Quantifying the significance of the hydrological contribution of a rock glacier – A review.

Maxime A. Duguay[1], Alan Edmunds[2], Lukas U. Arenson[3] & Pablo A. Wainstein[1]
[1]BGC Engineering Inc. Calgary, Alberta, Canada
[2]BGC Ingeniería Ltda. Santiago, Chile
[3]BGC Engineering Inc. Vancouver, British Columbia, Canada

ABSTRACT
The role of uncovered glaciers in the hydrological cycle has been well studied and documented in the scientific literature. On the other hand, very little is known of rock glaciers. Despite the lack of data and understanding as to the role of rock glaciers within the hydrological cycle some legislations have recently been implemented to protect them from any human impact, by erroneously including rock glaciers as part of the glacial environment. This paper reviews available literature on rock glacier hydrology and the different positions authors have adopted in order to synthesize available knowledge on the hydrological significance and hydrograph response of these cryoforms. Mountain permafrost hydrology is discussed to clarify its applicability to rock glacier hydrology. We recommend that rock glaciers should be assessed under a holistic approach; their significant differences in genesis, morphology, dynamics, and energy exchange to glaciers must be acknowledged. Detailed site investigation is required in order to properly determine the role of rock glaciers and the periglacial environment on the hydrological cycle in a mountain watershed.

RÉSUMÉ
Le rôle des glaciers découverts dans le cycle hydrologique a été bien étudié et documenté dans la littérature scientifique. D'autre part, peu est connu sur le rôle hydrologique des glaciers rocheux. Malgré le manque de données et de compréhension quant au rôle des glaciers rocheux dans le cycle hydrologique, certaines législations ont récemment été mises en place pour les protéger de tout impacts humains, en incluant à tort glaciers rocheux parmi l'environnement glaciaire. Cet article passe en revue la littérature disponible sur l'hydrologie des glaciers rocheux et les différentes positions adopté par les auteurs afin de synthétiser les connaissances disponibles sur l'importance hydrologique de ces cryoformes. L'hydrologie de pergélisol de montagne est discutée afin de clarifier son applicabilité à l'hydrologie de glaciers rocheux. Nous recommandons que les glaciers rocheux doivent être évalués selon une approche holistique; leurs différences significatives en termes de genèse, morphologie, dynamique, et d'échange énergétique en relations aux glaciers doivent être reconnues. De la recherche sur le terrain détaillée est nécessaire afin de déterminer correctement le rôle des glaciers rocheux et l'environnement périglaciaire sur le cycle hydrologique dans les bassins versants de montagne.

1 INTRODUCTION

The hydrology of mountain areas has been well studied, including glaciated terrain. However, for mountain areas where glaciers are absent but the presence of rock glaciers is considerable, there is no consensus on the relationship between rock glaciers and hydrology. Rock glaciers are only special landforms from a geomorphological point of view. In simple terms, they are colluvium that contains or contained at one time, massive ground ice. This specific constitution allows the frozen talus and ice mixture to creep downslope due to gravity (Berthling, 2011). Research on rock glaciers can be traced back to a paper by Steenstrup in 1883 (Humlum, 1982). At the beginning of the twentieth century, rock glaciers were considered a peculiar form of talus (Spencer 1900) and it wasn't until 1910 when the term "rock glacier" was introduced to explain these landforms (Capps 1910). Wahrhaftig and Cox (1959) demonstrated that the landforms had a tendency to creep downslope in the manner of a glacier, apparently as a result of the inclusion of ice within the talus. Rock glaciers have been identified in nearly all major mountain ranges, regardless of past or present glaciations (Burger, 2000), and formation of rock glaciers is dependent upon several factors. First, a tectonically active mountain range with bedrock that forms coarse blocky debris is necessary as these mountain ranges generally have steep slopes and high rates of denudation. Secondly, a high-frequency freeze-thaw regime that promotes intensive frost-weathering is needed as this process separates debris from headwalls and permits its transport by gravity to the rock glacier surface; and thirdly, the topography must be of an appropriate aspect and elevation (French, 2007).

Although denominations (glacier versus rock glacier) may sometimes result in confusion in the general public, it is worth noting that these two cryoforms belong to two different environments (glacial versus periglacial) and present marked differences in their genesis, morphology and dynamics (Barsch, 1996; French, 2007).

Continued climate change is expected to reduce water security in arid mountain regions globally (Barnett et al., 2005; Kundzewiz et al., 2008). In the South American Andes this is a real risk to the local livelihoods (Vuille et al., 2008; Chevallier et al., 2011, IPCC, 2014). Vulnerable water supplies in semi-arid zones and the tropical Andes are predicted to be further stressed through changes in air temperature, precipitation patterns, increased sublimation and evapotranspiration together with glacier recession, negatively affecting water availability (IPCC, 2013; 2014). Uncovered glaciers and rock glaciers react differently to climate change and their hydrological contribution must be assessed separately.

Glacier growth and residence are affected by air temperature and precipitation, hence glacier mass balance (Benn and Evans, 1998). If more mass, in terms of snow, is deposited at high elevation than the ice melt at the bottom, the glacier volume increases and it advances (Benn and Evans, 1998). While an increase in air temperature causes the equilibrium line of the glacier to elevate and more ice to ablate (Haeberli et al., 2013), a decrease in precipitation reduces the accumulation of new ice at higher elevation, which would typically be transported downslope through viscous flow (Benn and Evans, 1998). Therefore, negative glacier mass balance and retreat occurs if precipitation decreases, even under steady air temperature conditions.

