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PERMAFROST INVESTIGATIONS WITH GIS – A CASE STUDY IN THE FLETSCHHORN AREA, WALLIS, SWISS ALPS

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Abstract

To quantify the impact of predicted climatic change on the distribution of Alpine permafrost it is vital to know its present-day conditions and distribution patterns. This knowledge will allow comparisons with the situation in the future. In the study area, an inventory of periglacial landforms – such as rock glaciers, perennial snow patches and spring temperatures – has been established from interpretation of aerial photographs and field analyses. All data were integrated into a GIS-System. The field data were then used as indicators to verify two existing digital permafrost models. The evaluation of the models showed that they correspond well with the empirical data at high altitudes, whereas the accuracy of the estimations diminishes towards lower altitudes. Especially at a local scale, further information such as seismic soundings, geo-electrical measurements etc., is needed to make exact statements about the local permafrost distribution.

Introduction

In preparation for future changes in areas above today's timberline, it is important to know the present-day conditions and active processes dominating in these areas. Based on this knowledge it will be possible to quantify the predicted impact of climatic change on these mountain regions. Computer-based simulation models are useful tools in assessing regional permafrost occurrence. Yet, the increasing demand for the results of such simulations leads to a growing gap between them and the scientific knowledge on which the models are based. This trend has to be observed critically. It raises the question about the accuracy of the models and their transferability into other mountain regions.

The main objectives of the present work were: (1) to achieve an overall view of the permafrost distribution in the study area and (2) to evaluate the two existing computer-based permafrost distribution models, PERMAKART (Keller, 1994) and PERMAMAP (Hoelzle, 1994), using the results of the first step as a basis for model verification.

The study is part of a long-term monitoring program of the Swiss Permafrost Network, with the aim of detecting changes in the Alpine periglacial zone within time periods of 20 to 30 years. Therefore, detailed inventories and descriptions of these morpho-dynamically active zones are urgently needed.

The field site

The Fletschhorn area is located in the southern Swiss Alps and covers approximately 60 km^2. A high mountain chain with peaks rising over 4000 m a.s.l. subdivides the region into two parts: the Saas valley on the western slopes of the mountain range and the Simplon region on its eastern slopes. Climatically the whole region is characterised by local continental conditions, typified by low precipitation coupled with high amplitudes of temperature. Glaciers are nevertheless abundant, though - due to the climatic conditions - they show small mass turnovers and reach only medium size.

Practically all important processes and forms of the periglacial realm in the Alps (e.g., rock glaciers, perennial snow patches, solifluction forms, etc.) can be found in the area. This was a major reason for choosing the region as a study site.

Models

The original model for predicting mountain permafrost was developed in the mid-1970's on the basis of several geophysical methods as well as on the morphological description of creeping permafrost bodies, natural outcrops, surface characteristics (vegetation, grain size) and the analysis of active-layer temperatures, temperatures of water in springs and bottom temperatures of the snow cover (BTS) (Haeberli, 1973; 1975). The results were then used as main components of the "rules of thumb to predict alpine permafrost" which were published by W. Haeberli at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW), Federal Institute of Technology (ETH), Zurich in 1985 (cf. Haeberli et al., 1996).

In order to have a tool for permafrost mapping in the Alps, the permafrost distribution model PERMAKART was implemented into the GIS-software ARC/INFO (Keller, 1992; 1994). The program is based on the empirical topo-climatic key – a relation between slope, aspect, altitude, and permafrost occurrence – which is included in the original "rules of thumb". The model differentiates three permafrost categories: probable permafrost, possible permafrost and no permafrost. A special feature of the model is its ability to consider the effects of avalanche snow deposits on permafrost distribution, by taking into account foot slope areas in the digital terrain model.

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. Permafrost is represented by a spatial relation between BTS measurements, mean annual air temperature and potential direct solar radiation (Hoelzle, 1992; Hoelzle et al., 1993). Based on this relation, the model PERMAMAP was implemented in ARC/INFO (Hoelzle, 1994). The model distinguishes between the two permafrost classes probable permafrost and no permafrost. A speciality of this model is its capability of detecting permafrost occurrences at low altitudes (e.g., in extremely shaded areas) that are caused by radiation effects.

