APPLICATION OF BTS-MEASUREMENTS FOR MODELLING MOUNTAIN PERMAFROST DISTRIBUTION

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In the early 1970s, *rules of thumb* to predict local permafrost occurrences in the Swiss Alps were based on a considerable number of field measurements and the assumption that the main governing factors were (1) mean annual air temperature (altitude, regional scale), (2) solar radiation (slope aspect, local scale) and (3) snow redistribution by wind and avalanches. Information from a large number of BTS-measurements and potential direct solar radiation as calculated from digital terrain models can now be used for improving the model. Mean annual air temperature and potential direct solar radiation can now be introduced explicitly, replacing 'altitude' and 'slope aspect' in the original *rules of thumb*. This important result helps to explain permafrost existence at low-altitude sites with extremely reduced solar radiation (well below the 0°C-isotherm). It also makes simulation of effects from various future climatic scenarios more realistic.

INTRODUCTION

Modelling distribution patterns of discontinuous mountain permafrost at a regional scale (e.g., Dingman and Koutz 1974, Harris 1981, Greenstein 1983, Gorbunov 1978, Jorgenson and Kreig 1988) is a basic tool in connection with the planning of human activities in these especially sensitive environments (Haeberli 1992). Furthermore, the simulation of permafrost distribution for past and future climatic conditions in view of ongoing warming trends and their effects on natural hazards in high mountain areas has become increasingly important. The present contribution discusses the basic concept of predicting permafrost occurrences in the Swiss Alps as a function of topographic and climatic parameters. It presents results from tests of existing models and discusses ongoing efforts to further improve such tools.

MOUNTAIN PERMAFROST AND THE ENERGY BALANCE

On a worldwide scale, permafrost characteristically occurs in cold regions at high latitudes ('polar permafrost') and high altitudes ('mountain permafrost'). However, it must be emphasized that air temperature does not 'cause' permafrost (Williams and Smith 1989), even though it is the result of the energy exchange processes. In particular, the local pattern of discontinuous permafrost distribution can only be explained through an understanding of these processes involved.

The energy balance governing the existence or absence of permafrost is determined by radiative and mass fluxes. It is the driving factor for heating/cooling, evaporation/condensation and the acceleration/delay of chemical processes. The relative magnitude of the different energy balance components varies greatly in space and time as an effect of atmospheric (climatic) and site-specific (microclimatic) factors, which are linked together via intensive interactions and feedback mechanisms. A basic step is to determine which parameters in the energy balance are important to permafrost distribution in mountain areas and to assess their influence. The energy balance equation can be written:

$$Q_R + Q_H + Q_{LE} + Q_G = 0 \qquad (1)$$

Q_R = Net radiation
Q_H = Sensible heat flux
Q_{LE} = Latent heat flux
Q_G = Ground heat flux

Modelling permafrost distribution for a given area must be based on consideration of the energy balance as a function of space and time. Due to the limited information available about the critical parameters and about the complex boundary conditions influencing them, index models consisting of easily-measureable or computable parameters are in most cases applied as reliable tools (Abbey et al. 1978).

Solar radiation (K↓) is a climatic factor, which depends on latitude, time (year, day), clouds and atmospheric turbidity. The site-specific effects of the local topography (slope angle, aspect and shading effects of the horizon) are very important, especially in mountain areas where the orientation of a surface with respect to the solar beam is a powerful variable in determining energy income. This effect can lead to considerable differences in the entire energy balance (Oke 1987 p.175). The great variability of K↓ and of the albedo (a) strongly influences the local occurrence of permafrost (cf. measurements by Ohmura 1981 or Abbey et al. 1978 for Arctic regions or Schrott 1990, Happoldt and Schrott 1992 for the Andes). Radiation is even of great importance beyond the meso-scale: Cheng (1983) described the worldwide permafrost distribution as a function of latitude and altitude in relation to net radiation. Sensible heat flux Q_H is determined by eddy conductivity (index for the turbulent transfer) which depends on windspeed (climatic factor), surface roughness (site-specific factor) and the difference between surface and air temperature. The short-term variability of the heat flux can be very large but will be smaller over time scales of years. The overall influence of the air temperature on the energy balance is considerable (Ng and Miller 1977). In comparison with solar radiation and sensible heat, latent and ground heat fluxes are usually considered to be smaller (Oke 1987).