Rock glaciers, on the other hand, contain ground ice which is less susceptible to short-term air temperature variations and instead the thermal regime depends on long term air temperature variations, precipitation, and characteristics of the ground (Harris et al., 2009). The latter of which affects heat flow based on thermal conductivity, heat capacity and latent heat of the soil together with the condition at the ground surface.

Because surface snow and ice (glacial environment) reacts differently than ground temperatures (periglacial environment), effects of climate change on these two environments have to be assessed and discussed differently. Surface snow and ice is, in contrast to ground ice, extremely dynamic. As illustrated in IPCC (2013), surface snow and ice has a life persistence of hours (i.e. snow) to decades (i.e. typical valley glaciers), whereas ground ice spans from months (i.e. seasonal frost) to thousands of years (i.e. permafrost). Glaciers, therefore, react very quickly to changes in climate, whereas rock glaciers (permafrost) and ground thermal regimes adapt very slowly to changes in atmospheric conditions (Lachenbruch and Marshall, 1986). Consequently, glaciers are good proxies for studying recent climate change and climate variability because immediate response can be measured (Barry, 2006), while periglacial landforms provide information on long-term changes only, and cannot be used to evaluate changes in the short term (Summerfield, 1991). Uncovered glaciers are therefore important hydrological contributors to downstream watersheds and have been studied extensively (Benn and Evans, 1998). Quantitative research on the contribution of the periglacial environment, including rock glaciers, is lacking.

With respect to the contribution of rock glaciers to runoff, very few studies have been published and mostly the assessments have been done qualitatively without a detailed investigation on the origin of the water observed at the front of a rock glacier. Corte (1976), for example, mentions that the runoff, especially in the Eastern South American Andes, is largely determined by rock glaciers. Similarly, Falaschi (2014) states that rock glaciers in the Andes in Argentina provide an important supply of water for local agriculture. However, Falschi (2014) and Corte (1976) have no data to support their hypothesis. Azócar and Brenning (2010) used statistical methods to estimate the distribution of rock glaciers in the arid Andes and concluded that the ice stored in rock glaciers is significantly more important than glacier ice. The lack of measurements and erroneous conclusion was subsequently criticized by Arenson and Jakob (2010).

This paper presents a review of available scientific publications on rock glacier hydrology and attempts to summarize current state of knowledge. It further attempts to provide a comprehensive overview of the various elements that play a role in the hydrology of rock glaciers. However, the lack of detailed studies results in diametrically opposed views, strengthening the need for good site investigations and associated research.

2 METHODOLOGY

Rock glacier genesis, nomenclature and classification have long been debated in the scientific community and the disagreements continue to present day (Janke et al., 2013; Berthling, 2011). Furthermore, very little is known about rock glacier’s hydrological significance (if they contribute to total runoff) and their impact on the hydrograph response. To better understand this gap in knowledge, we examined the available peer-reviewed literature to quantify and qualify studies on the hydrological significance of rock glaciers. In June 2014, we searched the ISI Web of Science™ for peer-reviewed articles and reviews published from 1900-2014 using topic searches (abstracts/keywords/title) for all spelling variance of “rock glacier” and “glacier”.

Further search in Geobase™ were restricted to “Journal Articles” published from 1973-2014 for all the spelling variances of “rock glacier” and “glacier” using topic searches (subject/title/abstract). Sub-topic searches were conducted in both databases on these papers for key words including: hydrology, hydrological, runoff, discharge, meltwater, water, water source, water storage, and water equivalent.

3 REVIEW RESULTS

The ISI Web of Science™ “all fields” from 1900-2014 search generated 313 articles and reviews for rock glaciers and 11,142 for glaciers respectively (Table 1). Papers published in the past 10 years from 2004-2014 totaled 294 (68.5% of the available literature) for rock glaciers and 429 (26% of the available literature) for glaciers. The Geobase™ search generated 429 journal articles for rock glaciers compared to 111,142 articles for glaciers from 1973-2014 with the “all fields” search criteria (Table 2). Journal manuscripts published in the past decade (2004-2014) represent 68.5% (294 articles) and 69% (7689 articles) of the available literature for rock glaciers and glaciers respectively. A total of 219 papers resulted from the sub-topic results of both databases, which were further analyzed for relevance to rock glacier hydrology. From those papers, 73 were retained for further study of which only 28 were found to have an appropriate discussion on the hydrology to be further analyzed. The combined search results from both these databases indicate the major lack of the research on rock glaciers compared to glaciers that has been conducted in the past decade. Furthermore, sub-topic search results reveal that research on the hydrological significance of rock glaciers is also lacking.

Table 1: ISI Web of Science™ topic and subtopic search results for peer-reviewed articles and reviews publish from 1900-2014 (abstracts/keywords/title). The subtopic searches are for all the spelling variances of "rock glacier".

