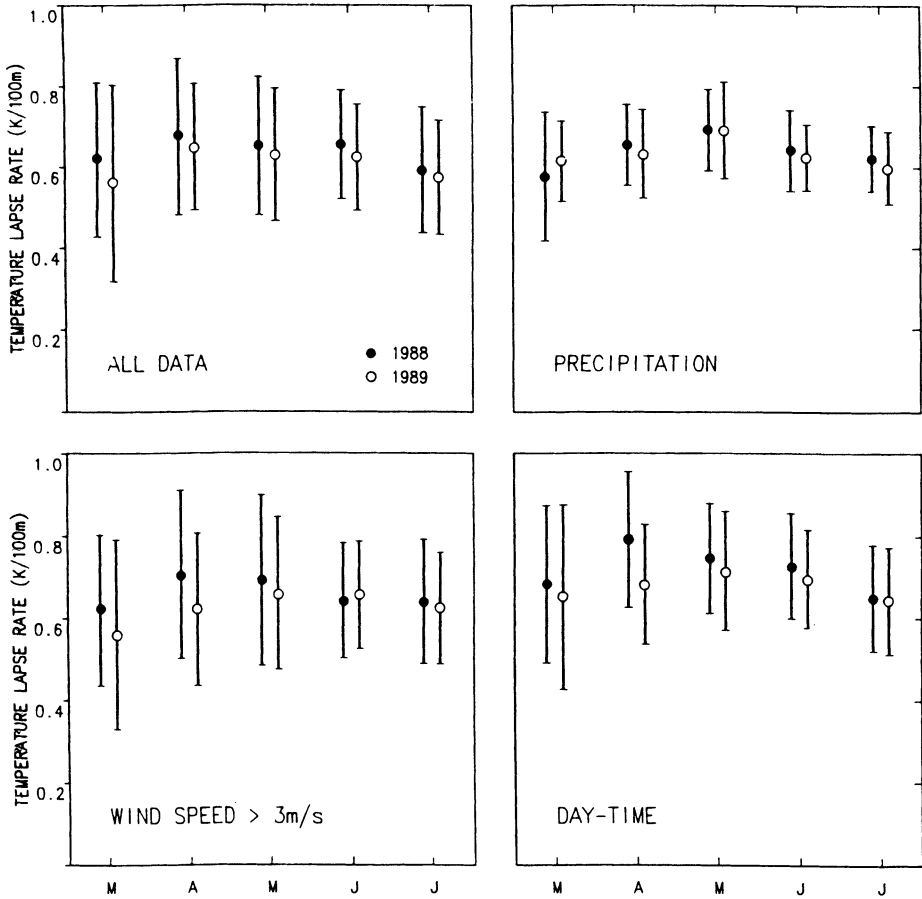


Fig. 3. Mean monthly lapse rates and standard deviations of hourly temperatures in the Sellrain region.

## The Effect of Air Temperatures

### Spatial Variability

As a first step, lapse rates of air temperature based on linear regression of hourly data with elevation are calculated (Fig. 3). All stations shown in Fig. 1 are included. Since the focus of this study is on snowmelt, only the months March to July are analyzed. Data from 1988 and 1989 yield similar results. Mean monthly lapse rates are approximately 0.65K/100 m and standard deviations are in the order of 0.2K/100 m. Maximum lapse rates are found from April to June and a minimum standard deviation in June and July. Analyzing hours exclusively with precipitation

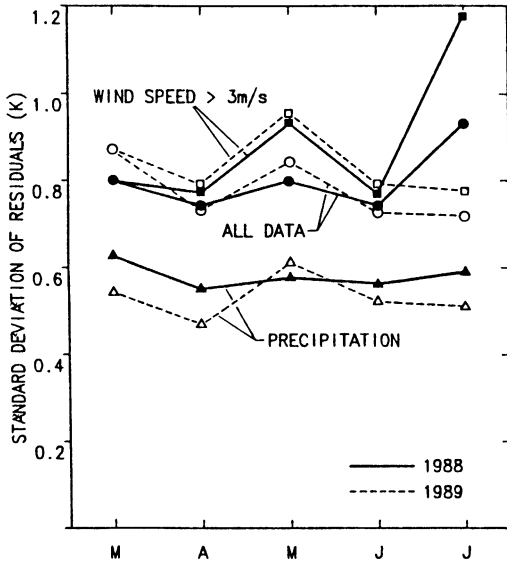


Fig. 4. Mean monthly standard deviations of residuals of air temperatures to a regression line with elevation in the Sellrain region.

yields a reduced variability. Including hours of high wind speeds only, gives a slightly increased variability. Day-time lapse rates (7 to 18h) are significantly larger than the daily average. These results are close to values reported in the literature for various climatic conditions (e.g. Moore and Owens 1984a; Braun 1985). Lapse rates obtained here also correspond to those used in operational forecasting (WMO 1986).