BTS-MEASUREMENTS

The temperature at the bottom of the winter snow cover (BTS) is a reliable tool to investigate the distribution of permafrost in areas where the winter snow cover is thick enough (0.8 meter). The method was introduced by Haeberli (1973) and has often been applied since then (e.g. Haeberli and Patzelt 1982, King 1983, Stingl and Veit 1988, Hoelzle 1992). The snow cover with its low heat transfer capacity insulates the soil from short-term variations in the surface energy balance (Keller and Gubler 1993). During the months of February and March, when the snow cover in the Alps is about one meter thick or more and surface melting is negligible, the BTS remains nearly constant and is mainly controlled by the heat transfer from the upper ground layers, which in turn is strongly influenced by the presence or absence of permafrost (cf. Haeberli 1985, Stoop 1990, Vonder Mühll and Haeberli 1990).

The BTS-measurements used in the present work were performed in six different areas at altitudes between 1800 and 3400 m a.s.l. Five areas are situated within or near the Upper Engadin (eastern Swiss Alps) and one region lies in the northern Swiss Alps (cf. Haeberli et al. 1993).

THE EXISTING *RULES OF THUMB*

The original model and its implementation for automated mapping

The original model for predicting permafrost distribution patterns in the Alps was developed as part of the first systematic study on Alpine permafrost in the region of Flüelapass/Piz Grialetsch in the Grisons (Haeberli 1975). On the basis of visual inspection of natural outcrops, active-layer temperatures, ramsonde profiles, seismic refraction, geoelectrical resistivity, temperatures of spring water in late summer/fall, BTS-measurements in high winter, head areas of active rock glaciers, collapsed frontal parts of fossil/relic rock glaciers and bergschrunds above glaciers, about 150 point observations were collected. One important finding was the fact that permafrost mainly occurred in vegetation-free areas (75%) or in the transition zone of pioneer vegetation/alpine meadows (25%) and that permafrost occurrences in areas with well-developed vegetation were rare. In order to differentiate this general picture and to interpolate information from the point observations, empirical *rules of thumb* were derived. Altitude as the parameter reflecting the influence of air temperature and slope aspect as the parameter representing the influence of solar radiation were considered together with the following typical topographic situations representing the influence of snow redistribution:

- slopes steeper than 5 to 10°,
- sites at the foot of high and steep slopes (avalanche runout zones with long-lasting snow),
- flat and wind-protected depressions (cirque floors, etc.) with increased accumulation of winter snow and
- flat and wind-exposed crests and summits with reduced winter snow cover.

The basic assumption behind this procedure was that the sensible heat flux (mean annual air temperature) determines permafrost occurrence at a regional scale (altitudinal belts), that radiation predominantly influences the permafrost distribution pattern at a local scale and that the snow cover with its influence on sensible heat and radiative fluxes (thermal insulation against winter cold, protection against summer heating due to latent heat of fusion, albedo) is being redistributed by wind and avalanches as a function of general topography. A first and rather qualitative but nevertheless quite successful test of the applicability of these *rules of thumb* was the mapping of permafrost distribution patterns in the Hochebenkar region, Austrian Alps (Haeberli and Patzelt 1982) using mainly BTS measurements and seismic refraction soundings. It became evident from this study that the inclusion of surface characteristics (vegetation, fine/-coarse material, etc.) could give additional information and that a larger number of BTS measurements would greatly increase the size of the statistical sample for developing more sophisticated models. Based on the generally encouraging experience, a transformation of altitudinal limits into temperature limits was made for better application in paleoclimatic studies (Haeberli 1982) and written recommendations were handed out to earth scientists and engineers in Switzerland as a help for practical work in mountain areas of the Alps (VAW/ETH 1985). A graphic presentation of the *rules of thumb* is shown by Keller (1992).

A computer program 'PERMAKART' was recently developed to map permafrost distribution in Alpine regions by implementing the *rules of thumb* in the Geographical Information System ARC/INFO (Keller 1992). The basic input for using 'PERMAKART' is a digital terrain model (DTM) which must exist as an ARC/INFO coverage in the form of a contour map or a set of x,y points with the identification code representing z-values. Surface analyses will then create a data base of surface parameters, whereas aspect, slope and elevation values can directly be computed using the triangulated irregular network of the DTM. The significance of the general morphology has to be adjusted for considering sites at the foot of slopes, which receive long-lasting deposits of avalanche snow in spring: a square grid with a mesh-width of 100 meters is calculated taking the concavity of topographic forms into account. With regard to the resolution of the presently available DTM Rimini, a better determination of avalanche deposits would not yield better results. An important task in connection with the data base is the management of the topology, i.e., the mathematical procedure for defining spatial relationships. The data base furnishes the data for the application of the *rules of thumb*. In connection with the topologically determined spatial relationships, the permafrost item can be organized in a triangulated irregular network which represents a thematic permafrost surface. The map of the supposed permafrost distribution is the result of interpolating polygons ranged into three classes separated by the lower limits of possible and probable permafrost respectively (cf. Keller 1992 for more details of the computing procedure). Implementation of the *rules of thumb* in a Geographical Information System now enables fast assessments of plausible permafrost distribution over large mountain areas with complex topography. It also facilitates simulation of possible past and future scenarios of permafrost distribution (for instance: Late glacial time, Little Ice Age, 21st century).

