Mountain Permafrost Hydrology

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Summary

Permafrost is widespread in the Swiss Alps and hidden in talus slopes and bedrock above the tree line. Frozen ground in mountain slopes is highly variable in its spatial distribution, can contain high amounts of ice and can creep downslope. Research on mountain permafrost has a short history and studies on hydrology interaction are still scarce. Permafrost ice may have different origins and can be several thousand years old. Its total volume in the Alps is roughly estimated to be one quarter of current glacier ice. Permafrost modifies mountain hydrology due to its low storage capacity and high impermeability. Ice melt contributes to stream runoff in small amounts. Permafrost observations in the Swiss Alps show generally increasing ground temperatures and active layer thickness, decreasing ice contents and rising rock glacier creep velocities. Rock fall activity from the active layer seems to be increasing during heat waves. Large rock avalanches are rare and occur year-round, with permafrost acting as a long-term catalyser.

By the end of the 21st century mountain permafrost in the Swiss Alps may retreat to 10 m depth at ice-rich sites and disappear completely below 3500 m asl. in steep rock slopes. In ice-rich ground, permafrost degradation is a slow process and subsurface temperature fields are projected to deviate strongly from steady state conditions in the future. Active layer thickening and permafrost degradation promote mass movements and hazardous process chains reaching low elevations are possible. Concerning hydrology, degradation of mountain permafrost can increase runoff during thaw and when permafrost has disappeared, it can decrease flood peaks. Further, permafrost degradation can have adverse effects on water chemistry downstream. Long-term measurements and complementing observations are fundamental to better understand permafrost processes in high mountains, improve models and enhance awareness of the impacts of permafrost degradation. Intensified investigation of the processes linking permafrost degradation and slope instability is required. Knowledge gaps exist regarding the age, distribution and volume of permafrost ice stored in European mountains, its potential impact on future water resources and hydrological systems.

Keywords: *Ice-rich ground, permafrost degradation, mountain permafrost hydrology, climate change impacts, mass movements, monitoring techniques*

Zusammenfassung

Permafrost ist weit verbreitet in den Schweizer Alpen und existiert verborgen in Schutthalden und steilen Felswänden oberhalb der Waldgrenze. Permanent gefrorener Untergrund kann viel Eis enthalten, talabwärts kriechen, und seine räumliche Verbreitung ist sehr variabel. Gebirgspermafrost ist noch ein sehr junger Forschungszweig und es gibt erst wenige Studien zur Interaktion von Permafrost und Hydrologie. Das im Permafrost enthaltene Eis ist sehr unregelmässig verteilt: Schutthalden oder Blockgletscher sind oft eisübersättigt, während Eis in steilen Permafrost-Felswänden vor allem in Klüften oder Poren enthalten ist. Das gesamte Eisvolumen im Permafrost in den Europäischen Alpen wird grob auf etwa einen Viertel des Gletschervolumens geschätzt. Permafrosteis kann verschiedenen Ursprungs sein und ein Alter von mehreren Tausend Jahren aufweisen. Permafrost beeinflusst die Gebirgshydrologie vor allem durch eine verminderte Speicherkapazität und hohe Impermeabilität, z.B. von Felsklüften oder Schutthalden. Die Eisschmelze im Sommer trägt nur wenig zum Gesamtabfluss bei. Systematische Beobachtungen von Permafrost in den Schweizer Alpen seit dem Jahr 2000 zeigen eine Zunahme der Temperaturen im Untergrund und der Mächtigkeit der sommerlichen Auftauschicht, eine Abnahme des Eisgehalts und eine Zunahme der Kriechgeschwindigkeit von Blockgletschern. Oberflächennahe Felsstürze aus Permafrostgebiet ereignen sich vor allem in den warmen Sommer- und Herbstmonaten. Sie werden nicht flächendeckend dokumentiert, scheinen aber während Hitzewellen zuzunehmen. Grössere Ereignisse aus tieferen Schichten sind dagegen seltener und können ganzjährig auftreten. Hier kann Permafrost als langfristiger Katalysator einen Einfluss haben.

Bis zum Ende des 21. Jahrhunderts könnte der Gebirgspermafrost in der Schweiz in eisreichem Untergrund bis in eine Tiefe von etwa 10 m und im steilen Fels oberhalb von 3500 m ü.M. verschwunden sein. In steilen und sehr hochgelegenen Felsgipfeln degradiert der Permafrost am schnellsten, da nur wenig Eis im Untergrund vorhanden ist und die Wärme von mehreren Seiten in den Boden eindringen kann. In eisreichem Untergrund von Blockgletschern oder Schutthalden zieht sich der Permafrost nur langsam zurück, da sehr viel Energie für den Phasenwechsel benötigt wird. Wegen der starken Verzögerung, mit der Temperaturänderungen an der Oberfläche in den Untergrund weitergeleitet werden, können Permafrosttemperaturen in Zukunft stark vom stationären Zustand abweichen: während in den oberflächennahen Schichten bereits keine Permafrostbedingungen mehr herrschen, ist der Untergrund noch dauernd gefroren. Die Zunahme der Auftauschicht und die Permafrostdegradation können zu Massenbewegungen und gefährliche Prozessketten bis in tiefe Lagen beitragen, wie sie im Sommer 2017 im Val Bondasca beobachtet wurden. Bezüglich Hydrologie, kann Permafrostdegradation zu einer Abflusszunahme während der Schmelze führen sowie zu einer Verkleinerung der Abflussspitzen nach dem Verschwinden des Permafrosts. Als Folge von Permafrostdegradation sind auch negative Auswirkungen auf die Wasserqualität stromabwärts möglich. Langfristige Messungen sowie ergänzende Beobachtungen weiterer Parameter sind fundamental für ein besseres Prozessverständnis, für die Verbesserung von Modellen, sowie für die Antizipation der Auswirkungen von Permafrostdegradation in den Schweizer Alpen oder den Gebirgen weltweit. Insbesondere müssen Prozesse, welche die Stabilität steiler Gebirgsflanken beeinflussen, besser untersucht werden. Weiter sind das Alter, die Verteilung und das aktuelle sowie zukünftige Volumen von Untergrundeis in den Alpen noch immer erst in den groben Zügen untersucht. Das gilt insbesondere auch für dessen Auswirkungen auf die Wasserverfügbarkeit und Hydrologie für heutige wie auch für zukünftige Klimabedingungen.