Both PERMAKART and PERMAMAP need a digital terrain model (DTM) as their main input. PERMAKART works with a DTM with a resolution of 100 m. A DTM with a resolution of 25 m is entered into the model PERMAMAP. The models were developed for estimations in the range between regional and local scale. To get a quick overview of the regional permafrost distribution pattern, a combined usage of both models is recommended.

Concepts and methods

Consistent with the two focal points of this work, research tasks were divided into two groups. First, an inventory of periglacial landforms – such as rock glaciers, perennial snow patches, periglacial lakes, debris flows, etc. – was established from interpretation of infrared aerial photographs taken in 1991 (scale 1:30,000) and field data analyses. The collected data were verified during several field trips in the summer of 1995. Additional data, e.g., spring temperatures, locations of burrows of hibernating marmots (Marmota marmota), were obtained during these field trips. Measurements of the bottom temperature of the snow cover (BTS) were carried out in three test regions in the spring of 1996.

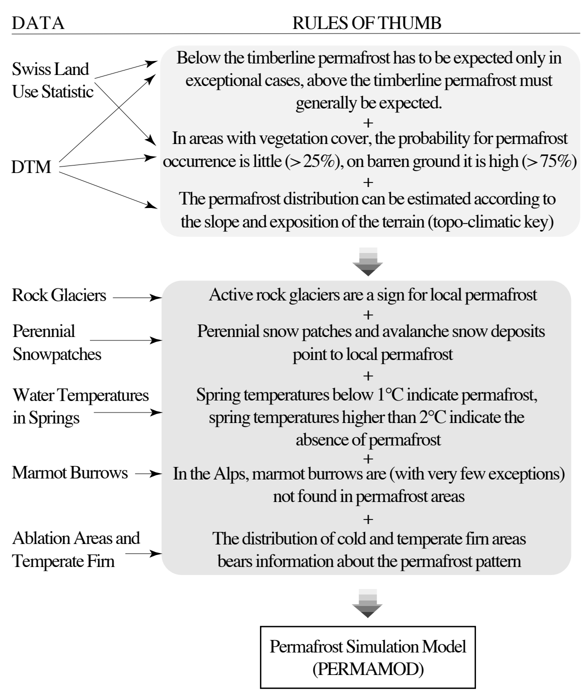

Figure 1. Structure of the model PERMAMOD. In a first step the data of the Swiss Land Use Statistics and the DTM are processed according to the instructions in the "rules of thumb". In a second step the field data are integrated into the model and classified in accordance to their value as permafrost indicators. In a third step, all intermediate results are synthesised in the permafrost model PERMAMOD.

In a second step, all data were integrated into the GIS-system ARC/INFO. The field data were then used as indicators to verify the two digital models PERMAKART and PERMAMAP.

Based on the field data and the "rules of thumb" (Haeberli et al., 1996), an additional model PERMAMOD (Frauenfelder, 1997) (cf. Figure 1) was developed and applied in the study area. This model joins topo-climatic information with bio-geographical features – extracted from the data base of the Swiss Land Use Statistic (BFS, 1992) – and the information that is included in the permafrost indicators (rock glaciers, perennial snow patches, spring temperatures, etc.).

Results

The Periglacial Inventory of the Fletschhorn Area

The inventory of periglacial landforms comprises the descriptions of 13 rock glacier parameters (such as length, width, co-ordinates, altitude above sea level, spring temperatures, percentage and composition of vegetation cover, etc.) for 74 rock glaciers. Additional information is included for features in the vicinity of the rock glaciers (i.e., existence of perennial snow patches, solifluction forms, etc.)