Test with BTS measurements

The numerous BTS measurements collected during the past years offer the possibility of investigating the reliability of the original *rules of thumb*. After elimination of soundings on glaciers and lakes, 701 measurements remained for testing.

Figure 1 demonstrates the relation between permafrost occurrence and vegetation cover, confirming that 89% of the investigated permafrost sites are more or less free of vegetation and that 71% of the permafrost-free areas are covered with alpine meadows or forest. Table 1 shows the results of the comparison between the BTS measurements and the *rules of thumb*. According to the original definition of the permafrost zones and boundaries, an unsuccessful prediction was defined as a contradiction to the *rules of thumb* (permafrost found in areas predicted as permafrost-free and permafrost-free sites found in areas with permafrost existence predicted to be probable). The uncertainty range (permafrost possible) was excluded from the test. The mean (weighted) rate of unsuccessful predictions is 25%. In view of the fact that no topographic differentiation was applied to the test sample, the mean error probability in predicting permafrost areas and permafrost-free areas from the original *rules of thumb* can be estimated at less than 25%. The safety of the prediction is, however, a function of aspect. Permafrost terrain is especially well predicted for slopes exposed to W, NW, N and NE (12 to 24% error) and permafrost-free terrain can quite safely be delineated on slopes exposed to W, SW and NE (9 to 18% error). Problems mainly exist for permafrost terrain on SW-exposed slopes and in permafrost-free areas exposed to S, SE, E and N, NW, respectively. Such uncertainties have obvious reasons. Concerning SW-exposures, the sample is still too small and does not reach high-enough altitudes to safely predict permafrost areas. In southern to eastern exposures, the special condition of the foot of slopes with long-lasting avalanche snow is responsible for the high error rate in the test when predicting permafrost-free terrain (the full application of the *rules of thumb* with the topographic differentiation would give considerably better success). On slopes exposed to N and NW, special conditions of extremely reduced solar radiation make predictions of permafrost-free terrain uncertain. Eliminating from the test sample all sites at altitudes below 1900 m a.s.l. which were not considered in the original *rules of thumb* would reduce the error probability for slopes exposed to N from 50% to 20%. The phenomenon of low-altitude permafrost sites is, however, real and must be dealt with by more appropriate consideration of the energy balance parameters involved.

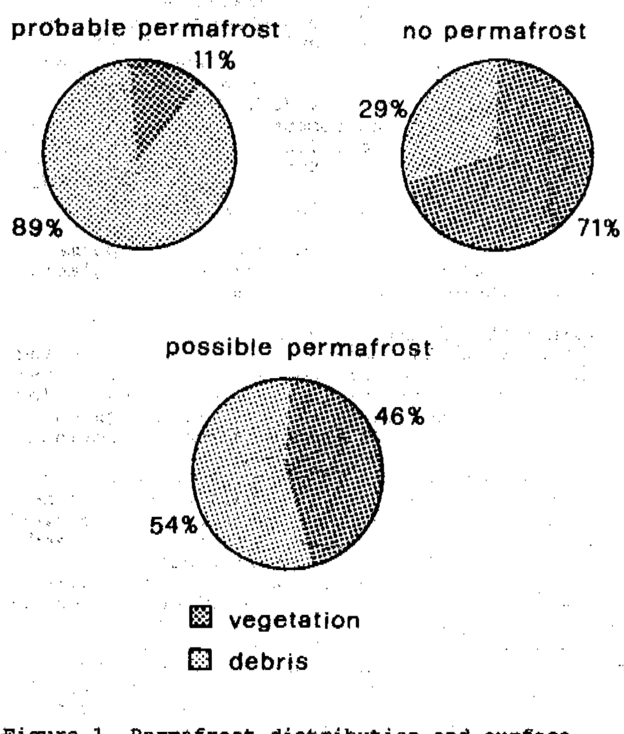

Figure 1. Permafrost distribution and surface characteristics (debris and vegetation). The sample size is N = 701 whereas n = 311 probable permafrost (BTS < -3°C), n = 151 possible permafrost (BTS between -2°C to -3°C) and n = 239 permafrost-free sites (BTS > -2°C).

