Часть 7 Мониторинг водных ресурсов и качества
Part 7 Water Resource and Quality Monitoring

Основная глава 7.1 Водные ресурсы и использование
Main Chapter 7.1 Water Resources and Utilisation

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

Глава II/71: Гидрогеология каменных глетчеров: емкость и динамика стока. Обзор

Gerfried Winkler*[1]; Thomas Wagner[1]; Karl Krainer[2]; Markus Ribis[3], Stefan Hergarten[4]
DOI 10.25680/8822.2018.82.81.168
*Email: gerfried.winkler@uni-graz.at
1.Institute of Earth Sciences, NAWI Graz Geocenter, University of Graz, Heinrichstr. 26, 8010 Graz, Austria
2.Institute of Geology, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria
3.geo.zt gmbh – poscher beratende geologen, Saline 17, 6060 Hall in Tirol, Austria
4.Institut für Geo- und Umweltnaturwissenschaften, University of Freiburg, Albertstr. 23B, 79104 Freiburg

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.

Резюме. Недавние исследования показывают, что потепление климата оказывает существенное воздействие на гидрологию горных районов с многолетней мерзлотой, особенно на каменные глетчеры. Ожидается, что деградация мерзлоты в существующих каменных глетчерах и превращение в реликтовые каменные глетчеры увеличит емкость и, таким образом, изменит динамику расхода подземных вод. Пики расхода во время снеготаяния и летних грозовых дождей становятся менее выраженными, в то время как расход в зимний период возрастает. В случаях, когда реликтовые каменные глетчеры рассматриваются как источники питьевой воды, эти процессы становятся более важными также для управления местными водными ресурсами. Однако ряд проблем остаются нерешенными, и для лучшего понимания гидро(гео)логических процессов в таких формах высокогорного рельефа, как существующие и реликтовые каменные глетчеры, и их воздействия на высокогорные водосборы необходимы дальнейшие междисциплинарные исследования, включая, например, применение красителей, изотопные, гидрохимические и геофизические исследования.

KEYWORDS: landscape, alpine catchment, rock glacier, mountain permafrost, sampling method, groundwater flow in alpine regions, storage capacity
Ключевые слова: ландшафт, альпийский водосбор, горный ледник, горная вечная мерзлота, метод отбора проб, поток подземных вод в альпийских районах, емкость

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].

Figure 1 – Active Rock Glacier “Ölgrube-Süd” in Tyrol, Austria. Note the spring at the base of the RG. (Photo: G. Winkler)

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.

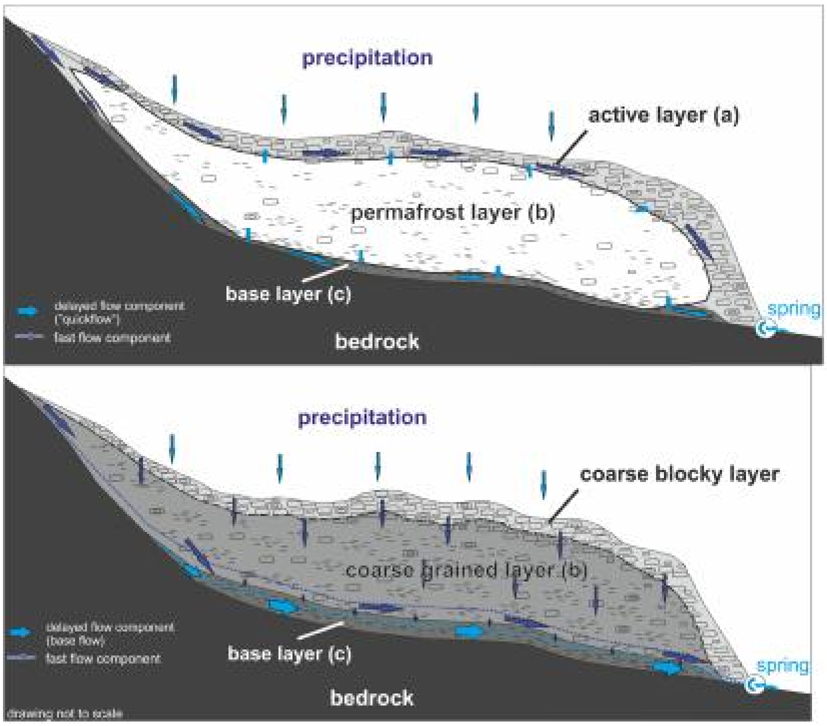

Figure 2 – water flow through rock glaciers a) intact rock glacier (modified after [21, 22]) and b) relict rock glacier (modified after [8])