The goodness of fit of temperature data to the regression lines, may give an overall measure of errors to be expected in the Sellrain region. Mean monthly standard deviations of residuals are presented in Fig. 4. Standard deviations using all data are in the order of 0.8K. During hours of precipitation a significantly better fit is found, whereas hours of high wind speeds yield a poorer fit. The latter result might derive from the fact that changing weather conditions are often associated with high wind speeds and variable thermal gradients. Seasonal variations in the goodness of fit are in accordance with results presented in Charbonneau *et al.* (1981). However, the figures found here are somewhat lower, probably resulting from the higher network density in this study.

### The Effect of Interpolation Errors on Melt Rates

Fig. 5 shows estimation errors of air temperatures at Kühtai using three combinations of stations (see Table 1). The average monthly bias ranges from -0.5 to 1.5K with a tendency for overestimating temperatures later in the season. »Substituted« temperatures give too high estimates for all months analyzed. Standard deviations of errors using substituted and interpolated temperatures are approximately 0.75K whereas those derived from extrapolations are about double the value. Clearly,

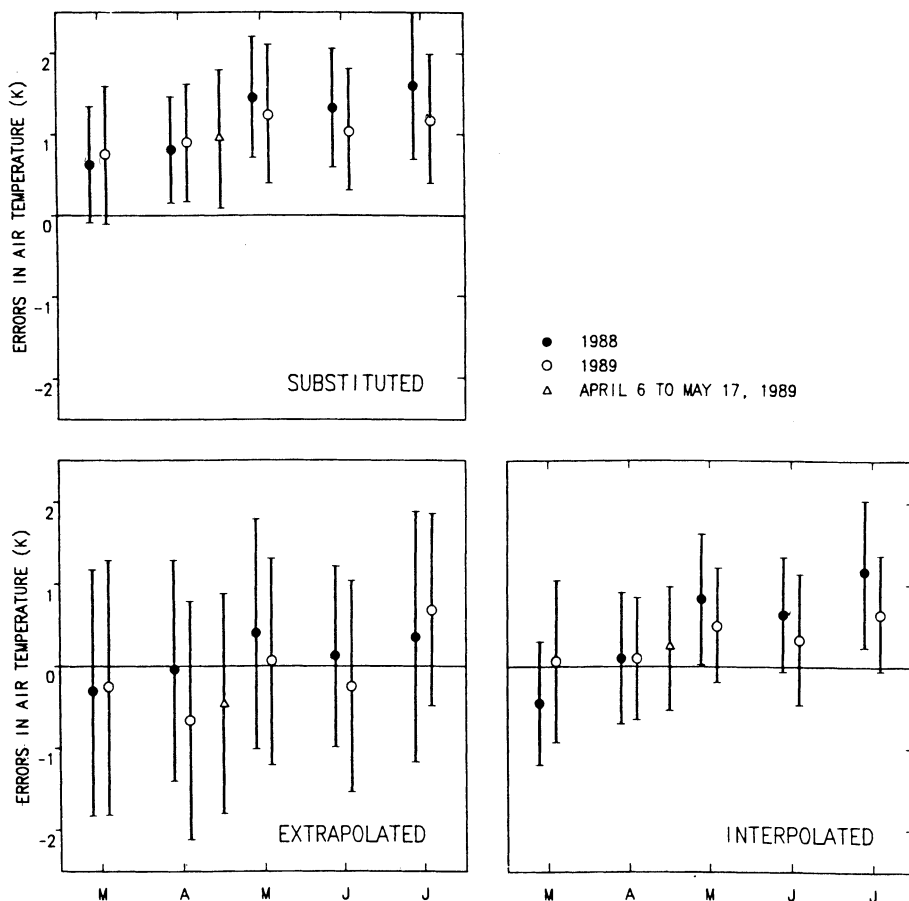


Fig. 5. Mean monthly estimation errors and standard deviations of air temperatures at Kühtai. For estimator stations see Table 1.