Table 1. Comparison between the BTS-measurements and the *rules of thumb*. The test shows the errors from permafrost (BTS < -3°C) areas predicted as permafrost-free and permafrost-free (BTS > -2°C) areas predicted as probable permafrost. The uncertainty range (BTS between -2°C to -3°C: possible permafrost) is excluded from the test.

Exposure	errors (no permafrost in probable permafrost areas)	number of sites
N	18%	34
NE	12%	28
E	–	
SE	–	
S	–	
SW	59%	12
W	13%	62
NW	24%	118
Total	21%	

Exposure	errors (probable permafrost in permafrost-free areas	number of sites
N	50% (20%)	8
NE	12%	9
E	45%	20
SE	41%	46
S	31%	64
SW	18%	22
W	9%	33
NW	44%	34
Total	32%	

DIRECT USE OF POTENTIAL RADIATION AND ESTIMATED AIR TEMPERATURE

Permafrost as well as the BTS are functions of the mean annual surface temperature (MAST) and therefore a result of the entire energy balance at the surface. In the spatial relation between permafrost and energy balance parameters, permafrost can be represented by BTS-measurements and the energy balance by a combination of the mean annual air temperature (MAAT) and the potential direct solar radiation (PR). MAAT and PR can be determined. PR represents the potential energy income as a function of the local topography. Especially in mountain areas, the local topography gives the largest variability of the energy income which, in turn, strongly influences the distribution patterns of discontinuous permafrost. MAAT describes the sensible heat flux.

In order to statistically analyze the relation between permafrost/BTS and the most important energy balance parameters, MAAT was determined for each BTS-point from 27 meteorological stations and by using typical regional values for gradients of air temperature with altitude (Gensler 1978, Hoelzle 1989): values of 0.56°C-/100m were chosen in the Upper Engadin, and of 0.60°C/100m in the Northern Alps. In addition, mean daily PR between July to October was computed (during this time interval the investigated areas are more or less free of snow and the radiation has its strongest effects on the surface) for each BTS-point on the basis of a digital terrain model with a mesh-width of 100 meters (Funk and Hoelzle 1992). The uncertainty with respect to estimates of MAAT is about ± 100 meters (± 0.5 to 0.6 °C). The error of the calculated PR is mainly determined by the resolution of the digital terrain model. A higher resolution of the DTM with more precise determination of the surface topography would lead to significant improvements. The first result of statistical analysis with these data was a significant relation between BTS and PR (Hoelzle 1992).

Next the BTS-measurements were grouped into three classes according to their significance with respect to permafrost occurrence:

A) permafrost probable: BTS equal to or colder than -3°C
B) permafrost possible (uncertain information): BTS warmer than -3°C and colder or equal to -2°C
C) probably no permafrost: BTS warmer than -2°C

The BTS-points which are located in Class B (possible permafrost) were considered to be in a climatic environement where the conditions are just marginal for permafrost existence. MAAT and PR were averaged for all BTS points in this BTS class and for altitude intervals of 100 meters: Figure 2 shows the corresponding relation between MAAT, PR *for* BTS (Class B). From MAAT = -1°C (approx. 2300 m a.s.l.) to -2.7°C (approx. 2800 m a.s.l.) the sample size can be considered representative. Because of avalanche risks and difficult access, the sample is still small for altitudes above 2800 m a.s.l. At altitudes below 2300 m a.s.l., suitable permafrost sites for measuring BTS are not numerous. Nevertheless, a permafrost site at 1800 m a.s.l. was found in the northern Swiss Alps and BTS-values could be measured (Funk and Hoelzle 1992). Two other sites of low-altitude permafrost were found in the north-eastern Swiss Alps (Alpstein group: Bächler 1930) and in the *Jura mountains* (Creux du Van: Pancza 1988). For each of these sites, PR was calculated and the results plotted on Figure 2.

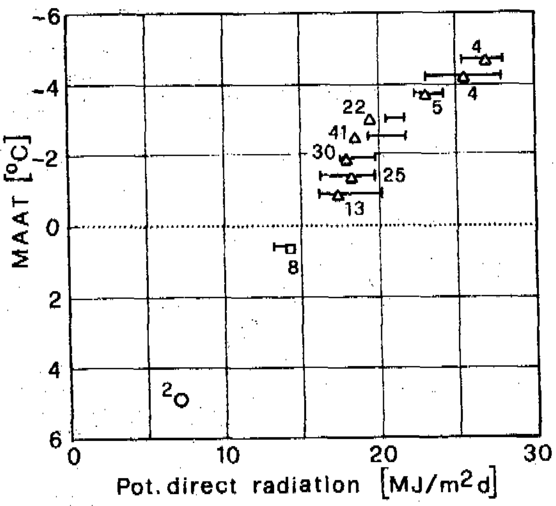

Figure 2. Relation between potential direct solar radiation (PR) and mean annual air temperature (MAAT) at the limit of permafrost existence (BTS between -2°C to -3°C: possible permafrost). The numbers represent the count of measurements. The symbols indicate mean values (PR and MAAT) in this BTS-class for altitude intervals of 100 meters. Double bars represent the range where indications of permafrost presence (BTS < -3°C) and absence (BTS > -2°C) overlap.

