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НОВЫЕ МЕТОДЫ И РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ ЛАНДШАФТОВ В ЕВРОПЕ, ЦЕНТРАЛЬНОЙ АЗИИ И СИБИРИ

Монография в 5 томах

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Chapter II/71: HYDROGEOLOGY OF ROCK GLACIERS - STORAGE CAPACITY AND DRAINAGE DYNAMICS - AN OVERVIEW

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ABSTRACT. Recent studies show that climate warming has a significant impact on the hydrology of permafrost areas in mountain ranges, particularly on rock glaciers. Degradation of permafrost ice in intact rock glaciers and the transformation into relict rock glaciers is expected to increase the storage capacity and thus change their discharge pattern. Peak discharges during snowmelt and summer thunderstorms become less pronounced, while discharges during winter period increase. These processes are increasingly important also for local water resources management when relict rock glaciers are considered as reservoirs for drinking water. However, a number of problems remain still unsolved and further interdisciplinary research including e.g. dye tracer tests, isotope studies, permafrost ice and water chemistry and geophysical investigations is needed to better understand the hydro (geo)logical processes in alpine landforms such as intact and relict rock glaciers and their impact on alpine catchments.

KEYWORDS: landscape, alpine catchment, rock glacier, mountain permafrost, sampling method, groundwater flow in alpine regions, storage capacity

INTRODUCTION

A large volume of water is stored in form of snow and ice in alpine headwaters [e.g. 1] where climate warming causes shrinkage of glaciers, degradation of permafrost and significant changes in the storage capacity of related landforms and sediment accumulations. The glacier volume loss in e.g. the European Alps has been quantified to be about 50% of their total volume between 1850 and around 1975, further 25% of the remaining amount up to 2000 and another 10-15% till 2005 [2]. The permafrost-affected area in the European Alps (estimated area of about 6200 km² with an permafrost index ≥ 0.5) is roughly three times larger compared to glaciated areas [3], meaning that a relevant amount of water is also stored as
permafrost ice in periglacial landforms. The most prominent permafrost-affected landforms are rock glaciers (RG) (Fig.1) which can be morphologically distinguished into intact and relict ones [e.g. 4]. Intact rock glaciers are a mixture of debris and ice. They can be further subdivided into active rock glaciers moving gravitationally downwards and inactive rock glaciers where no movement occurs at the moment. Relict rock glaciers contain no permafrost-ice any more.

Rock glaciers occur worldwide in cold regions, in particular in mountain ranges, and are considered to be important markers for permafrost distribution and paleoclimate research [e.g. 5, 6]. During the last decades rock glacier inventories of mountain ranges were compiled using remote sensing methods such as digital elevation models (DEM) with different horizontal resolutions, satellite imagery and photogrammetry. Inventories from numerous mountain ranges are known from all over the world listed by e.g. [7]. In particular in recent years air-borne laser scan (LIDAR) data, yielding DEMs with a very high horizontal resolution of 1 or 2 m, support the identification of rock glaciers in particular in areas with extensive vegetation cover [e.g. 8, 9, 10].

The hydrological importance of rock glaciers was highlighted by several studies conducted in various mountain ranges [e.g. 8, 11, 12, 13, 14]. Considering the storage capacity of rock glaciers recent results highlight the relevant impact of rock glaciers on the hydrology of alpine catchments and its downstream river systems [13, 15].

The objective of this paper is to give an overview of the present state of research related to the hydro(geo)logy of rock glaciers in alpine catchments, their storage capacity and drainage mechanisms. Existing conceptual models of rock glaciers as aquifers will be presented, also including the impact of these landforms on downstream river systems.

**ROCK GLACIERS - AQUIFERS AND THEIR INTERNAL STRUCTURE**

Different methods were applied during the last decades to characterize the storage capacity and flow dynamics of intact rock glaciers in alpine catchments. The results lead to a conceptual model of the internal structure of rock glaciers (Fig.2) and their role as an aquifer. Moreover, their impact on downstream river systems is considered (see next chapter).

The hydrological relevance of intact rock glaciers in alpine catchments was already shown by Corte [16] in the Andes in dry and semi-dry climate zones more than 40 years ago. Additional studies in the Andes support these findings and confirm intact rock glaciers as very important water storages [11, 14, 17] being even more important than glaciers in some regions [11].

Gardner & Bajewsky observed at the intact Hilda rock glacier in the Canadian Rocky Mountains a similar daily maximum discharge as at an adjacent glacier, but with a more damped daily discharge range [18]. They concluded that the debris cover of rock glaciers insulates the ice from direct meteorological factors such as air temperature or solar radiation. Tracing techniques were already applied by Tenthorey (1992) at three intact rock glaciers in the Upper Val de Réchy in Switzerland to identify different flow components depending on the size and degree of activity of the rock glaciers [19]. Two rock glaciers showed rapid superficial flow and one has slow interstitial flow. Krainer & Mostler investigated three intact rock glaciers in the Austrian Alps detecting that a majority of the runoff was derived from snowmelt and precipitation during the peak melt season and summer thunderstorms, respectively [20]. Based on higher electrical conductivity values measured at the springs, they concluded that groundwater is more important than melting of internal ice in late summer runoff seasons. Additional investigations with stable isotopes allowed for the differentiation of three flow components (precipitation including snow melt, permafrost ice melt and groundwater) in two rock glaciers in the Austrian Alps [13]. Continuous discharge measurements revealed that the discharge of intact rock glacier is characterized by strong seasonal and diurnal variations [20]. Annual discharge of the investigated intact rock glaciers is mainly derived from rainfall and snowmelt and inferiorly by ice-melt and groundwater [20].