Résumé

Le pergélisol est très répandu dans les Alpes suisses et caché dans les talus rocheux et les parois rocheuses au-dessus de la limite des arbres. Le sol gelé des pentes montagneuses est très variable dans sa répartition spatiale, peut contenir de grandes quantités de glace et peut se déplacer vers l'aval par fluage. La recherche sur le pergélisol de montagne a une courte histoire et les études sur les processus hydrologiques sont encore rares. Le pergélisol peut avoir des origines différentes et peut être vieux de plusieurs milliers d'années. Son volume total dans les Alpes est estimé à environ un quart de la glace de glacier actuelle. Le pergélisol modifie l'hydrologie des montagnes en raison de sa faible capacité de stockage et de sa grande imperméabilité. La fonte des glaces contribue en petites quantités au ruissellement des cours d'eau. Les observations du pergélisol dans les Alpes suisses montrent généralement une augmentation de la température du sol et de l'épaisseur de la couche active, une diminution de la teneur en glace et des vitesses de fluage des glaciers rocheux. La fréquence des éboulements provenant de la couche active semble augmenter pendant les vagues de chaleur. Les grands éboulements sont rares et se produisent toute l'année, le pergélisol agissant comme catalyseur à long terme.

D'ici la fin du 21e siècle, le pergélisol de montagne dans les Alpes suisses pourrait reculer jusqu'à 10 m de profondeur sur les sites riches en glace et disparaître complètement en dessous de 3500 m d'altitude dans les pentes rocheuses raides. Dans les sols riches en glace, la dégradation du pergélisol est un processus lent et les températures du sol devraient s'écarter fortement des conditions d'état stationnaire à l'avenir. L'épaississement de la couche active et la dégradation du pergélisol favorisent les mouvements de masse et les chaînes de processus dangereux atteignant les altitudes basses sont possibles. En ce qui concerne l'hydrologie, la dégradation du pergélisol de montagne peut augmenter le ruissellement pendant le dégel et, lorsque le pergélisol a disparu, elle peut réduire les pointes de crue. De plus, la dégradation du pergélisol peut avoir des effets néfastes sur la chimie des eaux en aval. Les mesures à long terme et les observations complémentaires sont essentielles pour mieux comprendre les processus du pergélisol en haute montagne, améliorer les modèles et accroître la sensibilisation aux impacts de la dégradation du pergélisol. Il est nécessaire d'intensifier l'étude des processus qui lient la dégradation du pergélisol et l'instabilité des pentes. Il existe des lacunes dans les connaissances sur l'âge, la distribution et le volume de la glace du pergélisol stockée dans les montagnes européennes, ainsi que son impact potentiel sur les ressources en eau et les systèmes hydrologiques futurs.

Inhalt

List of abbreviations

ALT	Active layer thickness
ERT	Electrical resistivity tomography
MAGST	Mean annual ground surface temperature
PERMOS	Swiss Permafrost Monitoring Network
RCM	Regional climate model
TWE	Total water equivalent

1 Introduction

1.1 Permafrost in Switzerland

Permafrost is a widespread thermal phenomenon in polar and alpine environments and essentially controlled by climatic conditions. Contrary to glaciers, permafrost and its changes are invisible because permafrost is below the surface and defined thermally: ground with a maximum temperature of 0 °C throughout the year. The practical relevance and the difference to non-permafrost ground, however, is due to the ice contained in the ground: pore- and excess ice, ice lenses or ice-filled fractures can significantly alter geotechnical and hydrological characteristics. In mountain areas, permafrost is mainly relevant for landscape evolution (Müller et al. 2014), infrastructure (Bommer et al. 2010), and natural hazards (Haeberli & Gruber 2009).

Permafrost is estimated to underlie 5% of the area of Switzerland (Boeckli, et al. 2012b; BAFU 2005), or twice the area covered by glaciers, and exists above the tree line in high-elevation bedrock slopes and the talus slopes at their base. The majority of permafrost is located between 2600 and 3000 m asl. (Boeckli et al. 2012b) with temperatures between –3 and 0 °C (PERMOS 2019) and is hence particularly sensitive to atmospheric changes. The coldest permafrost is located in shady rock walls at the highest elevations: recent mean annual ground surface temperatures (MAGST) measured north of the Matterhorn summit are –12 °C, i.e. values typically measured in the high Arctic (Noetzli et al. 2018 and Arpa Aosta personal Communication). The active layer that thaws annually in summer is a few metres thick in the Alps (PERMOS 2019). If the topography is steep enough, ice-rich rock debris masses can creep downslope and produce distinct landforms called rock glaciers (Fig. 1, Haeberli et al. 2006), which are indicators of past or present existence of permafrost.

Figure 1: Active rock glacier below Marchhüreli, Davos GR. Photo: J. Noetzli.

The steep and complex Alpine topography influences surface cover, snow distribution and subsurface characteristics. Ground surface temperatures can thus vary considerably over short distances: The difference in MAGST between south and north faces at the same elevation can be as high as 8 °C (Gruber et al. 2004b; PERMOS 2007). Fine scale variations can be a few degrees Celsius over a few metres in homogeneous terrain (Gubler et al. 2011). At depth, permafrost integrates over larger surface areas and time periods and its pattern of occurrence is driven by the geometry of the topography and by the spatial and temporal variability of the surface temperatures (Noetzli et al. 2007). The thickness of the permafrost body in the Swiss Alps ranges from decametres at the lower limit of permafrost occurrence to several hundreds of metres in the highest mountain peaks. Due to the high thermal inertia of the system, permafrost temperatures at depths of hundreds of metres are still influenced by climate conditions of the last glacial period (Haeberli et al. 1984; Noetzli & Gruber 2009; M. Luethi & Funk 2001).

The invisibility of permafrost, together with challenging access and measurements in rough terrain make the understanding of spatial and temporal patterns of occurrence, characteristics and changes the principal challenge of mountain permafrost research. Research is largely based on a limited number of local measurements, biased to easily accessible locations, and models of different complexity and spatial extent. Mountain permafrost research has a relatively short history of 40–50 years and intensified in the past two decades (Haeberli et al. 2011). After the summer 2003 heat wave the investigation of frozen bedrock in high mountains and related questions regarding slope stability has been in the focus of interest.