Table 2 = Simulated water equivalent (mm) at Kühtai using air temperature as estimated by different methods. Simulations started on April 6, 1989 when the water equivalent was 301 mm

method of determining air temperature	sim. water equivalent, May 11 (mm)	decrease in water equiv. April 6 to May 11	
		(mm)	difference to reference (%)
measured (reference)	98	203	0
substituted	17	284	40
extrapolated	81	220	8
interpolated	54	247	22



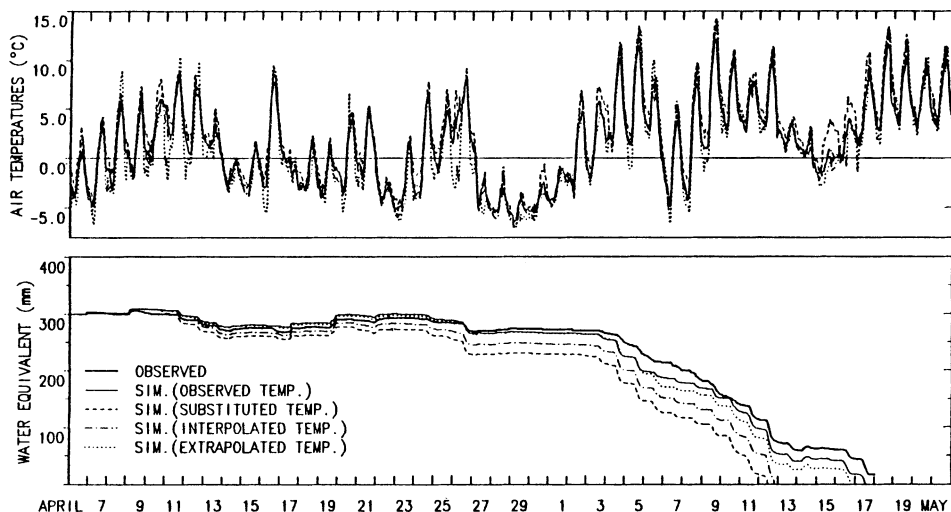


Fig. 6. Estimated air temperatures and simulated water equivalent at Kühtai, April 6 to May 21, 1989. For estimator stations see Table 1.

these figures demonstrate that the information content decreases with increasing distance (see Table 1) and the fact that extrapolations generally tend to be less accurate than interpolations.

The period April 6 to May 17, 1989 is analyzed in more detail. The range of errors in temperature during this period lies well within that of other months analyzed (Fig. 5). Fig. 6 shows estimated temperatures and simulated water equivalents. In all cases water equivalent is underestimated, extrapolated temperatures yielding the best and substituted temperatures yielding the poorest results. Table 2 contains values on the errors in snowmelt from April 6 to May 11 that range from 8 to 40% as compared to the initial simulations with observed temperatures.

### The Effect of Albedo

Albedoes simulated with three parameter sets (see Fig. 1) are presented in Fig. 7. For reasons of clarity, weighted daily means are given. As would be expected, albedo is overestimated with the parameter set derived for the accumulation period. The ablation period parameters give satisfactory results. On April 25 and May 1, both being days of overcast sky conditions, albedo is underestimated. This is due to the effect of cloud cover. Though known to increase albedo (*e.g.* Choudhury and Chang 1981), it has not been included in the simple model employed here.