Topic searches (all dates)	Title		Topic	
Glacier*	5,409		14,286	
2004-2014	2,818		8,629	
Rock Glacier**	251		313	
2004-2014	122		259	
Sub-Topic searches	Title (all dates)	Title (2004-2014)	Topic (all dates)	Topic (2004-2014)
Hydrology	3	1	12	9
Hydrological	3	3	16	12
Runoff	0	0	6	4
Discharge	0	0	12	9
Meltwater	2	1	21	14
Water	4	3	104	79
Water Source	0	0	3	3
Water Storage	0	0	4	3
Water Equivalent	0	0	6	5

* include: "Glacier" or "Glaciers".

** include: "Rock Glacier" or "Rock Glaciers" or "Rockglacier" or Rockglaciers" or "Rock-glacier" or "Rock-glaciers".

Table 2: Geobase™ topic and subtopic search results for peer-reviewed journal articles publish from 1973-2014 (subject/title/abstract). The subtopic searches are for all the spelling variances of "rock glacier".

Topic searches (all dates)	Title	Subject Title Abstract	All Fields
Glacier*	4,124	7,621	11,142
2004-2014	2,831	10,999	7,689
Rock Glacier**	207	429	429
2004-2014	134	294	294
Sub-Topic searches	(all dates)	(all dates)	(all dates)
Hydrology	2	13	19
Hydrological	4	15	16
Runoff	0	5	5
Discharge	1	10	10
Meltwater	2	23	23
Water	4	86	95
Water Source	0	2	2
Water Storage	0	4	4
Water Equivalent	0	5	5
Sub-Topic searches	(2004-2014)	(2004-2014)	(2004-2014)
Hydrology	1	11	15
Hydrological	4	10	11
Runoff	0	4	4
Discharge	1	8	8
Meltwater	1	17	17
Water	3	67	72
Water Source	0	2	2
Water Storage	0	3	3
Water Equivalent	0	5	5

* include: "Glacier" or "Glaciers".

** include: "Rock Glacier" or "Rock Glaciers" or "Rockglacier" or Rockglaciers" or "Rock-glacier" or "Rock-glaciers".

Our analysis of all papers with sufficient relevance to rock glacier hydrology showed that there is no consensus on the relationship between rock glacier and hydrology. Even though the hydrology of watersheds containing rock glaciers have not been thoroughly studied, several authors suggest that rock glaciers, especially ice-cored rock glaciers, are an essential component of the basin hydrology. Some authors even suggest that discharge from rock glaciers is similar to or greater than discharge from uncovered glaciers of similar size (Corte 1978; Gardner and Bajewsky, 1987). Several research articles have recognized rock glaciers as potential storage reservoirs for water (Corte 1976; Corte 1978; Barsch 1988). Others, such as Giardino et al. (1987), indicate that rock glaciers act as aquifers and there is a system of inputs and outputs from various processes within alpine drainage basins. Geiger (2008) further suggests that rock glaciers in Utah have a pronounced influence on the hydrology of an alpine catchment. Due to the scarcity of glaciers in the Chilean and Argentinean Andes, some authors have emphasized the hydrologic importance of thawing ground ice in mountain permafrost environments and in particular, of rock glaciers (e.g., Brenning, 2005; 2008). Corte (1978), working in the Argentinean Andes of Mendoza Province, claims that rock glaciers provided 56% of the total annual discharge of the Cuevas River, while glaciers provided only 44% of discharge, despite the fact that uncovered glaciers occupy a larger area. Other authors such as Buk (2002) and Schrott (2002) have presented qualitative evidence on the hydrological contribution of rock glaciers in South America. Milana and Guell (2008), on the other hand, after conducting a study on the mechanical and hydrological differences of rock glaciers in the Andes, concluded that the hydrological role of rock glaciers is variable and heavily depends on the origin of the feature. Finally, Brenning (2005; 2008) and Azócar and Brenning (2010) hypothesise that rock glaciers play an important role within hydrological systems of the semi-arid mountain environment. However, their approach was criticized by Arenson and Jakob (2010) because of the lack of data that would support such a hypothesis.

Although a number of authors suggest that rock glaciers contribute to total annual runoff that is important to down-stream water use, these conclusions are generally based on non-quantitative data for support. A recent paper by Falaschi et al. (2014), for example, illustrates the prevailing myth as they relate to rock glacier hydrology in the first sentence of the abstract: "*Rock glaciers near the Andean mountains of central and northwestern Argentina provide an important supply of water for agriculture, but data on their number, size, geographic distribution and altitudinal range are poorly known."* While providing no measurement or theoretical consideration based evidence, the sheer number of rock glaciers identified by the authors made them conclude that they must provide an important supply of water for downstream users.

Hence, in criticism, some researchers warn that others draw their conclusions on qualitative and highly selective information only, which does not account for the multitude of other surface and subsurface water sources. Additional authors suggest that the hydrological contribution of rock glaciers to stream flow is negligible and depends on the amount of interstitial ice encountered and the thermal regime of the rock glacier. A detailed downstream discharge monitoring study of three rock glaciers in the Austrian Alps found that hydrograph peaks occurred after local storms and during the spring melt, indicating that a majority of the runoff was derived from snowmelt and precipitation (Krainer and Mostler. 2002). Higher electrical conductivity in late summer derived from the metamorphic bedrock indicated that groundwater is more important than potential melting of internal ice later in the runoff season. Additional stable isotope analysis of the rock glacier runoff, snow, and ice indicate peak flows are a result of snowmelt, while base flow is a combination of groundwater and surficial ice melt discharge (Krainer et al., 2007). Krainer et al. (2007) further state that the presence of active rock glaciers in high alpine catchments exerts little influence on the total runoff due to the relatively small amount of meltwater derived from melting of internal ground ice.