A thorough analysis of the field data leads to the following conclusions:

- The mean altitude of active rock glacier fronts is 2635 m a.s.l., while the average for fossil rock glaciers is 2510 m a.s.l. Hence the frontal parts of fossil rock glaciers are – on average – 120 m lower than the frontal parts of active rock glaciers. Some active rock glaciers reach down to lower altitudes (2300–2400 m a.s.l.). With some exceptions, all these rock glaciers are large forms. In contrast, small rock glaciers can only be found at altitudes between 2400 m and 3000 m a.s.l. This distribution may indicate ongoing permafrost degradation: only large active rock glaciers which have their accumulation areas at higher altitudes are able to creep into lower regions (2300–2400 m a.s.l.), and to maintain their thermal conditions at lower altitudes. Small active rock glaciers however seem to be in a state of decreasing activity due to degrading ground ice.

- The occurrence of debris flows in the study area is strongly connected to the permafrost distribution. Over fifty percent of the 67 investigated starting points of debris flows are situated in zones with a high probability of permafrost. One third of the starting points are situated at altitudes which show an abundance of fossil rock glaciers. Thus – relating to the conclusions made above – they are situated in areas which were characterised by permafrost in the past. In areas where permafrost is currently wide-spread, frost weathering and hence the production and accumulation of debris is considerable. As long as this debris is held together by ground ice, it is resistant to slide- and slip-translations. Melting of the ground ice leads to potential instability of steep slopes because of a high amount of debris that has accumulated. Results of investigations in other regions of the Swiss Alps (Zimmermann, 1990) suggest that an increase in debris flow activity should be expected in the Fletschhorn area, if climatic warming continues.

- The measurements of bottom temperatures of the snow cover (BTS) confirm the relation between altitude, exposition and permafrost probability that has been formulated in the original "rules of thumb". According to this topo-climatic relation, the lower boundary of permafrost on eastern slopes is distinctively higher than on W, N and NE exposures, but lower than on S, SW and SE aspects. Some BTS-measurements, which indicate permafrost at lower altitudes than expected, reveal the complex conditions at the lower boundary of discontinuous permafrost. Here the permafrost zones breaks up more and more into individual isolated patches.

Results of the Model Analysis

A comparison of the models showed that 61.3% of the area was classified the same way in both models, 20.1%

Table 1. Percentage of the correspondence between the models and the empirical field data of the Fletschhorn area. In the category of the BTS-measurements S stands for the test site Simplon, H for the site Hohsaas

	Rock glaciers			Perennial snow patches	Water temperature of springs			Bottom temperature of snow cover (BTS)			Marmot burrows
	active	inactive	fossil		< 1°C	≥ 1°C and ≤ 2°C	> 2°C	< -3°C	≥ -3°C and ≤ -2°C	> -2°C	
PERMAKART	78.5	71.9	44.7	79.6	63.6	28.6	70	S: 14.3	S: 30.0[2]	S: 97.8 H: 32.0	64
PERMAMAP	79.0	75.8	64.5	89.4	27.3	[1]	100	S: 4.8	[1]	S: 98.9 H: 80.0	98

of the area was classified in opposite ways and 18.7% of the area was classified in the class possible permafrost which exists only in the model PERMAKART.

The model PERMAKART indicates higher percentages of probable permafrost on S, SW, W and NW exposures than PERMAMAP. In contrast to this, PERMAMAP calculates larger areas of probable permafrost occurrences on the N- and NE-slopes. These results do not correspond with the results from other test regions of the Swiss Alps (Haeberli et al., 1996), where both models underestimate permafrost occurrence. The differences are small compared to the total area that has been calculated as permafrost area in both models, but the occurrence of such differences points to the fact that the transfer of the models from region to region should be done carefully and that the results of such simulations have to be verified with additional data.

The evaluation of the two existing models PERMAKART and PERMAMAP with the field data (Table 1) showed that both models correspond well with empirical data at high altitudes. The accuracy of the estimates diminishes towards lower altitudes where the permafrost becomes increasingly scattered.

The analyses also showed that the computer-based models are not yet able to explain all the occurrences. In detailed studies, further information, especially high resolution data from seismic soundings, geo-electrical measurements, etc., is needed to make precise statements about local permafrost occurrence.