Water equivalent is overestimated in all cases (Fig. 7), but there are marked

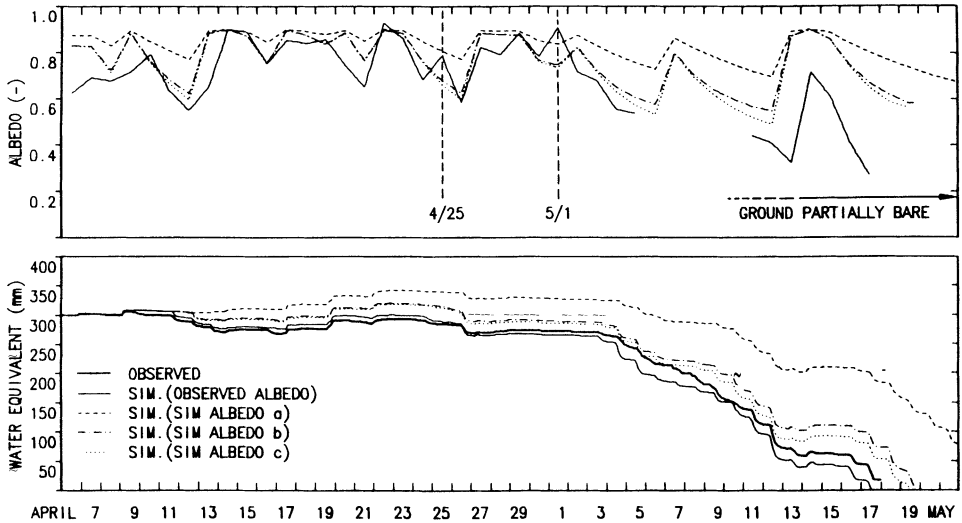


Fig. 7. Simulated albedo and water equivalent at Kühtai, April 6 to May 21, 1989. Parameter sets of the albedo model (a, accumulation period; b, c ablation period) see Fig. 2.

differences between individual simulations. Corresponding to estimated albedo, accumulation and ablation period parameters give poor and satisfactory results, respectively. Table 3 contains figures on simulation errors between April 6 and May 11, ranging from 16 to 68 % as compared to the initial simulations.

### Assessment of Results

Simulations of water equivalent (Fig. 6) were found to give best results using estimated temperatures with the poorest information content (extrapolation). This seemingly contradictory result may be easily interpreted on the basis of Fig. 5 and Table 4. Clearly, random errors (Fig. 5) largely cancel, whereas the bias in temperature controls simulation errors. However, water equivalent is underestimated in all cases, whereas temperature errors are of different sign. This finding is attributable to the non-uniform distribution of errors over a day along with the varying magnitude of temperature-influence on melt. When the snow surface is frozen (*e.g.* at night), the surface temperature responds quite sensitively to changes in air temperature thus compensating for inaccuracies (Obled and Rosse 1977; Blöschl and Kirnbauer 1991). When the surface reaches 0°C (*e.g.* at day-time), however, errors in air temperature directly affect the energy balance calculated by the model through turbulent fluxes and counter radiation (Blöschl *et al.* 1988). Table 4 contains estimation errors of temperatures listed separately for day and night-time. It can be seen that the mean day-time errors (*e.g.* 0.94K for substituted tem-

## Snowmelt – Uncertainty in Data

Table 3 – Simulated water equivalent (mm) at Kühtai using albedoes as estimated by different methods (see Fig. 2). Simulations started on April 6, 1989 when the water equivalent was 301 mm

method of determining albedo	sim. water equivalent, May 11 (mm)	decrease in water equiv. April 6 to May 11	
		(mm)	difference to reference (%)
measured (reference)	98	203	0
a	237	64	68
b	145	156	23
c	130	171	16

Table 4 – Estimation errors in air temperature, April 6 to May 17, 1989 as compared to measurements at Kühtai. Mean +/- standard deviation

method of determining air temperature	mean error in air temperature +/- s.dev.		
	day & night	day-time	night-time
substituted	0.93+/-0.84	0.94+/-0.91	0.93+/-0.75
extrapolated	-0.43+/-1.36	-0.08+/-1.34	-0.79+/-1.29
interpolated	0.23+/-0.76	0.48+/-0.78	-0.01+/-0.67

peratures) are closely related to errors in simulated water equivalent (*e.g.* 81 mm in Table 2).

Simulations showed albedo to substantially affect snowmelt. The period selected was characterized by frequent snowfalls. During longer fair weather periods even more influence is to be expected. Clearly, varying model parameters may only give rough indications on the spatial variability of albedo. In the upper part of a high-relief catchment accumulation conditions may prevail, while in the lower parts most of the snow has melted. The range of albedoes within that basin should be of the same order of magnitude as those simulated here since parameter sets for accumulation and ablation conditions were considered. Accordingly, errors introduced by ignoring or neglecting the spatial distribution of albedo may be similar to those presented in this study.

The relative importance of estimation errors of air temperature and albedo should be compared with caution because of the different data base. Certainly, the spatial distribution of air temperature is usually much better known than that of albedo. This is particularly true of alpine catchments during the ablation period when the variability of albedo is large. For these conditions the results obtained here indicate that in estimating snowmelt more uncertainty is introduced by uncertainty in albedo than through interpolating air temperatures.