Despite the importance of the hydrology of rock glaciers, most studies are qualitative, rather than based on reliable measurements of individual system components, over sufficient time periods, combined with a quantitative analyses. Furthermore, such studies often ignore the geothermal characteristics of rock glaciers which cannot support significant annual runoff contribution from rock glaciers. The following section conceptually explains why rock glacier contribution to downstream water use is negligible compared to other water sources such as snowmelt and rain.

4 DISCUSSION

4.1 Mountain Permafrost Hydrology

In order to understand the hydrological contribution from a rock glacier, it is important to introduce the specifics of mountain permafrost hydrology. Water and permafrost have an intricate non-linear relationship. The presence of water affects the distribution and thermal regime of permafrost whereas the spatial distribution, depth and thickness of permafrost affect the general hydrology, runoff and infiltration of a watershed (Brown, 1974). In areas of warm permafrost the amount and frequency of precipitation particularly influences the depth of seasonal thaw and the soil thermal profile (French, 2007). The amount of moisture in the soil immediately before it freezes determines the ice content of the layer and the amount of surface water and infiltration capacity of the soil affects the depth of thaw during the following summer (French, 2007). With respect to the influences of permafrost on the hydrology of watersheds, the main effect is the restriction of exchange between surface waters and subpermafrost groundwater (Cheng and Jin, 2012). The hydraulic conductivity of frozen soils can be several orders of magnitude lower than comparable unfrozen soils, depending on ice content and thickness of the unfrozen active layer (Kane et al., 2013). The result is a perched water table within the active layer above the frost table. This vertical flow restriction, especially in continuous permafrost zones, results in surficial ponding of water within flat terrain and high rates of surface soil erosion in steeper terrain where surface runoff is considerable due to the limited percolation (Cheng and Jin, 2012). The presence of permafrost also affects the time distribution of surface runoff. Watersheds underlain by permafrost tend to have a quick response to precipitation and their hydrographs peak earlier in time than basins without permafrost (Prouse and Ommanney, 1990). Figure 1 is an attempt to illustrate seasonal runoff from the active layer and its approximate hydrograph.

The relationship between permafrost and hydrology in mountainous regions is even more particular and susceptible to local weather and thermal conditions (French and Slaymaker, 2011). Mountain permafrost is heterogeneous, rarely continuous and is found in areas that the local radiation and weather conditions allow its accretion (French, 2007). In addition, mountain hydrology is highly controlled by local weather patterns, air temperature and altitude which determine the spatial distribution of precipitation and its physical state (i.e., solid or liquid) (Prouse and Ommanney, 1990). Generally speaking, mountain regions are considered as regulators of the down-stream hydrology. There is common consensus that during winter precipitation which is typically in the form of snow, is easily stored on the surface of the terrain by accumulation processes. This is especially true for glaciated basins which store water in the form of ice and snow (Benn and Evans, 1998). This results in a dry winter landscape, at high altitudes, and a wetter environment down-stream, where precipitation is in the form of rain (Benn and Evans, 1998). During summer when rain is minimum at lower elevations, the melting of snow and ice provides the water for surficial runoff (Benn and Evans, 1998). Although the contribution from snow melt and surface ice melt can generally be picked up in hydrographs that record discharge of a certain watershed, there is a fundamental difference between snow-melt / surface ice melt and ground ice / permafrost ice thaw (Woo, 2012). Surface snow and ice is directly influenced by solar radiation and air temperature and will therefore respond quickly (Woo, 2012). Ground ice, however, is only affected by ground temperatures since it is protected by the snow (during winter) and the ground surface (during summer) from solar radiation (Ireson et al., 2013). Hence, the changes in ground temperature with time and depth are a function of conductive and convective heat transfer parameters, as well as the latent heat effects of ice and water (Ireson et al., 2013). As such, it takes time for the summer temperatures to penetrate into the ground to warm and thaw any ground ice at depth. Given the noted temporal delays, it is very difficult to link watershed hydrographs for a whole basin to permafrost thaw, or even to the effect of permanently frozen ground. Frampton et al. (2013) used a three-phase water flow model coupled to heat transport to show that decreased seasonal variability in groundwater discharge may serve as an early indicator of permafrost degradation, since increased annual mean flows may take a longer time to become apparent. Only if surface water runoff, precipitation values, sublimation rates, evaporation rates and groundwater flows are recorded individually as well as spatially, a clear understanding of the water flow regime is obtained and credible conclusions may be made.