The information about the permafrost distribution that is included in the field data is implemented in the model PERMAMOD. This model offers a synthesis of the relevant permafrost indicators and the topo-climatic function of the "rules of thumb". Compared to permafrost estimates calculated by PERMAKART and PERMAMAP (Figure 2), the most striking difference is the large extent of the possible permafrost area predicted by PERMAMOD. This results from the high weight that the bio-geographical data has in the model PERMAMOD (Figure 1). The estimation of the probable permafrost distribution however is much more detailed in this model. The information that is included in the field data and brought into the model allowed the generation of a differentiated permafrost map of the Fletschhorn area. Due to its high content of area-specific data, the model PERMAMOD probably shows the most accurate estimation of the local permafrost distri-

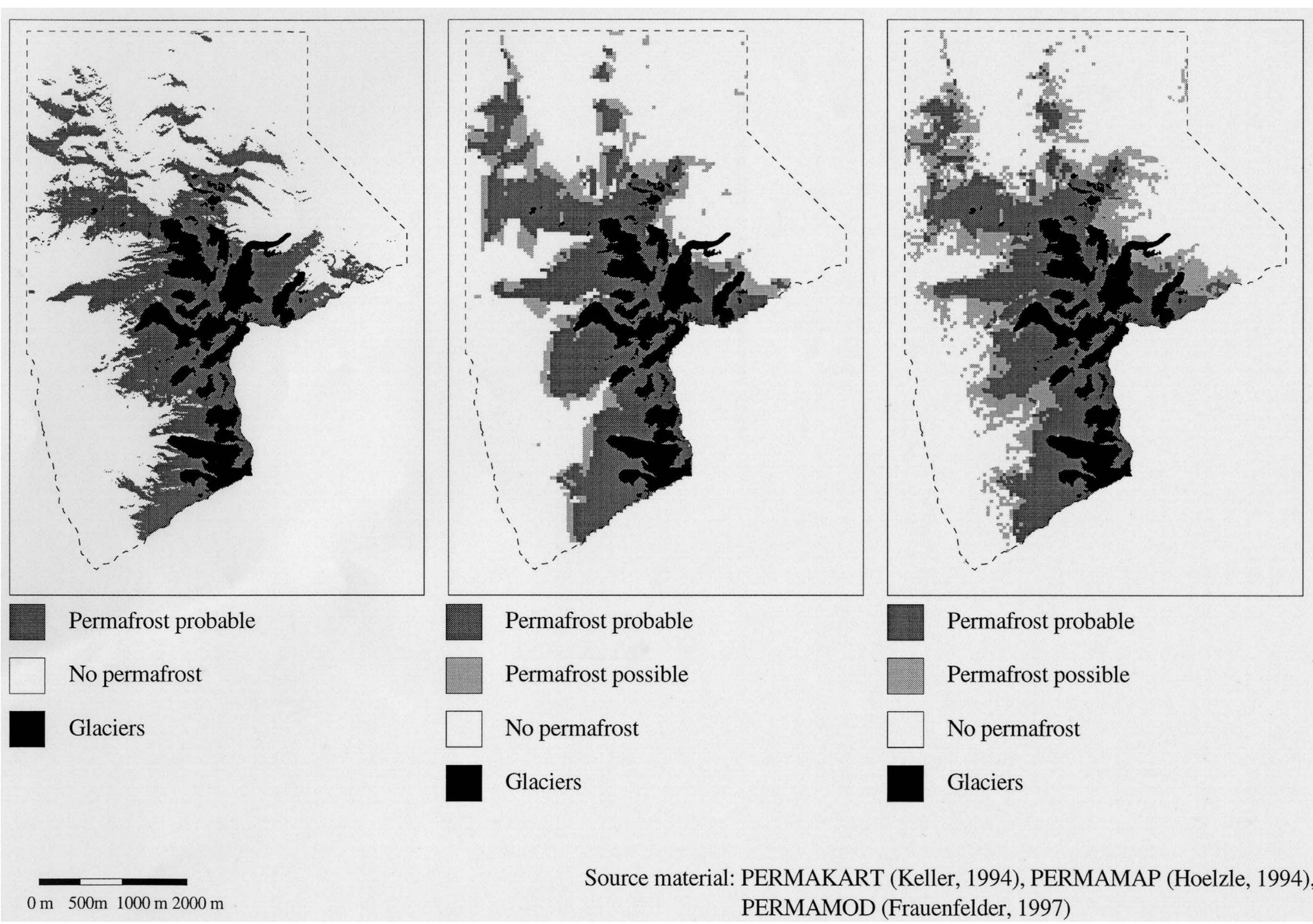

Figure 2. Comparison of the model results of the three permafrost distribution models PERMAKART (Keller, 1994), PERMAMAP (Hoelzle, 1994) and PERMAMOD (Frauenfelder, 1997).

bution. However, it has to be taken into account that one might lose independent variables – which could otherwise be used as important factors for model calibration and critical reflection – by combining different approaches in one model.

Perspectives

In the future, understanding of periglacial landforms must be improved. The importance of investigations relating to high mountain regions outside the Alps will increase. Especially for regions where detailed field studies and measurements are not available, the development of computer-based models can help to better understand the physical processes and improve natural hazard monitoring.

The application of such models should be thoroughly verified, e.g., by parallel study of maps and aerial photographs, or where possible by specific measurements (for instance BTS-measurements). The application of such computer models, together with their verification, would allow the generation of area-specific estimates as undertaken in the present work.

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References