1.2 *Objectives of this chapter*

In earlier reports such as the CH2014-IMPACTS report (CH-Impacts 2014), the topic of mountain permafrost hydrology was not addressed. With this report, we provide a baseline of the available knowledge of mountain permafrost in the Swiss Alps for future reference. We compile an overview of the current understanding of mountain permafrost in the Swiss Alps, its distribution and characteristics, observed and projected changes, and expected impacts on slope stability, infrastructure and hydrological aspects. We also briefly describe the measurement techniques and modelling approaches applied. The chapter closes with a summary of the most important open research questions. The literature cited mainly includes studies on mountain permafrost published in scientific journals and assessments of long-term observation data. We focus on permafrost hydrology interactions wherever information is available. However, systematic studies on permafrost hydrology in mountain areas are still limited.

Take-home messages

Permafrost is widespread in the Swiss Alps and hidden in talus slopes and bedrock above the tree line. Frozen ground in mountain slopes is highly variable in its spatial distribution, can contain high amounts of ice and can creep downslope.

Mountain permafrost research has a short history and studies on mountain permafrost hydrology are scarce.

2 Ground ice and mountain permafrost hydrology

2.1 Origins and age of permafrost ice

The potential origins of the ice contained in mountain permafrost can be summarized in two categories (Haeberli & Vonder Mühll 1996; Berthling 2011): Congelation ice (epigenetic formation) includes freezing of a water body, segregation or injection ice that exists as ice lenses or massive ice. Sedimentary ice (syngenetic formation) results from the firnification of avalanche snow and patches of glacier ice buried by rock fall. The available information comes from rare outcrops, chemical analyses of drill cores and electrical resistivity soundings. The exact origin of the ice is often unclear and a combination of sources is likely (Haeberli & Vonder Mühll 1996; Lambiel & Pieracci 2008). In rock glaciers, permafrost ice may have existed for several millennia throughout at least the upper Holocene (Haeberli & Vonder Mühll 1996; Frauenfelder et al. 2001; Frey et al. 2016), because the thick debris layer at the surface efficiently insulates and conserves the underlying ice.

In bedrock, water infiltration into joints can lead to ice formation upon contact with the cold rock and vapour transport along temperature gradients can lead to the formation of segregated ice lenses. The growth of ice in cracks and pores can be an efficient contribution to rock weathering and fracture widening (Matsuoka & Murton 2008) and occur over several millennia. This was confirmed by dating of plant material in ice samples from rockfall detachments (cf. Fig. 2, Phillips et al. 2016, pers. comm. L. Ravanel, Univ. de Savoie).

Figure 2: Ice in the detachment zone of a rock fall on Piz Kesch. Photo: M. Phillips.

2.2 Ice volumes in Alpine permafrost

Boeckli (2013) provides a review on the internal structure and ice content of typical periglacial landforms in mountain regions. Permanently frozen talus slopes and rock glaciers usually have high volumetric ice contents (ca. 20–90%) and are supersaturated. Talus slopes can contain thick layers of ice or ice lenses, particularly in the lower parts (Scapozza et al. 2011; Lambiel & Pieracci 2008). In rock glaciers, massive ice is often present and covered by a thick layer of rock debris (Hoelzle et al. 2002). In frozen bedrock slopes, the ice is contained in fractures and in the rock pores (Matsuoka & Murton 2008), so ice contents are low and in the order of the porosity (cf. Gruber & Haeberli 2007). Large surfaces of ice are often observed in permafrost rock fall scars (Fig. 1). Considerable ground ice is found in moraines (Hauck et al. 2003) or as dead ice in recently deglaciated glacier forefields (Kääb & Kneisel 2006).

The spatial distribution of mountain permafrost is modelled using different approaches (Section 4) and the distribution of rock glaciers is analysed in regional inventories (Kenner & Magnusson 2016; Cremonese et al. 2011). However, no complete rock glacier inventory is available for Switzerland. The distribution of ice-bearing talus slopes – one of most common landforms in mountain environments – has hardly been investigated. Thus, little is known on the regional distribution and total volume of the permafrost ice. A first estimation for the entire European Alps was provided by Boeckli (2013) based on statistically modelled MAGST and subsurface structures parameterized based on values found in literature. The results indicate that about 75% of the ice volume is contained in talus slopes, around 20% in rock glaciers and 5% in bedrock with a total water equivalent (TWE) of the permafrost ice of 24–28 km^3. Such estimates are highly uncertain because of the spatial extrapolation of scarce information on subsurface structures and paleo-climatic effects. For comparison, Farinotti et al. (2009) estimated a glacier ice volume of 65 km^3 in Switzerland for 2008. The TWE found by Boeckli (2013) is about one quarter of the TWE of Alpine glaciers (Levermann (2012). In dry mountain ranges such as the Chilean Andes, however, the TWE of permafrost ice is estimated to be significantly higher than the TWE of glaciers (Azócar & Brenning 2010; Arenson & Jakob 2010).

2.3 Mountain permafrost hydrology

Permafrost hydrology is a rapidly progressing research field in arctic areas and a recent review is given by Walvoord and Barret (2016). In mountain areas, the available knowledge is limited to a number of specific studies and information from polar areas cannot be transferred directly because of the different characteristics of high latitude permafrost (i.e., vegetation layer, fine sediments and flat topography prone to surface ponding above the permafrost table). In mountain catchments, most of the water from snowmelt and rain flows through the ground before entering a stream. Ice-rich ground affects the hydrology mainly by changing runoff paths due to the lower storage capacity induced by the lower sediment porosity and hydraulic conductivity of frozen versus non-permafrost ground (Rist & Phillips 2007; Rogger et al. 2017). It can also induce water accumulation, for example due to the presence of ice plugs in bedrock fractures (Krautblatter et al. 2013) or lake damming by rock glaciers (Fig. 3, Colombo et al. 2018). Significant water accumulations (70–80 m high) were for example visible in the 2017 Pizzo Cengalo rock avalanche detachment zone.