Hydrochemical and isotopic methods were applied to separate different flow components of intact rock glaciers in the Colorado Front range [12]. Based on existing models of the drainage of an intact rock glacier [21, 22] a conceptual model of drainage mechanisms of intact rock glaciers was developed. Millar and Westfall [23] and Millar et al. [24] characterized the hydrologic and thermal behavior of rock glaciers and related landforms in the Californian Sierra Nevada (USA).

Information on the internal structure of intact rock glaciers have been derived from geophysical investigations such as seismic refractions, ground penetrating radar (GPR), electromagnetics and gravimetry, and from core drillings [e.g. 4, 25, 26, 27, 28, 29, 30]. Geophysical studies showed that intact rock glaciers are composed of the following layers (Fig.2): (a) unfrozen surface debris layer (active layer), up to several meters thick, underlain by (b) frozen permafrost body composed of either a mixture of debris and ice
(“ice-cemented rock glacier”) or, less common, by a core of pure ice (“ice-cored rock glacier”) up to several tens of meters thick. Between the frozen permafrost body and the bedrock commonly a layer of ice-free, fine-grained sediment (c) is present. This layers is up to more than 10 m thick [28, 29, 30] and is interpreted to be the main aquifer for such landforms. This internal structure was confirmed by core drillings on the active rock glacier Lazaun [25].

Recent investigations on relict rock glaciers confirm three layers but with a layer (b) lacking in any ice content and being characterized by coarse and finer-grained debris [8]. Spring-discharge hydrographs and natural and artificial tracer data suggest a heterogeneous aquifer with this layered internal structure (Fig. 2) which was supported by seismic refraction data. Relict rock glaciers represent complex aquifers [8, 31, 32] and based on their fine-grained basal layer they may have a high storage capacity [8]. The high storage is also reflected in a large portion (about 80%) of groundwater relative to event water in the discharge peaks [8].

Some significant differences can be highlighted between intact and relict rock glaciers:

Intact rock glaciers contain a frozen permafrost body, therefore most of the precipitation and snowmelt infiltrates to the surface of the frozen permafrost body causing a very fast flow component (quickflow) and thus pronounced discharge peaks after precipitation events.

In summer the amount of ice-melt and groundwater discharge is very low compared to quickflow caused by precipitation and snow melt.

In intact rock glaciers the storage capacity for recharged water is much smaller than in relict rock glaciers. Ice-melt and groundwater dominate the discharge during recession periods.

Based on the low storage capacity of intact rock glaciers, they are characterized by a very low to absent discharge in winter.

Relict rock glaciers do not contain permafrost ice anymore and most of the snow melt and precipitation infiltrates into the whole debris body causing less pronounced discharge peaks after precipitation events in summer have a high storage capacity which is bound on a pronounced fine-grained basal layer. Most of the drained water during and after a precipitation event is groundwater and the minor amount is event water.

provide some discharge during winter due to the high storage capacity.
IMPACT ON ALPINE HYDRO(GEO)LOGY

In addition to the conceptual models of drainage mechanisms and flow components of rock glaciers a few studies focused on the impact of rock glaciers on downstream runoff. Corte (1976) could already show that the annual rock glacier runoff share is higher than the annual glacier runoff share of the Cuevas River in the Mendoza Andes of Argentina (56% vs. 44%) [16]. Additional insights of the impact of rock glaciers on the hydrology downstream were given by Geiger et al. [33]. They examined summer runoff from two basins in the La Sal Mountains, Utah, a catchment in which intact rock glaciers are absent, and one in which intact rock glaciers are present. They could show that alpine drainage basins with intact rock glaciers display greater surface runoff and higher flood peaks than drainage basins that lack these landforms. Based on the conceptual model of the drainage mechanisms of relict rock glaciers [8], Wagner et al. [15] investigated the impact of relict rock glaciers on downstream runoff applying a lumped-parameter rainfall-runoff model in the Austrian Alps. Their findings suggest that the daily contribution reaches more than four times the areal share of the rock glacier catchments. Recently, Rogger et al. [34] investigated the flow paths and the hydrological response in a 5 km$^2$ large alpine catchment in the Austrian Alps, and their changes resulting from a loss of permafrost ice in four types of hillslopes (talus, rock glaciers, Little Ice Age (LIA) till, pre-LIA till). Their research results indicate that complete disappearance of permafrost ice will reduce flood peaks and increase runoff during recession. This result agrees to [33] and further highlights the potential storage capacity (and buffer function) of relict rock glaciers.

CONCLUSIONS

1. The presented brief overview highlights the importance of rock glaciers not only as markers of the former and present permafrost distribution but also as aquifers with a relevant impact on the hydrology of alpine catchments.
2. Due to climate warming the permafrost distribution in alpine areas is expected to change in the future. Thus, a process-based understanding of the storage behavior and the drainage mechanisms of these landforms is crucial for prognosis of expected changes of the hydrology in alpine catchments and the related water resources management in these sensitive ecosystems.
3. However, there are still some research questions and perspectives such as:
   - Better quantification of the amount of ice stored in intact rock glaciers (core drillings, geophysics).
   - Quantification of outflow components of intact rock glaciers and their temporal variability.
   - Drainage pattern within rock glaciers.
   - Thermal behavior of the surface debris layer and permafrost body as base for process-based understanding of permafrost ice-melting, preservation or even build-up.
Ice volume changes related to melting of permafrost ice in relation to volume added by e.g. snow avalanches.

How much permafrost ice is formed by refreezing of infiltrating water during the cold season (winter)?

REFERENCES


