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Rock glaciers as water stores in the Bolivian Andes: an assessment of their hydrological importance

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Abstract

Water scarcity is a growing issue for high altitude arid countries like Bolivia, where serious water resource concerns exist because of climate change and population growth. In this study we use a recent Bolivian rock glacier inventory (Rangecroft et al., 2014) to estimate the water equivalent storage of these understudied cryospheric reserves. This paper shows that Bolivian rock glaciers currently store between 11.7 and 137 million cubic meters of water. Rock glacier water equivalents are compared to corresponding ice glacier water equivalent to allow an assessment of the hydrological importance of rock glaciers as water stores in this water scarce region. It can be seen that in the densely glaciated Cordillera Real (15°–16°S) rock glaciers form a small component of mountain water stores; however, along the Cordillera Occidental (17°–22°S), where ice glaciers are absent, rock glaciers are a more important part of the cryospheric water store, suggesting that they could be important for local water management. This is the first time that the water equivalence of the Bolivian rock glacier store has been quantified and is a first step toward assessing the contribution and importance of alternative high altitude water sources.

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Introduction

Water resources in Bolivia have been the subject of considerable debate over the past decade (Barnett et al., 2005; Bradley et al., 2006; Vuille et al., 2008). Over a third of the Bolivian population reside in high altitude cities in the Altiplano such as La Paz and El Alto (Vergara, 2009; WMO, 2011; World Bank, 2014) and in mountain communities where water stores are limited. Consequently, rainfall and glacier melt are the two most important water sources providing water for domestic and industrial use, agriculture, and power generation (Jordan, 1998; Vuille et al., 2008; Chevallier et al., 2011). During the dry season, rainfall is limited (66 mm on average falls between May and September in the Cordillera Real; Francou et al., 2003), and thus glacier meltwater becomes the most important source of potable water during this time of year. It is estimated that glaciers of the Cordillera Real provide 12%–40% of the potable water for the capital city La Paz (Vergara, 2009; Soruco, 2012).

However, glacier recession is widespread in the Bolivian Andes and is projected to accelerate in coming decades (Francou et al., 2003; Ramirez et al., 2007; Rangecroft et al., 2013). A decrease in the potable water supply from glaciers by 2050 is therefore projected for La Paz (Ramirez et al., 2007; Buxton et al., 2013), exacerbated by population increase (IPCC, 2007; Magrath, 2011; Buytaert and De Bièvre, 2012). Current urban water shortages in Bolivia represent a major social and economic problem (World Bank, 2010), and the demand on dwindling water supplies is increasing with population growth, rural-to-urban migration, and westernization of lifestyles (Painter, 2007; Mölg et al., 2008; Vanham and Rauch, 2010; WMO, 2011; Buytaert and De Bièvre, 2012; Rangecroft et al., 2013). All of these factors combine to produce strong evidence that Bolivia will continue to experience sustained water shortages in the future (Rosenthal, 2009; Rangecroft et al., 2013). There is now a pressing need for information about alternative stores of water at high elevations (Brenning et al., 2007; Rangecroft et al., 2013).

In the Andes, glaciers, debris-covered glaciers, and rock glaciers are the three main features of the cryosphere (Bodin et al., 2010a). Until now, most research has focused on rock glacier reserves in the Chilean Andes (Brenning, 2005a; Brenning and Azócar, 2008; Azócar and Brenning, 2010; Bodin et al., 2010a) and the Argentinean Andes (Schrott, 1996; Trombotto et al., 1999; Croce and Milana, 2002; Perucca and Esper Angillieri, 2008, 2011; Esper Angillieri, 2009; Arenson et al., 2010; Falaschi et al., 2014). Research in the Bolivian Andes is conversely quite sparse, with published information only on one, Caquella rock glacier (21.5°S) (Francou et al., 1999; Bodin et al., 2010b).

ROCK GLACIERS

Rock glaciers (Fig. 1, part a) are cryospheric landforms developed from accumulations of ice and debris, generally occurring in high mountainous terrain (Harrison et al., 2008; Berthling, 2011). In shape they resemble small glaciers and form a mix of angular rock debris with a core of ice or ice-cemented fine clasts, usually with a distinct ridge and furrow surface pattern (Potter, 1972). Rock glaciers are often classified by their activity status and subdivided into “active” and “inactive” (containing ice, also known as “intact”) or “relict” (not containing ice, sometimes referred to as “fossil”) (Barsch, 1996; Baroni et al., 2004; Krainer and Ribis, 2012; Falaschi et al., 2014). Active rock glaciers are considered indicators of contemporary permafrost (Barsch, 1996; Burger et al., 1999; Haeberli, 2000). It is estimated that active rock glaciers contain a range of between 40% and 60% ice covered by a surface layer of rock, which insulates the ice from low amplitude and high frequency temperature changes (Brenning, 2005a). They have a steep front (snout) and side slopes and give a visual representation of a swollen body due to ice content (Baroni et al., 2004). It is these surface features of ridges and furrows and steep front and sides that allow for rock glacier identification from high-resolution satellite images for inventory mapping (Paul et al., 2003). However, there is considerable variation in surface morphology occurring between locations in response to