The active layer influences near-surface water storage, drainage, and routing (Walvoord & Kurylyk 2016; Rogger et al. 2017). Krainer and Mostler (2002) distinguish near-surface run-off in a coarse grained surface layer with high hydraulic conductivity and base flow in a finer-grained layer below the permafrost for rock glaciers. Measurements of stream runoff rates, electrical conductivities and isotopes below rock glaciers indicate that snow melt is the dominant water source in spring, whereas rainfall dominates during summer and thawing permafrost increases base flow in late summer (Colombo et al. 2018; Krainer & Mostler 2002; Williams et al. 2006; Leopold et al. 2011). Water temperatures are generally below 1 °C (Thies et al. 2013), indicating water-ice contact either at the permafrost table (Colombo et al. 2018), below the permafrost at the base of the rock glacier (Vonder Mühll 1992) or in intra-permafrost taliks (Zenklusen Mutter & Phillips 2012). Observations and hydrological modelling indicate that active rock glaciers can be saturated during the snow melt period, while talus slopes are never completely saturated due to their high hydraulic conductivity (Rogger et al. 2017).

Figure 3: Suvretta rock glacier in the Upper Engadine is damming the stream Ova da Suvretta. Photo: A. Bauder.

Many active rock glaciers lose some water in summer. The actual fraction of the runoff contribution based on the melt of ground ice is hardly known and difficult to quantify because substantial amounts of water can be lost to subsurface infiltration and evapotranspiration. A few studies based on remote sensing indicate highly variable annual ice melt rates with surface subsidence of centimetres to decametres per year and volume losses between 320 m^3 in the Schafberg rock glacier in the Engadine (pers. comm. R. Kenner, SLF) and 7515 m^3 in the Austrian Hinteres Langtalkar rock glacier (Kellerer-Pirklbauer & Rieckh 2016). Rock glaciers and ice-rich talus slopes only have little influence on total runoff because the debris cover insulates the underlying ice and the amount of ice melt water is small. They do however have a strong effect on discharge patterns because water is released faster than in catchments with dry bedrock or talus (Krainer & Mostler 2002). The seasonal discharge pattern is similar to that of glaciers, but fresh water stored in rock glaciers is primarily considered relevant for local water management in arid areas during the melt season (Colombo et al. 2018; Krainer & Mostler 2002).

Little is known on hydro-thermal processes in steep permafrost bedrock slopes, but they are relevant for their stability and the timing of rock fall activity (Gruber et al. 2004a; Hasler et al. 2012).

Active rock glaciers can efficiently contribute to sediment transfer in periglacial environments (e.g., Gaertner-Roer 2012; Barsch 1977) and a few studies quantify the transfer from the rock glacier front into torrential gullies. Kummert & Delaloye (2018) estimated annual sediment transfer rates between 1500 m^3y^{-1} to 7800 m^3y^{-1} for three rapidly moving rock glaciers in the Valais, for slowly moving landforms the sediment transfer rates are expected to be considerably smaller. Kummert & Delaloye (2018) showed that the eroded sediments accumulate in the upper sectors of the torrential gullies, where they can be mobilized as debris flow. According to this study there is a clear relation between rock glacier creep velocities and sediment transfer rates at the rock glacier front, and hence the sediment availability in the headwater of the studied torrents.

Take-home messages

Permafrost ice may have different origins and can be several thousand years old. Its total volume in the Alps is estimated to be one quarter of current glacier ice.

Permafrost modifies mountain hydrology due to its low storage capacity and high impermeability. Ice melt contributes to stream runoff in small amounts. Rock glacier creep velocities influence the sediment availability of periglacial environments.

3 Recent changes in mountain permafrost in Switzerland

The Swiss Permafrost Monitoring Network PERMOS systematically collects data to describe the state and changes of mountain permafrost in the Swiss Alps (PERMOS 2019). Systematic observations only cover the past 15–30 years, which is short for the determination of long-term trends. In addition, this period was significantly warmer than the 1961–1990 average in Switzerland (Figs. 4, CH2018 2018, PERMOS 2019). The relation between atmospheric conditions and surface temperatures is not straightforward. In particular, the snow cover insulates the ground from the atmosphere and can have a warming or cooling effect depending on its timing. Heat transfer into the permafrost largely occurs through conduction and surface temperature variations are delayed and dampened with depth (Lachenbruch et al. 1988). Latent heat exchange during phase change can mask atmospheric changes.

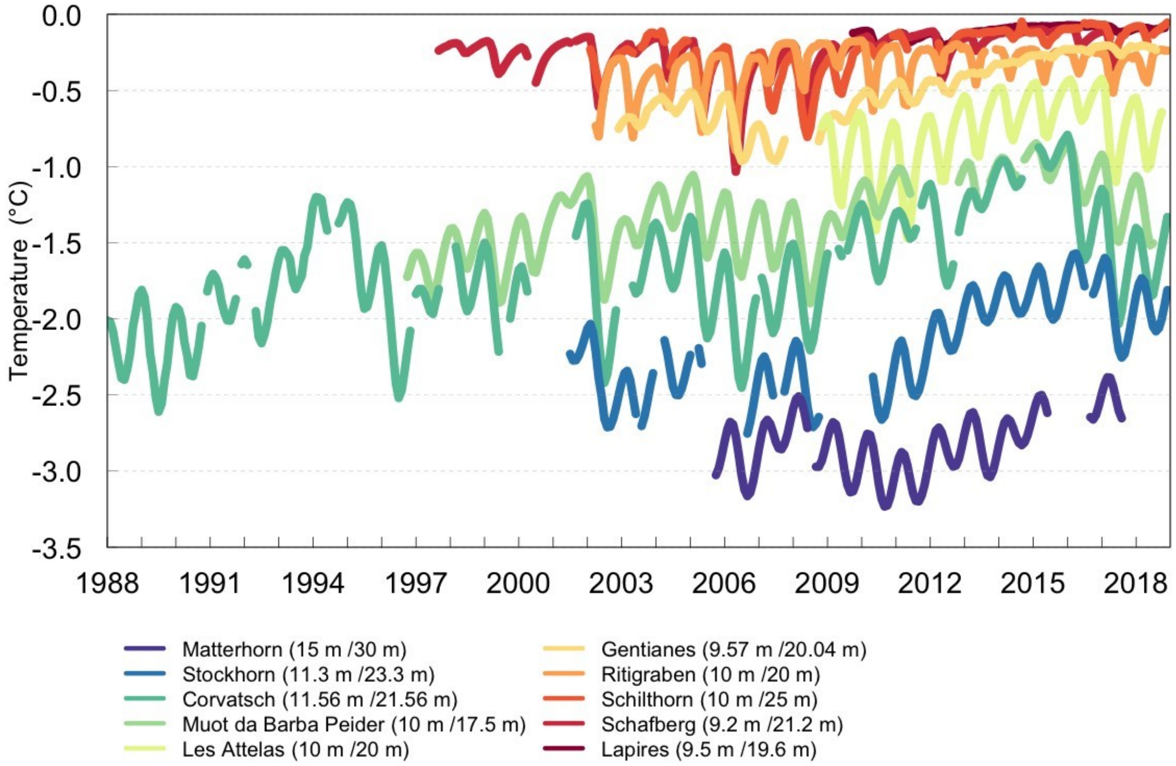

Figure 4: Borehole temperatures measured at around 10 m depth in permafrost in the Swiss Alps. Source: PERMOS.