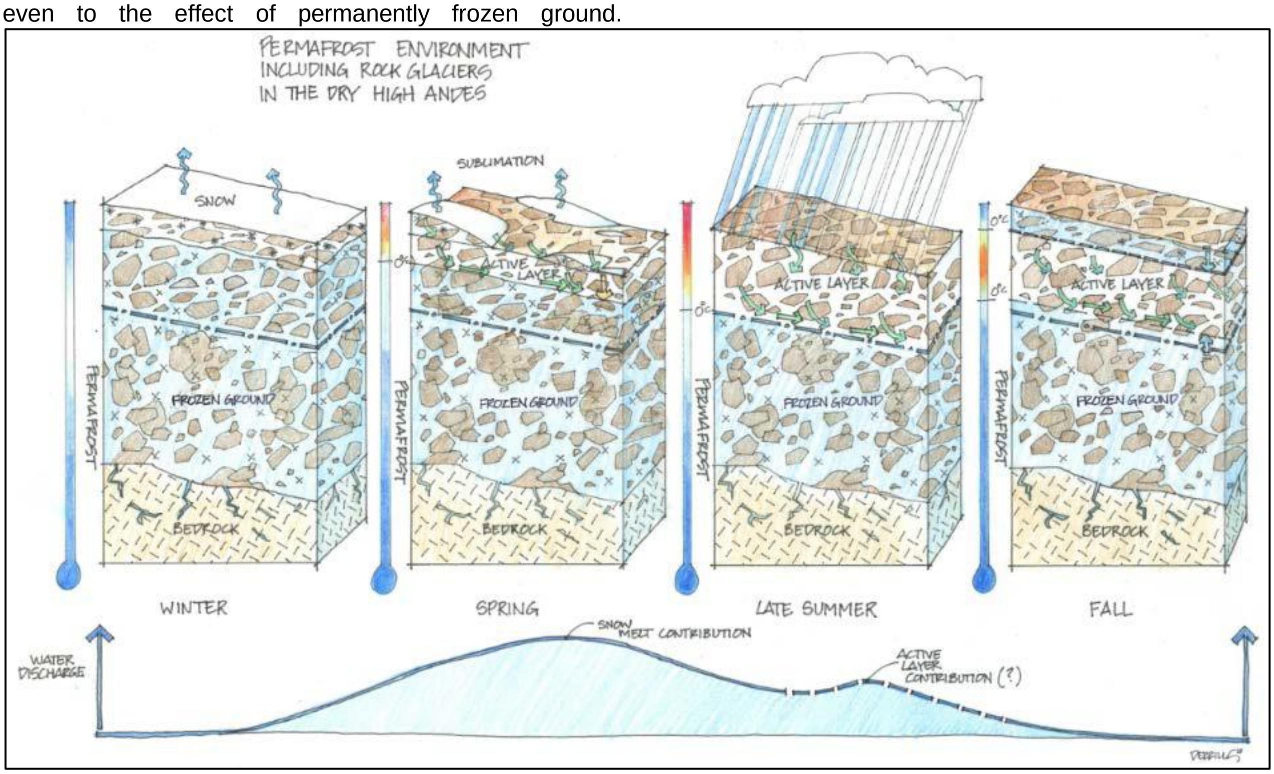

Figure 1. Schematics of runoff seasons from active layer and approximate hydrograph.

4.2 Rock Glacier Hydrology

Rock glaciers are part of the periglacial environment and present permafrost in the form of ice within their core which varies in concentration depending on genesis and type. In terms of their dynamics, three types of rock glaciers exist: active, inactive and relict (e.g., Barsch, 1996). Active rock glaciers have ice in the form of matrix ice or massive, depending on the genesis of the form. These forms present active movements and deformations, and the only way they could be able to supply water to downstream users would be by permafrost degradation and the release of previously frozen interstitial ice. Due to the slow conduction of heat though the ground, the degradation of rock glaciers is a very slow process and only occurs when the rock glacier or any other landform in the permafrost-underlain terrain is not in equilibrium with the current climate (i.e., atmospheric warming). Rock glacier transition from active to inactive and eventually to relict, occurs over centuries to millennial time scales. Konrad et al. (1999) dated a rock glacier in Wyoming to have formed before the Little Ice Age which may contain ice dating to the mid-Holocene or earlier. On the other hand, glaciers of similar volume loose ice at rates that are orders of magnitude higher. This explains why many small glaciers in the European Alps have completely disappeared since the Little Ice Age (WGMS, 2013), while in the same time period, very little visible changes have been observed for rock glaciers in the Alps. The latter only react to long-term trends in changes in precipitation (Bodin et al., 2009; Buchli et al., 2013) and longer-term (decadal scale) air temperature variability (Sorg et al., 2015), being insulated from shorter term changes in air temperature, while the former are more sensitive. For the same reason, many more rock glaciers exist in the dry Andes than glaciers.

Rock glaciers are permafrost landforms with a far more complex mass balance than that of a glacier (Figure 2). The mass of a rock glacier consists of ice and debris from various sources. In addition, complex energy fluxes occur in the active layer that control the thermal regime in the rock glacier in response to atmospheric conditions

(Scherler et al., 2013). Mass gain occurs in the form of snow, groundwater, precipitation and debris. The loss of interstitial ice comes from various forms of permafrost degradation, but due to the thermal protection of the interstitial ice by the active layer, any changes in the permafrost temperatures are very slow.

What has been described in the previous section on permafrost hydrology is also applicable to rock glaciers. They have an active layer and their hydrological role can be summarized as a temporal storage of water in the form of seasonal ground ice within the active layer (which is not part of the permafrost) during winter months which is released during the summer months as the thaw front penetrates the active layer. Runoff typically flows laterally on top of the permafrost table (bottom of the active layer). There is little melt of ground ice from the permafrost body due to protection from the active layer and latent heat effect.