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

[1]Stewart, I. T. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. Hydrological Processes 23(1), 78-94.
[2]Haeberli, W., Hoelzle, M., Paul, F., Zemp, M. 2007. Integrated monitoring of mountain glaciers as key indicators of global climate change: the European Alps. Annals of Glaciology 46(1), 150-160.
[3]Boeckli, L., Brenning, A., Gruber, S., Noetzli, J. 2012. Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. The Cryosphere 6(4), 807-820.
[4]Barsch, D. 1996. Rock glaciers: indicators for the present and former geoecology in high mountain environments. Springer Series in Physical Environment 16. Springer, Berlin.
[5]Hughes, P.D., Gibbard, P.L., Woodward, J.C. 2003. Relict rock glaciers as indicators of Mediterranean palaeoclimate during the Last Glacial Maximum (Late Würmian) in northwest Greece. Journal of Quarternary Science 18(5), 431-440.
[6]Paasche, Ø., Dahl, S.O., Løvlie, R., Nesje, A. 2007. Rock glacier activity during the last glacial–interglacial transition and Holocene spring snow melting. Quaternary Science Reviews 26,793-807.
[7]Onaca, A., Ardelean, F., Urdea, P., Magori, B. 2017. Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors. Geomorphology 293, 391-404.
[8]Winkler, G., Wagner, T., Pauritsch, M., Birk, S., Kellerer-Pirklbauer, A., Benischke, R., Leis, A., Morawetz, R., Schreilechner, M.G., Hergarten, S. 2016. Identification and assessment of groundwater flow and storage components of the relict Schöneben Rock Glacier, Niedere Tauern Range, Eastern Alps (Austria). Hydrogeology Journal 24(4), 937-953.
[9]Colucci, R.R., Boccali, C., Žebre, M., Guglielmin, M. 2016. Rock glaciers, protalus ramparts and pronival ramparts in the south-eastern Alps. Geomorphology 269, 112-121.
[10]Scotti, R., Brardinoni, F., Alberti, S., Frattini, P., Crosta, G.B. 2013. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. Geomorphology 186, 136-149.
[11]Azócar, G.F., Brenning, A. 2010. Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile. Permafrost and Periglacial Processes 21(1), 42-53
[12]Williams, M. W., Knauf, M., Caine, T.N., Liu, F., Verplanck, P. 2006. Geochemistry and source waters of rock glacier outflow, Colorado Front Range. Permafrost and Periglacial Processes 17, 13-33.
[13]Krainer, K., Mostler, W., Spötl, C. 2007. Discharge from active rock glaciers, Austrian Alps: a stable isotope approach. Austrian Journal of Earth Sciences 100, 102-112.
[14]Rangecroft, S., Harrison, S., Anderson, K. 2015. Rock glaciers as water stores in the Bolivian Andes: An assessment of their hydrological importance. Arctic, Antarctic, and Alpine Research 47(1), 89-98.
[15]Wagner, T., Pauritsch, M., Winkler, G. 2016. Impact of relict rock glaciers on spring and stream flow of alpine watersheds: Examples of the Niedere Tauern Range, Eastern Alps (Austria). Austrian Journal of Earth Sciences 109(1), 84-98.
[16]Corte, A.E. 1976. Rock glaciers. Biuletyn Peryglacjalny 26, 175-197.
[17]Schrott, L. 1996. Some geomorphological-hydrological aspects of rock glaciers in the Andes (San Juan, Argentina). Zeitschrift für Geomorphology (Supplement 104), 161-173.
[18]Gardner, J. S., and Bajewsky, I., 1987. Hilda rock glacier stream discharge and sediment load characteristics, Sunwapta Pass area, Canadian Rocky Mountains. In: Giardino, J. R., Shroder, J. F. Jr.,
Vitek, J. D. (eds.), Rock Glaciers. London: Allen & Unwin, 161–174.
[19]Tenthorey, G. 1992. Perennial névés and the hydrology of rock glaciers. Permafrost and Periglacial Processes 3, 247-252.
[20]Krainer, K., Mostler, W. 2002. Hydrology of active rock glaciers: examples from the Austrian Alps. Arctic, Antarctic, and Alpine Research 34, 142-149.
[21]Giardino, J.R., Vitek, J.D., Demorett, J.L. 1992. A model of water movement in rock glaciers and associated water characteristics. In: Dixon, J.C., Abrahams, A.D. (eds.), Periglacial Geomorphology. Wiley, Chichester, 159-184.
[22]Burger, K.C., Degenhardt, J.J., Giardino, J.R. 1999. Engineering geomorphology of rock glaciers. Geomorphology 31, 93-132.
[23]Millar, C.I., Westfall, R.D. 2008. Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climatic relationships. Quaternary International 188 (1), 90-104.