The only direct permafrost observations are ground temperatures measured in boreholes. Data from over 20 boreholes in the Swiss Alps reveal a general warming trend in the last three decades, and particularly in the past decade (PERMOS 2019). In rock glacier Murtèl an increase of ca. 1 °C between 10 and 20 m was recorded since 1988. A temporary cooling to about 20 m depth was observed following two winters with late and thin snow covers in 2016 and 2017. Changes at sites with temperatures just below 0 °C are smaller due to the latent heat effects, a pattern that is observed globally (Noetzli et al. 2018; Biskaborn et al. 2019; Romanovsky et al. 2010). Temperatures at the surface (and with some delay in the subsurface) of steep bedrock slopes with little to no snow closely follow air temperatures (Gruber et al. 2004b). Systematic measurements only started after 2003 (PERMOS 2007), however, rock temperatures were continuously high for the past decade (Noetzli et al. 2018; PERMOS 2019; Magnin et al. 2015) and are now expected to be at record level. The summer air temperatures and the winter snow cover mainly influence the annual active layer thickness (ALT), which is linearly interpolated between neighbouring thermistors in boreholes. In most of the PERMOS boreholes ALT increased by several decimetres (PERMOS 2019) since the start of the measurements. On Schilthorn, the ALT has doubled from 3–4 m in the year 2000 to 7 m or more since 2009. In contrast, ALT changes in ice-rich ground are smaller (Fig. 5). Despite the uncertainties of the method related to non-linear thawing processes, we consider the trend to be correct.

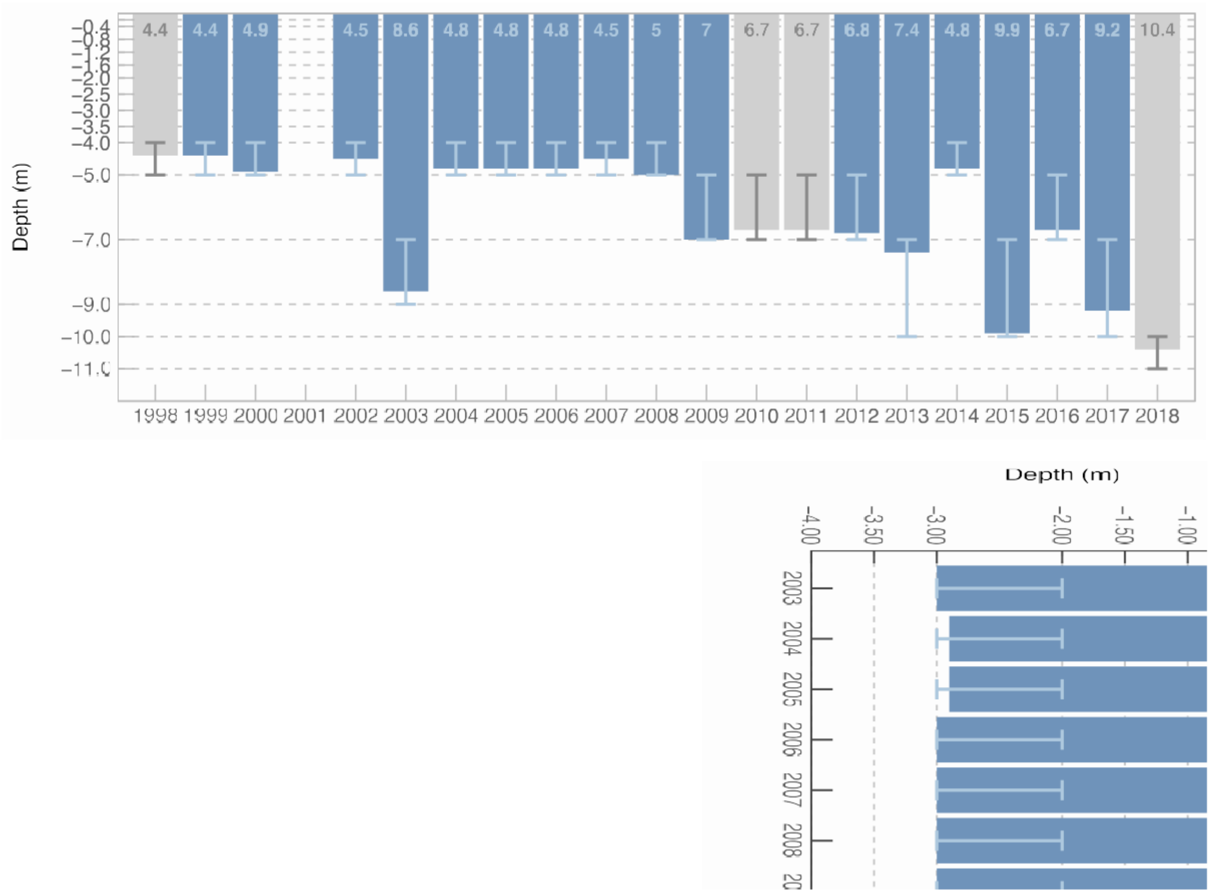

Figure 5: Evolution of active layer thickness (ALT) in the borehole on the north slope of Schilthorn and in an ice-rich talus slope on Flüelapass. Error bars mark the depths (thermistors) used to calculate the ALT, grey bars indicate years with reduced data quality. Source: PERMOS

Indirect geophysical measurements such as electrical resistivity tomography (ERT) describe the physical properties of the subsurface, including the distribution and changes of unfrozen water and ice content (Hilbich et al. 2008; Mewes et al. 2017; Hauck 2013). Annual surveys at several PERMOS sites reveal generally decreasing electrical resistivities indicating a decrease in ground ice content. These observations confirm permafrost degradation also for sites with small temperature changes due to latent heat effects (PERMOS 2019). The longest time series is measured since 1999 on Schilthorn (Figs. 4–7). Here, decreasing values were also observed during the recent temporary cooling, indicating that the ice content did not recover within this short time.