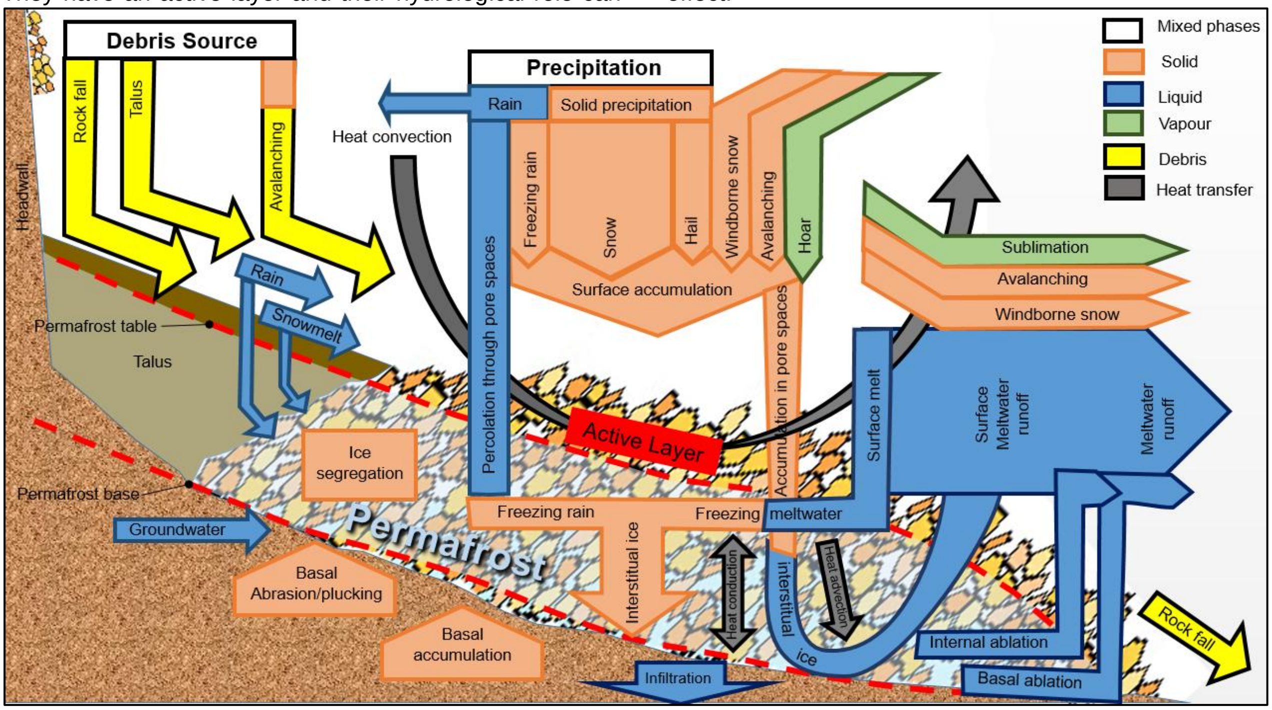

Figure 2. Simplified schematic of a rock glacier mass balance.

Inactive rock glaciers do not show signs of forward movement, but they still contain ground ice and precise topographic measurements demonstrate a lowering of their surface elevation. The lack of forward movement is a result of decreasing ground ice content. As the pore ice content decreases, the solid particle contact increases, and creep deformation ceases. Inactive rock glaciers often show signs of permafrost degradation such as mass loss and the formation of thermokarst features (Brenning, 2005; Springman et al. 2012) resulting in a small and slow contribution to the runoff from the thawing ground ice. On the other hand, relict rock glaciers no longer contain ground ice and may not reliably be distinguishable from hummocky moraine deposits. Some are vegetated while some are still bare rocks. Typically, they are no longer part of the periglacial environment and are predominantly found at lower elevations.

Lastly and independently of the type of rock glacier, the possibility of hydrological contribution should be relatively evaluated in relation to other sources of water in the watershed, before considering it significant (Arenson et al., 2013). Preliminary modelling approaches of the significance of the hydrological contribution of degrading permafrost in the arid Andes, suggest that this is negligible and non-measurable (Arenson et al., 2013).

5 CONCLUSION AND RECOMMENDATIONS

Our review shows that the number of publications focusing on rock glacier hydrology and potential water storage is small in comparison with published research on other aspects of rock glaciers, such as their morphology or dynamics. In mountain watersheds with glaciated terrain, hydrology has been studied intensively; whereas in mountain watersheds where glaciers are absent but the presence of rock glaciers is considerable, there is no consensus of the relationship between rock glaciers and their hydrological role. Although some authors suggest that rock glaciers do play an important role in the contribution of total runoff to down-stream water resources, there are also a number of publications that warn from such conclusions as they were based on qualitative information only, lacking actual data. Currently, rock glaciers and their respective hydrological characteristics are in the spotlight due to their prevalence, their obvious visual manifestation and their mention in legislation and guidelines in South America. However, the quantitative evidence is absent and the fact that the ground ice in rock glaciers is not an available water source is often ignored. It is important to note that ice contained in soils or rocks within rock glaciers is in permafrost and does not contribute to runoff because it is permanently frozen. It can only contribute to runoff if permafrost is degrading under warmer climate conditions with a thickening of the active layer below its seasonal variability. Permafrost degradation is a slow process due to protection from the active layer and the slow latent heat effects of thawing ice.