It should be noted that the results obtained here are based on simulation runs in an alpine catchment performed during the ablation period. Clearly, in lowlands and/or during the accumulation period short-wave radiation will be less important. In these cases more emphasis will be on other variables such as air temperature, wind speed and air humidity (Blöschl *et al.* 1988).

## **Conclusions**

Random errors in air temperature introduced by regionalization largely cancel when simulating water equivalent. However, bias which may result from local effects such as sensor exposure is of marked influence on the simulations. For deterministic modelling one may conclude that it is of utmost importance to select sites carefully and to check instruments frequently. Data from standard networks often do not meet these requirements. A simple albedo model gives satisfactory results at the site scale but proper selection of model parameters appears to be essential for simulating water equivalent. For distributed snowmelt models in alpine terrain, therefore, the spatial variability of albedo certainly is of key interest suggesting that further research should focus on that problem.

## **Acknowledgements**

The author is greatly indebted to R. Kirnbauer who initiated and supervised the project and provided invaluable guidance. I would also like to acknowledge the contribution of the Tyrolean Hydroelectric Power Company (TIWAG) who established the snow monitoring station at Kühtai. Thanks are extended to A. Siemer who provided the source code of the point snowmelt model and showed great interest in this work. My gratitude is due also to D. Gutknecht, K. Elder, and L. Braun for their comments and encouragement throughout this study. G. Haidinger assisted in preparing the graphics and his contribution is gratefully acknowledged. This research was supported by a grant from the Fonds zur Förderung der wissenschaftlichen Forschung under project Nos. P6387P and P7002PHY.

## **References**

- Anderson, E. A. (1973a) National Weather Service river forecast system – snow accumulation and ablation model, NOAA Tech. Memo. NWS HYDRO-17, U.S. Department of Commerce, Silver Spring, Maryland.
- Anderson, E. A. (1973b) Techniques for predicting snow cover runoff. In: *The Role of Snow and Ice in Hydrology* (Proc. Banff Symp., September 1972), IAHS Publ. No. 107, pp. 840-863.

## Snowmelt – Uncertainty in Data

- Anderson, E. A. (1976) A point energy and mass balance model of a snow cover, NOAA Tech. Rep. NWS HYDRO-19, U.S. Department of Commerce, Silver Spring, Maryland.
- Bauwens, W. (1988) Snowmelt models with different degrees of complexity applied to shallow and short-living snowpacks in lowland basins. Proc. 45th Eastern Snow Conference, Lake Placid, June 1988.
- Blöschl, G., and Kirnbauer, R. (1991) Point snowmelt models with different degrees of complexity – internal processes. Accepted for *J. Hydrol.*
- Blöschl, G., Gutknecht, D., and Kirnbauer, R. (1988) Berechnung des Wärmeeintrages in eine Schneedecke – Analyse des Einflusses unterschiedlicher meteorologischer Bedingungen (Simulation of heat input to snow – analysis of the influence of different meteorologic conditions), *Deutsche Gewässerkundliche Mitteilungen* 32 (1/2), pp. 34-39.
- Blöschl, G., Kirnbauer, R., and Gutknecht, D. (1990) Modelling snowmelt in a mountainous river basin on an event basis, *J. Hydrol*, Vol. 113, pp. 207-229.
- Braun, L. N. (1985) Simulation of snowmelt-runoff in lowland and lower alpine regions of Switzerland. Zürcher Geographische Schriften 21, Geographisches Institut der Eidgenössischen Technischen Hochschule Zürich.
- Charbonneau, R., Lardeau, J. P., and Obled, C. (1981) Problems of modelling a high mountainous drainage basin with predominant snow yields, *Hydrol. Sci. Bull.*, No. 26 (4), pp. 345-361.
- Choudhury, B. J., and Chang, A. T. C. (1981) The albedo of snow for partially cloudy skies, *Boundary-Layer Meteorology*, Vol. 20, pp. 371-389.
- Colbeck, S. C., and Davidson, G. (1973) Water percolation through homogeneous snow. In: The Role of Snow and Ice in Hydrology (Proc. Banff Symp., September 1972), IAHS Publ. No. 107, pp. 242-257.
- Jensen, H. (1989) Räumliche Interpolation der Stundenwerte von Niederschlag, Temperatur und Schneehöhe (Spatial interpolation of hourly values of precipitation, temperature and snow depth). Zürcher Geographische Schriften 35, Geographisches Institut der Eidgenössischen Technischen Hochschule Zürich.
- Kirnbauer, R., and Blöschl, G. (1990) A lysimetric snow pillow station at Kühtai/Tyrol. In: Hydrology in Mountainous Regions. I – Hydrological Measurements; the Water Cycle (ed. by H. Lang and A. Musy) (Proc. Lausanne Symp., August 1990), IAHS Publ. No. 193, pp. 173-180.
- Kuhn, M., and Pellet, F. (1989) Basin precipitation as residual in alpine water balances. In: Precipitation Measurement (ed. by B. Sevruk) (Proc. St. Moritz Workshop, December 1989), WMO/IAHS/ETH pp. 275-277.
- Lang, H. (1981) Is evaporation an important component in high alpine hydrology? *Nordic Hydrol*, Vol. 12, pp. 217-224.
- Lang, H. (1986) Forecasting meltwater runoff from snow-covered areas and from glacier basins. In: *River Flow Modelling and Forecasting* (ed. by D. A. Kraijenhoff and J. R. Moll), Reidel Publishing Company, Dordrecht, pp. 99-127.
- Leavesley, G. H. (1989) Problems of snowmelt runoff modelling for a variety of physiographic and climatic conditions, *Hydrol. Sci. J.*, Vol. 34 (6), pp. 617-634.
- Marshall, S. E., and Warren, S. G. (1987) Parameterization of snow albedo for climate models. In: Large Scale Effects of Seasonal Snow Cover (ed. by R. E. Goodison, R. G. Barry and J. Dozier) (Proc. Vancouver Symp., August 1987), IAHS Publ. No. 166, pp. 43-50.