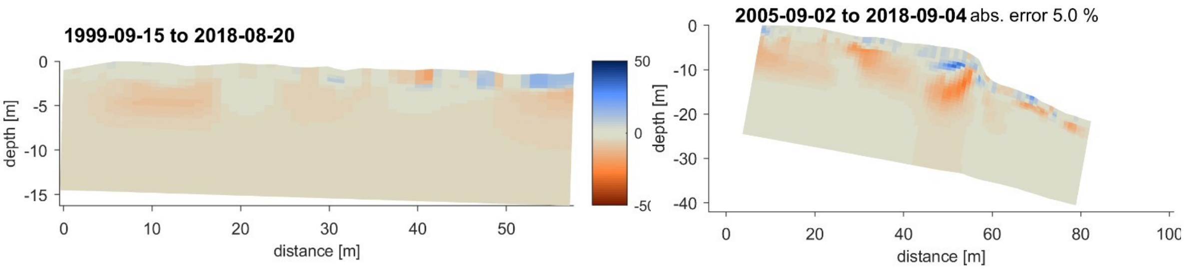

Figure 6: Percentual changes in electrical resistivity along a profile at Schilthorn (left) and Stockhorn (right). Red colours indicate a resistivity decrease and corresponding loss of ground ice. Figure: PERMOS.

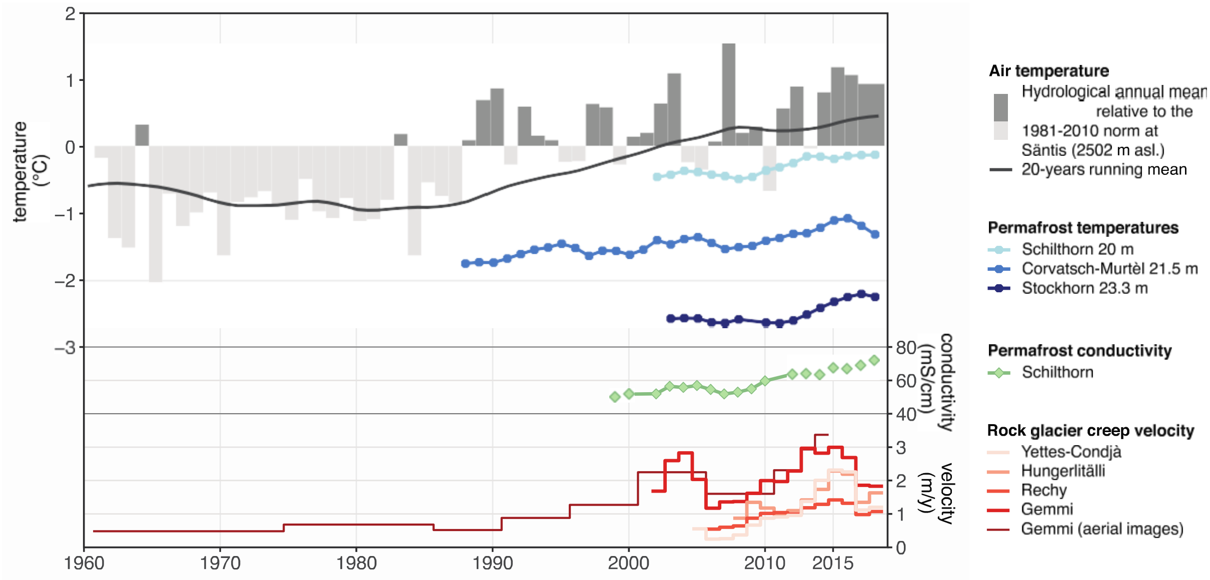

Figure 7: Evolution of PERMOS observations compared to air temperature anomalies 1960 to 2018: deviation to the mean air temperature 1961–1990 (light and dark bars) and 10-year running mean (black line), mean annual ground temperature at 20 m depth in boreholes (blue lines), electrical resistivities (green line) and annual creep velocities of rock glaciers (red lines). Data source: MeteoSwiss (meteo data), PERMOS (permafrost data and figure).

Rising ice temperatures and water contents influence the deformability of ice and thus the dynamics of rock glaciers. Creep velocities and changes in ground surface level can be quantified by terrestrial geodetic surveys (PERMOS 2010). Combinations of airborne and terrestrial techniques were used to reveal short-term, seasonal and annual creep velocity patterns (Wirz et al. 2015; Kenner et al. 2017). The pattern of inter-annual velocity variations is consistent for rock glaciers all over the Alps (Delaloye et al. 2010) and follows the permafrost temperatures observed (Fig. 7). Measured creep velocities in the 1990s were in the order of a few decimetres and the same landforms now move 2–10 times faster (PERMOS 2019).

Several recent summer heat waves (e.g. 2003, 2015, 2018) coincided with intensified rockfall activity during summer (e.g. Gruber et al. 2004a). These were mostly near-surface failures (active layer) with volumes of several 1000 m^3. Ice and/or water were often observed in the detachments. Large events of up to a several millions of m^3 also occurred from permafrost areas in the past decades (Fischer et al. 2012; Noetzli et al. 2003). Such large events can occur all year and may be related to deep-reaching thermal perturbations. Advective heat transport along clefts may be an important modifier for thermal and hydrological conditions of ice-filled clefts and their stability (Hasler et al. 2011). Trend analyses are difficult due to a lack of organized monitoring and potential observer bias. Nevertheless, recent studies underline the relation between temperature increase and rock fall activity in mountain permafrost, especially for larger events, where the observation bias is likely smaller (Paranunzio et al. 2018; Ravanel & Deline 2011; Allen & Huggel 2013; Huggel et al. 2012).

Take-home messages

Permafrost observations in the Swiss Alps show generally increasing ground temperatures and ALT, decreasing ice contents and rising creep velocities.

Rock fall activity from the active layer seems to be increasing during heat waves. Large rock avalanches are rare and occur year-round, with permafrost acting as a long-term catalyser.