We are not aware of any scientific study that has quantitatively established the complete hydrological role of the periglacial environment within a given watershed or region. We conclude that rock glaciers should be assessed under a holistic approach; their significant differences in dynamics, morphology and energy exchange to glaciers must be acknowledged. In addition, detailed field research is required in order to properly determine the role of rock glaciers and the periglacial environment on the hydrological cycle in mountain watersheds. Quantitative data is needed moving forward to address this gap in knowledge and there is a need to develop a field based method of separating runoff from rock glacier from the numerous main runoff sources of the adjacent slope.

REFERENCES

Anderson, D. 2004. *Glacial and periglacial environments (Access to Geography)*. Hodder Education. 144 p.

Arenson, L.U., and Jakob, M. 2010. The significance of rock glaciers in the dry Andes - A discussion of Azócar and Brenning (2010) and Brenning and Azócar (2010). *Permafrost and Periglacial Processes.* 21: 286–288.

Arenson, L.U., Jakob, and Wainstein, P. 2013. Hydrological contribution from degrading permafrost and rock glaciers in the northern Argentinean Andes. Mine water solutions in extreme environments: 171–181.

Azócar, G.F., and Brenning, A. 2010. Hydrological and Geomorphological Significance of Rock Glaciers in the Dry Andes, Chile (27°-33°S). *Permafrost and Periglacial Processes.* 21: 42–53.

Barnett, T.P., Adam, J.C., and Lettenmaier D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*. 438:303–309.

Barsch, D. 1988. Rockglaciers. In *Advances in Periglacial Geomorphology*, by M.J. Clark:69–90.

Barsch, D. 1996. *Rockglaciers: Indicators for the Present and Former Geoecology in High Mountain Environments*. Springer, Berlin Heidelberg: 331 p.

Barry, R.G. 2006, The status of research on glaciers and global glacier recession: a review, *Progress in physical geography,* 30(3), pp 285-306.

Benn, D.I. and Evans, D.J.A. (1998) *Glaciers and Glaciation*. Edward Arnold, London. 734 p.

Berthling, I.T. 2011. Beyond confusion: Rock glaciers as cryo-conditioned landforms. *Geomorphology*. Volume 131 (3-4).

Bodin, X., Thibert, E., Fabre, D., Ribolini, A., Schoeneich, P., Francou, B., Fort, M. 2009. Two decades of responses (1986-2006) to climate by the Laurichard Rock Glacier, French Alps. *Permafrost and Periglacial Processes*. 20: 331–344.

Brenning, A., 2005. Geomorphological, hydrological and climatic significance of rock glaciers in the Andes of Central Chile (33-35 degrees S). *Permafrost and Periglacial Processes.* 16(3): 231–240.

Brenning, A. 2008. The Impact of Mining on Rock Glaciers and Glaciers examples from Central Chile. In *Darkening peaks: glacier retreat, science, and society.* University of California Press, Berkeley: 196–205.

Brown, R. 1974. Distribution and environmental relationships of permafrost. In Permafrost hydrology. Proceedings of workshop seminar. *The international hydrological decade, Canadian National Committee*. Ottawa. 102 p.

Buchli, T., Merz, K., Zhou, X., Kinzelbach, W., and Springman, S.M. 2013. Characterization and Monitoring of the Furggwanghorn Rock Glacier, Turtmann Valley, Switzerland: Results from 2010 to 2012. *Vadose Zone Journal*. 12(1): 1–15.

Buk, E. 2002. Hidrologia de ambientes periglaciales. Cuenca Morenas Coloradas – Vallecitos, Cordon del Plata, Cordillera Frontal, Mendoza. IANIGLA 1973-2002. 73–76.

Burger, K.C., Degenhardt, J.J., and Giardino, J.R. 2000. Engineering geomorphology of rock glaciers. *Geomorphology.* 31: 93–132.

Capps, S.R. 1910. Rock glaciers in Alaska. *Journal of Geology*.18: 359–375.

Cheng, G., and Jin, H. 2012. Permafrost and groundwater on the Qinghai-Tibet Plateau and in northeast China. *Hydrogeology Journal*. 21: 5–23.

Chevallier, P., Pouyaud, B., Suarez, W., and Condom, T. 2011. Climate change threats to environment in the tropical Andes: Glaciers and water resources. *Regional Environmental Change*. 11:179–187.

Corte, A.E. 1976. The hydrological significance of rock glaciers. *Journal of Glaciology*. 17: 157–158.

Corte, A.E. 1978. Rock glaciers as permafrost bodies with a debris cover as an active layer. A hydrological approach, Andes of Mendoza, Argentina. *Proceedings of the Third International Conference on Permafrost, Edmonton, Alberta, Canada*. Ottawa: 262-269.

Falaschi, D., Castro, M., Masiokas, M., Tadono, T., and Ahumada, A.L. 2014. Rock Glacier Inventory of the Valles Calchaquíes Region (~ 25°S), Salta, Argentina, Derived from ALOS Data. *Permafrost and Periglacial Processes*. 25: 69-75.

Frampton, A., Painter, S. L., and Destouni, G. 2013. Permafrost degradation and subsurface-flow changes caused by surface warming trends. *Hydrogeology Journal*. 21(1): 271–280.