[24]Millar C.I., Westfall R.D., Delany D.L. 2013. Thermal and hydrologic attributes of rock glaciers and periglacial talus landforms: Sierra Nevada, California, USA. Quaternary International 310, 169-180.
[25]Krainer, K., Bressan, D., Dietre, B., Haas, J.N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H., Tonidandel, D. 2015. A 10,300-yearold permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). Quaternary Research 83(2), 324-335.
[26]Croce, F.A. & Milana, J.P. 2002. Internal structure and behaviour of a rock glacier in the Arid Andes of Argentina. Permafrost and Periglacial Processes 13, 289-299.
[27]Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N, Springman, S., VonderMühl, D. 2006. Permafrost creep and rock glacier dynamics. Permafrost and Periglacial Processes 17, 189-214.
[28]Hausmann, H., Krainer, K., Brückl, E., Ullrich, C. 2012. Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophsysical surveys. Austrian Journal of Earth Sciences 105(2), 12-31.
[29]Krainer, K., Lang, K., Hausmann, H. 2010. Active rock glaciers at Croda Rossa/Hohe Gaisl, Eastern Dolomites (Alto Adige/South Tyrol, Northern Italy). Geografia Fisica e Dinamica Quaternaria 33, 35-36.
[30]Krainer, K., Mussner, L., Behm, M., Hausmann, H. 2012. Multi-disciplinary investigation of an active rock glacier in the Sella Group (Dolomites; Northern Italy). Austrian Journal of Earth Sciences 105(2), 48-62.
[31]Pauritsch, M., Birk, S., Wagner, T., Hergarten, S., Winkler, G. 2015. Analytical approximations of discharge recessions for steeply sloping aquifers in alpine catchments. Water Resources Research 51(11), 8729-8740.
[32]Pauritsch, M., Wagner, T., Winkler, G., Birk, S. 2017. Investigating groundwater flow components in an Alpine relict rock glacier (Austria) using a numerical model. Hydrogeology Journal 25(2), 371-383.
[33]Geiger, S.T., Daniels, J.M., Miller, S.N., Nicholas, J.W. 2014. Influence of rock glaciers on stream hydrology in the La Sal Mountains, Utah. Arctic, Antarctic, and Alpine Research 46(3), 645-658.
[34]Rogger, M., Chirico, G.B., Hausmann, H., Krainer, K., Brückl, E., Stadler, P., Blöschl, G. 2017. Impact of mountain permafrost on flow path and runoff response in a high alpine catchment. Water Resource Research 53, 1288-1308.

Глава II/72: ВОДНЫЕ РЕСУРСЫ РЕСПУБЛИКИ ТАДЖИКИСТАН И ПУТИ ИХ РАЦИОНАЛЬНОГО УПРАВЛЕНИЯ И ИСПОЛЬЗОВАНИЯ

Chapter II/72: Water Resources of the Republic of Tajikistan and Ways of their Rational Management and Use

Исломкул И. Икромов*, Илхом И. Икромов, Ф. Икроми*****

DOI 10.25680/8220.2018.14.64.169

Эл. Почта: *islom _58@mail.ru; **ilhom_0808@mail.ru; ***firdavsi92_92@mail.ru
Таджикский аграрный университет им. Шириншох Шотемур, ул. Рудаки 146, 734003, Душанбе, Таджикистан

РЕЗЮМЕ. Республика Таджикистан (РТ), где горная территория занимает 93%, богат водными ресурсами. Территория РТ составляет всего 3,6% площади Центральноазиатских стран, однако, здесь формируется более 55,6% водных ресурсов региона, что составляет около 64 км^3 воды. Водные ресурсы РТ формируется на ледниках, речном стоке, озёрах, водохранилищах и подземных источниках. Главными водными артериями бассейна усыхающего Аральского море являются реки Амударья и Сырдарья. Р. Амударья образуется на юго-западной территории РТ в результате слияния крупных рек Пяндж и Вахш, берущие свое начало на горах республики, и 36 км южнее от места образования в нее впадает р. Кафирниган. Воды р. Зеравшан, берущее своё начало из границ северного Таджикистана полностью разбирается на орошение и, ее воды уже десятки лет не доходят до прежних устьев. Р. Сырдарья берёт своё начало в Ферганской долине, и проходит по северной территории РТ длиной в 185 км. Рекомендуемые мероприятия по рациональ ному управлению и использованию водных ресурсов, позволяют сохранять нормальное экологическое состояние окружающей среды и агроландшафт территории.