4 Projections and impacts of permafrost changes in the Swiss Alps

4.1 Model simulations of changes in mountain permafrost

Modelling techniques are applied to estimate permafrost conditions in time and space where no field data is available. The most suitable approaches to study the long-term evolution of permafrost are downscaling and coupling of regional climate models with regional to local process-based permafrost models. Major challenges are related to the high grid resolution of driving data to simulate fine-scale processes in heterogeneous terrain (Fiddes & Gruber 2014; Salzmann et al. 2007; Marmy et al. 2016; Westermann et al. 2016), the integration of the snow cover (Gisnas et al. 2014; Lehning et al. 2006), coupled water and heat transfer (Dall'Amico et al. 2011) or lateral heat fluxes (Fig. 8, Noetzli et al. 2007). Statistical approaches (Boeckli et al. 2012a; Hoelzle 1994; Deluigi et al. 2017) are usually calibrated with observations and used to estimate the current spatial distribution. They are thus not directly suitable to predict permafrost change.

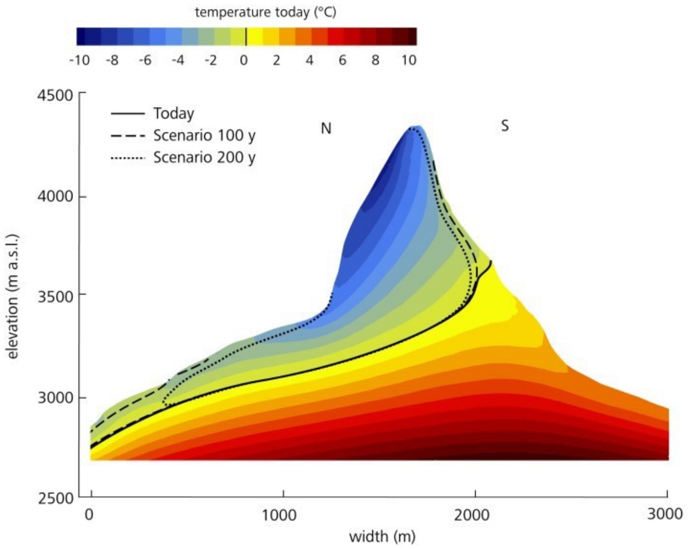

Figure 8: Idealized simulation of the subsurface temperature field of the Matterhorn. The 0°C isotherm defines the permafrost body today (black line) and in one or two decades (dashed/dotted lines). Adapted from Noetzli and Gruber (2009).

Recent long-term simulations driven by calibrated scenarios from an ensemble of RCM projections show a degradation trend at all of the borehole sites considered (Marmy et al. 2016; Scherler et al. 2013). The mean increase in air temperature until the end of the 21st century compared to the period 2000–2010 downscaled to the borehole sites is 3.4–4.2 °C, which is slightly less than the projection for unmitigated warming in Switzerland by CH2018 (CH2018 2018). The 10 m layer of all sites (and for some even the 20 m layer) is projected to be unfrozen by the end of the 21st century, but with considerable differences regarding the timing, indicating non-uniform rates of permafrost degradation and irregular spatial distribution of thaw. The main drivers are the reduction in snow cover duration and the increase in air temperature during the snow free period. A later and thinner snow cover (Schmucki et al. 2014) may lead to a temporary ground cooling and smaller ALT. Latent heat effects and insulation by coarse block layers may considerably slow down permafrost degradation in ice rich ground. Advective heat transport by water infiltration can locally accelerate warming and lead to an increase in supra- and intra-permafrost talik occurrence (Luethi et al. 2016). Model experiments for entire mountain peaks point to long-term and deep reaching perturbations with strongly transient patterns in the subsurface temperature fields (Noetzli & Gruber 2009). The steep topography accelerates the pace of a temperature signal entering the subsurface. Together with the direct reaction to changes in the atmosphere and the low ice content, this makes bedrock permafrost in high mountains particularly sensitive to climate change. Permafrost may disappear in steep bedrock peaks below about 3500 m asl, at southern aspects even up to 4000 m asl. and only remain as a frozen core (Magnin et al. 2017; Noetzli & Gruber 2009).

4.2 *Impacts on slope stability and mass movements*

While topography, rock properties and structure are usually taken to be the main factors influencing slope stability, permafrost may be important because it reacts to climate change. Permafrost warming and thaw may alter the frequency and magnitude of mass movements. These can affect areas previously considered safe based on historical evidence and are seen as the main problem related to permafrost degradation in high mountains (Haeberli & Gruber 2009), especially for the densely populated Alps with the potential of far-reaching catastrophic events due to process chains (Evans & Clague 1988; Haeberli et al. 2016).

The hypothesis of increased rock destabilization due to warming permafrost is supported by a) high rock fall activity during summer heat waves (Gruber et al. 2004a; Ravanel et al. 2017) and b) during warm periods in the 20th century (Fischer et al. 2012; Ravanel & Deline 2011), and c) the observation of ice in rock fall deposits or detachments (Dramis et al. 1995; Fischer et al. 2010; Pirulli 2009). Whereas cold permafrost can have a stabilising effect by increasing the shear strength of clefts and preventing water infiltration, the growth and expansion of ice promotes crack opening and destabilisation (Hasler et al. 2012). This process can occur over several millennia, while warming and melt of the ice by water infiltration can abruptly change the mechanical and hydrological conditions of rock walls and rapidly lead to destabilisation (Hasler et al. 2011). A combination of such processes likely contributed towards destabilising the permafrost rock wall at Pizzo Cengalo, resulting in the 2017 rock avalanche.

Faster transport of debris material to the rock glacier front or decreasing bonding of loose rock debris material with ice degradation can lead to an increase in debris flow activity or even a destabilisation of rock glaciers (Bodin et al. 2016; Delaloye et al. 2013; Roer et al. 2008; Kummert & Delaloye 2018; Lugon & Stoffel 2010). Recent debris flow events from rock glaciers that reached infrastructure in the main valley originated from the Bielzug in 2013 above Herbriggen (VS) or the Ritigraben above Grächen (VS) in 2018 (Fig. 9). In both cases, intense snow melt and precipitation coincided with strongly increased creep velocities in steep terrain.

Figure 9: Debris flow starting zone from the Ritigraben rock glacier (VS) on 02.07.2018, which reached the main road of the Matter valley. Ice was visible after the event. Photo: M. Phillips.