French, H. 2007. *The Periglacial Environment*. Third edition. Wiley. 458 pp.

French, H., and Slaymaker, O. 2011. *Changing cold environments: a Canadian perspective.* Wiley-Blackwell. 340 p.

Gardner, J.S., and I. Bajewsky. 1987. Hilda rock glacier stream discharge and sediment load characteristics, Sunwapta Pass area, Canadian Rocky Mountains. In *Rock Glaciers*.

Geiger, S. 2008. Influence of rock glaciers on stream hydrology, La Sal Mountains, Utah, USA. *M.A. Thesis*. University of Wyoming. 122 p.

Giardino, J.R., J.F. Shroder Jr., and J.D. Vitek. 1987. *Rock Glaciers.* London: Allen & Unwin.
Haeberli, W., C. Huggel, F. Paul, and M. Zemp. 2013. Glacial response to climate change. In: Shroder, J. (Editor in Chief), James, L.A., Harden, C.P., Clague, J.J. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, Vol. 13, *Geomorphology of Human Disturbances, Climate Change, and Natural Hazards*: 152–175.
Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., and Humlum, O. 2009. Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Reviews*. 92: 117–171.
Humlum, O. 1982. Rock glacier types on Disko, central west Greenland. *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography.* 82: 59–66.
IPCC. 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 p.
IPCC. 2014. In Climate Change 2014: Impacts, adaptation and vulnerability, Part B: Regional Aspects, contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed. V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, 688 pp. Cambridge: Cambridge University Press.
Janke, J.R., Bellisario, A.C., and Ferrando, F.A. 2015. Classification of debris-covered glaciers and rock glaciers in the Andes of Central Chile. *Geomorphology* 241: 98–121.
Konrad, S. K., Humphrey, N. F., Steig, E. J., Clark, D. H., Jr, N. P., and Pfeffer, W. T. 1999. Rock glacier dynamics and paleoclimatic implications. *Geology*. 27(12): 1131–1134.
Ireson, A. M., van der Kamp, G., Ferguson, G., Nachshon, U., and Wheater, H. S. 2013. Hydrogeological processes in seasonally frozen northern latitudes: understanding, gaps and challenges. *Hydrogeology Journal*. 21(1): 53-66.
Kane, D. L., Yoshikawa, K., and McNamara, J. P. 2013. Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA). *Hydrogeology Journal*. 21(1): 41–52.
Krainer, K., and W. Mostler. 2000. Hydrology of Active Rock Glaciers: Examples from the Austrian Alps. *Arctic, Antarctic, and Alpine Research*. 34(2): 142-149.
Krainer, K., Mostler, W., and Spötl, C. 2007. Discharge from active rock glaciers, Austrian Alps: A stable isotope approach. *Austrian Journal of Earth Sciences*. 100: 102–112.
Kundzewiz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Jimenez, B., Miller, K., Oki, T., Şen, Z., and Shiklomanov. 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*. 53:3-10.
Lachenbruch, A.H., and Marshall, B.V., 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science*, 234(4777): 689-696.
Milana, J. P. and Guell, A. 2008. Diferencias mecanicas e hidricas del permafrost en glaciares de rocas glacigenicos y criogenicos, obtenidas de datos sismicos en El Tapado, Chile. *Revista de la Asociacion Geologica Argentina*. 63 (3):310-325.
Prouse, T.D., and Ommanney, C. 1990. *Northern hydrology: Canadian perspectives.* Environment Canada. Inland Waters Directorate. NHRI science report. 308 p.
Scherler, M., Schneider, S., Hoelzle, M., and Hauck, C. 2013. A two-sided approach to estimate heat transfer processes within the active layer of rock glacier Murtèl-Corvatsch. *Earth Surface Dynamics Discussions*. 1: 141–175.
Schrott, L. 2002. Hidrologia del permafrost de Montana y su relacion con la radiacion solar. Estudio de una Cuenca colectora en Agua Negra, *Altos Andes de San Juan, Argentina.* IANIGLA 1973-2002. 83-87.
Sorg, A., Kääb, A., Roesch, A., Bigler, C., and Stoffel, M. 2015. Contrasting responses of Central Asian rock glaciers to global warming. *Scientific Reports*. 5: 1–6.
Spencer, A.C. 1900. A peculiar form of talus. *Science* 11: 188.
Springman, S. M., Arenson, L. U., Yamamoto, Y., Maurer, H., Kos, A., Buchli, T., and Derungs, G. 2012. Multidisciplinary investigations on three rock glaciers in the Swiss Alps: Legacies and future perspectives. *Geografiska Annaler, Series A: Physical Geography*. 94: 215–243.
Summerfield, M.A. 1991. *Global geomorphology. An introduction to the study of landforms.* Harlow: Longman; New York: Jphn Wiley Inc. xxii + 537 p.
Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., Bradley, R.S. 2008. Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*. 89:79–96.
Wahrhaftig, C., and Cox, A. 1959. Rock glaciers in the Alaska Range. *Bulletin of the Geological Society of America.* 70(4): 383–436.
Woo, M-K. 2012. *Permafrost Hydrology*. Springer. 564 p.
World Glacier Monitoring Service (WGMS). 2013. *Glacier Mass Balance Bulletin*. No. 21 (2010-2011). 106 p.