- Mohl, H., and Rudel, E. (1984) Partial-automatic climatological stations in Austria. WMO Technical Conference on Instruments and Cost-effective Meteorological Observations (TECEMO 84) Instruments and Observing Methods, Report No. 15, pp. 329-332.
- Moore, R. D., and Owens, I. F. (1984a) Modelling alpine snow accumulation and ablation using daily climate observations, *J. Hydrol (NZ)*, Vol. 23 (2), pp. 73-83.
- Moore, R. D., and Owens, I. F. (1984b) A conceptual runoff model for a mountainous rain-on-snow environment, Craigieburn Range, New Zealand, *J. Hydrol. (NZ)*, Vol. 23 (2), pp. 84-99.
- Obled, C., and Harder, H. (1979) A review of snow melt in the mountain environment. In: Modeling of Snow Cover Runoff (ed. by S. C. Colbeck and M. Ray) (Proc. Meeting, Hanover, New Hampshire, September 1978), U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A., pp. 179-204.
- Obled, C., and Rosse, B. (1977) Mathematical models of a melting snowpack at an index plot, *J. Hydrol. Vol. 32*, pp. 139-163.
- ÖNORM (1988) Önorm M9490 Teil 9. Meteorologische Messungen für Fragen der Luftreinhaltung; Wetterhütte (Meteorological measurements for purposes of air pollution control; screen), Austrian Standards Institute, Vienna.
- Petzold, D. E. (1977) An estimation technique for snow surface albedo. Climatological Bulletin, McGill University, Department of Geography, Montreal, No. 21, pp. 1-11.
- Siemer, A. H. (1988) Ein eindimensionales Energie-Massenbilanzmodell einer Schneedecke unter Berücksichtigung der Flüssigwassertransmission (A one-dimensional energy and mass balance model of a snow cover including effects of liquid water transmission), Berichte des Instituts für Meteorologie und Klimatologie der Universität Hannover, 34.
- U.S. Army Corps of Engineers (1956) Snow hydrology. Summary report of the snow investigations, Portland, Oregon.
- WMO (1986) Intercomparison of models of snowmelt runoff, WMO Operational Hydrology report No. 23, WMO Publ. No. 646, Geneva, Switzerland.
- Zuzel, J. F., and Cox, L. M. (1975) Relative importance of meteorological variables in snowmelt, *Wat. Resour. Res.*, Vol. 11 (1), pp. 174-176.

First received 4 December, 1990

Revised version received: 7 March, 1991

Accepted: 11 March, 1991

**Address:**

Technische Universität Wien,  
Institut für Hydraulik,  
Gewässerkunde und Wasserwirtschaft,  
Karlsplatz 13/223,  
A-1040 Wien,  
Austria.