4.3 *Impacts on mountain hydrology*

The most important hydrologic modifications induced by permafrost thaw are the increase in storage capacity and the changes in discharge patterns due to opening of previously blocked (permafrost-limited) vertical and lateral flow paths (Walvoord & Kurylyk 2016). In a high alpine catchment, Rogger et al. (2017) simulate that runoff in summer increases by 1–20% during permafrost degradation and its complete disappearance will reduce flood peaks by 5–15%. However, they did not consider subsidence due to melting ice in supersaturated talus slopes and rock glaciers, which can affect porosity and hydraulic conductivity.

Ice-rich permafrost features are a potentially interesting source of fresh water in the context of climate change, aridity and glacier retreat in arid areas (Azócar & Brenning 2010; Clow et al. 2003). However, in the second half of the 21st century, when surface ice in glaciers is assumed to have mostly disappeared, permafrost could be an interesting source of water in the European Alps (Clow et al. 2003).

Runoff from thawing rock glaciers can export enriched-solute fluxes and thereby cause significant changes in water chemistry downstream (Ilyashuk et al. 2014). Thies et al. (2013) report pronounced differences in the concentration of major ions, heavy metals, species composition and biodiversity in streams emerging from active rock glaciers, which are attributed to seasonally increasing release of melt water.

4.4 *Impacts on infrastructure*

Permafrost degradation can affect the stability of infrastructure: Creeping slopes or subsidence due to ice loss make permafrost a poor construction substrate. Water fluxes in permafrost can change ice contents, increase slope deformation rates or mechanically flush away building materials like anchor grout. The damage induced is particularly problematic for sensitive infrastructure such as cable cars or avalanche defence structures (Bommer et al. 2010).

Both construction activity and the use of infrastructure likely impact permafrost stronger and faster than climate change. At present, the impacts of both artificially induced (e.g., surface disturbance, heated infrastructure) and climate-related changes (e.g. increased creep velocities) on permafrost substrates during the design-life of mountain infrastructure are not considered during the planning phase.

Take-home messages

By the end of the 21st century mountain permafrost may retreat to 10 m depth at ice-rich sites and disappear below 3500 m asl. in steep rock slopes.

Permafrost degradation and active layer thickening promote mass movements and the formation of hazardous process chains reaching low elevations.

Degradation of mountain permafrost can decrease flood peaks and increase runoff during thaw. It can have adverse effects on water chemistry downstream.

In ice-rich ground, permafrost degradation is a slow process and large impacts related to permafrost thawing are likely to occur in the future.

5 Research gaps and open questions

Research of the subsurface phenomenon permafrost in remote mountain areas is largely based on a limited number of local measurements and modelling. A significant increase of available data is fundamental in order to better understand permafrost processes, improve model simulations and enhance knowledge of the impacts of permafrost change. This relates to 1) the coverage of long-term observation sites, which have a biased geographical distribution and have critical discrepancies in their physical characteristics, 2) including monitoring variables to cover hydrological aspects, e.g rock glacier runoff or soil moisture (Pellet et al. 2016), and 3) complementing data required for model input and calibration, such as hydrological measurements, meteorological data and subsurface characteristics at different scales (Beniston et al. 2018).

Although permafrost model simulations for different regions in Europe deliver similar results, there is no regional-scale future projection available so far. A comparison of permafrost models shows that improved representation of surface processes, such as detailed snow modelling, and 3D subsurface processes are required (Ekici et al. 2015; Beniston et al. 2018). Better knowledge of ground structure and ice content are crucial to correctly simulate latent heat transfer and water infiltration at local scales. For regional scale simulations, process-oriented model improvement and up- and downscaling issues are the greatest challenges. The current lack of subsurface information such as reliable ground ice maps causes the largest uncertainties in the simulations of spatial permafrost distribution today and in the future.

One of the major knowledge gaps concerns the origin, age, spatial distribution and total volume of mountain permafrost ice. Methods allowing rapid investigation of ground ice and water contents over large and highly heterogeneous surface areas need to be promoted. For ice-rich ground, indirect geophysical methods and complementing modelling approaches to detemine ground ice, liquid water or air contents are promising (e.g. 4 Phase Model, Hauck et al. 2011). Combinations of airborne and terrestrial surveying methods are required to display and quantify subsidence caused by melting ground ice. Improved modelling of ground ice distribution is also necessary, particularly in talus slopes, which likely store most of the permafrost ice but are sparsely studied and not yet considered in land use classifications. Whilst the current focus is mainly on ice degradation, little is known on ice aggradation, e.g., due to increased avalanche and rock fall activity leading to ice-rich accumulations at the base of slopes.

Research activities in mountain permafrost hydrology should be intensified in the Alps for a better understanding of changes in flow paths and runoff due to permafrost presence. The improvement of hydrological models requires data on flow paths and runoff in permafrost slopes for combined process and modelling studies to explore the effects of environmental change (Rogger et al. 2016). Hereby, the newly released CH2018 scenarios (CH2018 2018) have to be considered. The potential changes in hydrochemistry and -biology of stream runoff from permafrost thaw have hardly been investigated. Different combinations of microorganisms may appear in future runoff from permafrost, such as previously unknown bacteria several millennia old (Frey et al. 2016).

Understanding the mechanisms and conditions that produce ice-filled clefts and fissures as well as understanding the environmental conditions and magnitudes of the processes linking temperature and slope stability are priorities. Again, models are helpful in assessing the hazard potential of process chains and can provide insights not delivered by observations. A key focus are dynamic mixed events such as ice-rock avalanches and debris flows in glacierized areas, which can reach low elevations and have a high hazard potential, especially when involving newly forming lakes (Haeberli et al. 2016).

In summary, these still poorly known impacts of changes to mountain permafrost with potentially severe consequences need to be monitored and modelled carefully in future. Long-term observations such as those coordinated by the PERMOS network need to be maintained and improved, and new measurement variables and methods tested. Potential problems induced by or linked to warming and melting of permafrost ice – such as mass movements, process chains or biohazards need to be investigated and predicted. The contribution of permafrost to the freshwater supply in Alpine regions needs to be quantified and its usefulness assessed in specially designed mountain permafrost hydrological studies.

Take-home messages

Long-term measurements and complementing observations are fundamental to understand permafrost processes in high mountains, improve models and enhance awareness of the impacts of mountain permafrost degradation.

Intensified investigation of the processes linking permafrost degradation and slope instability is required.

Knowledge gaps exist regarding the age, distribution and volume of permafrost ice stored in European mountains, its potential impact on future water resources and hydrological systems.

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