BFS (1992). *Die Bodennutzung der Schweiz – Arealstatistik 1979/85, Kategorienkatalog,* Bundesamt für Statistik, Bern.

Frauenfelder, R. (1997, unpubl). *Permafrostuntersuchungen mit GIS – Eine Studie im Fletschhorngebiet.* Master thesis, Department of Geography, University of Zürich (77 pp.).

Haeberli, W. (1973). Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost in den Alpen. *Zeitschrift für Gletscherkunde und Glazialgeologie,* **XI (1-2)**, 221-227.

Haeberli, W. (1975). Untersuchungen zur Verbreitung von Permafrost zwischen Flüelapass und Piz Grialetsch (Graubünden). *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich,* **17**, 221 pp.

Haeberli, W. (1985). Creep of mountain permafrost. Internal structure and flow of alpine rock glaciers. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich,* **77**, 142 pp.

Haeberli, W., Hoelzle, M., Dousse, J. P., Ehrler, C., Gardaz, J. M., Imhof, M., Keller, F., Kunz, P., Lugon, R. and Reynard, E. (1996). *Simulation der Permafrostverbreitung in den Alpen mit geographischen Informationssystemen.* Arbeitsbericht im Rahmen des Nationalen Forschungsprogrammes NFP31 "Klimaänderungen und Naturkatastrophen" (58 pp.).

Hoelzle, M. (1992). Permafrost Occurrence from BTS Measurements and Climatic Parameters in the Eastern Swiss Alps. *Permafrost and Periglacial Processes,* **3**, 143-147.

Hoelzle, M. (1994). Permafrost und Gletscher im Oberengadin. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich,* **132**, 119 pp.

Hoelzle, M., Haeberli, W. and Keller, F. (1993). Application of BTS-measurements for modelling permafrost distribution in the Swiss Alps. In *Proceedings of the Sixth International Conference on Permafrost, Peking,* pp. 272–277.

Keller, F. (1992). Automated Mapping of Mountain Permafrost Using the Program PERMAKART within the Geographical Information System ARC/INFO. *Permafrost and Periglacial Processes,* **3**, 133–138.

Keller, F. (1994). Interaktionen zwischen Schnee und Permafrost – Eine Grundlagenstudie im Oberengadin. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich,* **127**, 145 pp.

Zimmermann, M. (1990). Debris flows 1987 in Switzerland: Geomorphological and meteorological aspects. Hydrology in Mountainous Regions. *II-Artificial Reservoirs; Water and Slopes. IHAS-Publication,* **194**, 387–393.