Both sites are exposed to the North and have a MAAT of 4.9°C (altitude is around 1150 m a.s.l.) but strongly reduced solar radiation income. Such extreme sites greatly help in extrapolating and assuring the statistically significant relation found within the periglacial belt at higher altitudes. An independent method for checking the relation of Figure 2 consists in calculating the overlap range between the BTS class with no permafrost (C) and the one with probable permafrost (A). By definition of the uncertainty zone (possible permafrost), this zone of mixed information also represents the limits of permafrost existence and should thus be equivalent to the sample used so far. The corresponding overlap ranges are marked by double bars on Figure 2. They indeed confirm the significance of the previously derived relation.

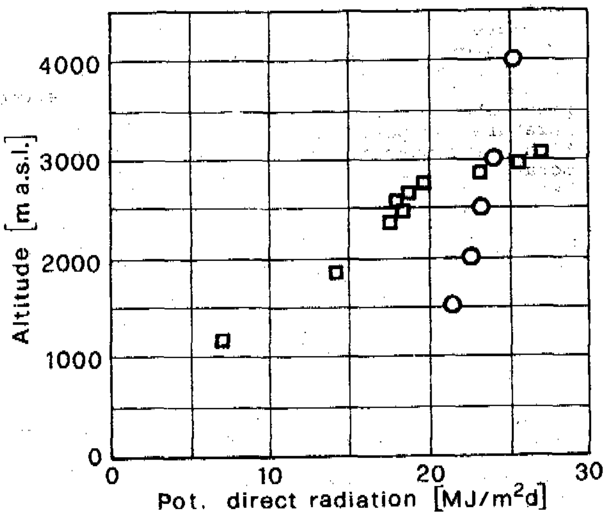

Figure 3. Potential direct radiation and altitude: comparison between measurements on horizontal surfaces after Müller (1984) and values calculated for limits of permafrost existence (BTS between -2°C to -3°C: possible permafrost).

Figure 3 shows that the effect of altitudinal increase in incoming direct radiation (circles, Müller 1984, Funk 1985) cannot be responsible for the relationship shown in Figure 2 (squares): the gradients differ by almost an order of magnitude.

With respect to modelling present-day distribution patterns and possible effects of climatic changes on mountain permafrost, the relation found in Figure 2 is an important step forward insofar as altitude and slope aspect of the original *rules of thumb* can now explicitly be replaced by careful estimates of air temperature and solar radiation as two important energy balance parameters. Transfer of the model to other mountain ranges should thus be possible and modelling effects of climatic changes become more realistic.

BTS, MAST and permafrost are results of the entire energy balance involving the whole set of climatic as well as site-specific factors:

$$BTS = f(MAST) = f(Q_R, Q_H, Q_{LE}, Q_G) \qquad (2)$$

They are strongly influenced by surface

characteristics such as snow cover, vegetation and debris. The distribution and height of the snow cover are especially significant (Smith and Riseborough 1983, cf. Keller and Gubler 1993): the accumulation of snow in autumn, for instance, heavily influences mean annual ground temperatures (Goodrich 1982, Haeberli 1985, Keller and Gubler 1993). Further improvement of predictive models for mountain permafrost distribution can, therefore, be expected from more realistic treatment of snow redistribution by wind and avalanches in winter and spring, of snow cover duration in early summer (remote sensing) and of ground surface characteristics (water content, coarse debris, bedrock, etc.).

CONCLUSIONS

The often-used *rules of thumb* for predicting permafrost distribution in high mountain areas of the Swiss Alps were tested with a great number of BTS measurements and have been used in the Geographical Information System for automated mapping of permafrost distribution over large mountain areas with complex topography. Further analysis of the large BTS sample showed that a close relationship exists between permafrost occurrence, mean annual air temperature and potential direct solar radiation. With computer-derived estimates for air temperature and solar radiation, more physically-based modelling of present-day permafrost distribution patterns (plus effects from past and potential future climatic changes) are possible. Further progress towards consideration of the full energy balance could be made by taking into account the snow-cover and ground surface characteristics as well as by using higher-resolution digital terrain models.

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