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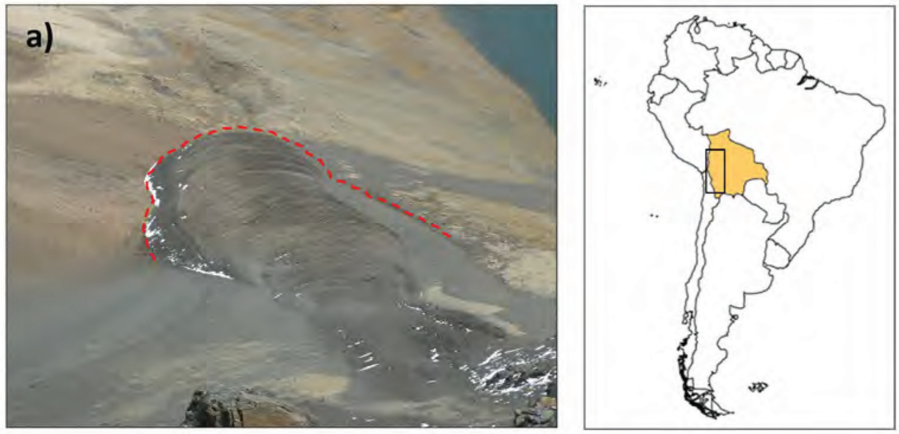

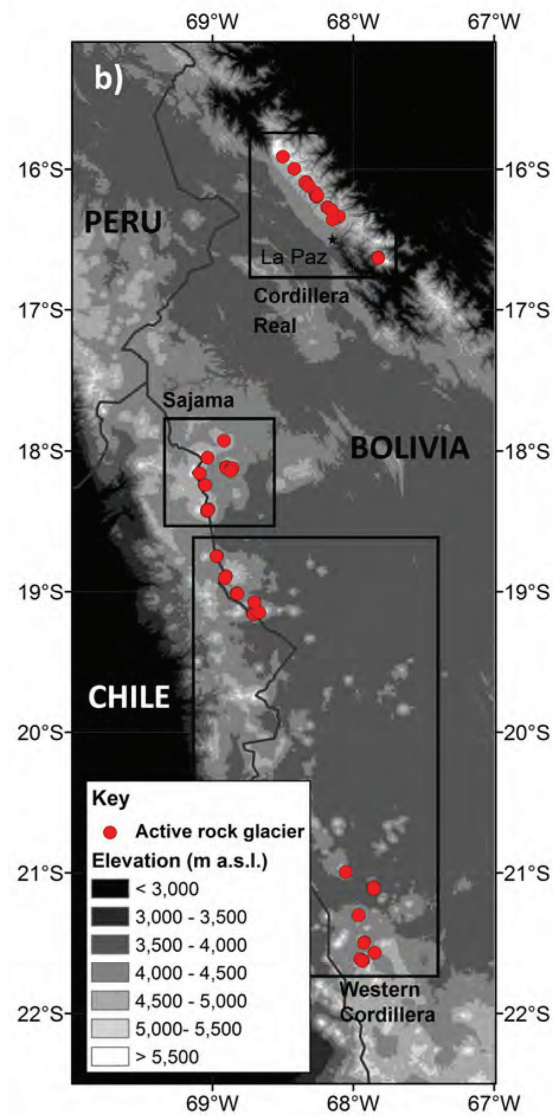

FIGURE 1. (a) Example from July 2011 of a Bolivian rock glacier with the sides and frontal slope indicated with a red dashed line (Pico Austria rock glacier in the Cordillera Real region, 16°11′35″S, 68°15′53″W). . Photo by S. Rangecroft. (b) The location of active rock glaciers in the Bolivian Andes on an elevation map of the study region, with annotations of the three main regions discussed in this paper: Cordillera Real, Sajama, and Western Cordillera.

both topographic and lithologic variables (Giardino and Vitek, 1988).

This study only focuses on active rock glaciers (those containing ice) and therefore those with relevance for water supplies. Active rock glaciers have been shown to contain significant volumes of water in the Chilean and Argentinean Andes where they are key stores and sources of water, especially during the dry season (e.g., Croce and Milana, 2002; Brenning, 2005a; Brenning et al., 2007; Azócar and Brenning, 2010). The hydrological role of the active layer in a rock glacier is important because it stores a significant quantity of water or ice due to the open debris texture (Croce and Milana, 2002). Rock glaciers trap and conduct water that enters with the active layer and subpermafrost material of active rock glaciers producing temporary aquifers and a seasonal release of water from the active layer (Burger et al., 1999; Croce and Milana, 2002).

The hydrological function and importance of rock glaciers is relatively well studied in other mountain regions of the world (Giardino et al.,1992; Cecil et al., 1998; Arenson et al., 2002; Williams et al., 2006; Azócar and Brenning, 2010); however, the hydrological importance of rock glaciers in Bolivia has never been assessed. Therefore, this research addresses this knowledge gap. We have documented the extent and size of the rock glacier resource in Bolivia in a previous study (Rangecroft et al., 2014), which concluded that there are 54 active rock glaciers covering a total surface area of 7 km^2 across the national extent of the Bolivian Andes (ranging from 15°S to 22°S) (Fig. 1, part b). However, the water storage potential of these permafrost features has not been explored. Therefore, this paper aims to estimate the ice content of Bolivian rock glaciers, calculate the water equivalent for Bolivian rock glaciers and ice glaciers, and therefore allow a comparison of these hydrological stores.

STUDY AREA

Bolivia is located in the center of the South American Andes (Payne, 1998), a region also known as the Dry Andes. The rock glacier inventory (Rangecroft et al., 2014) encompasses the two Cordillera mountain ranges of Bolivia between 15°S and 22°S (Fig. 1, part b), home to 20% of the world's tropical glaciers (Rabatel et al., 2013). Bolivia has a distinctive climate consisting of a dry season (May–August) and a wet season (December–February) (Francou et al., 2003), with aridity increasing toward the south of the country, resulting in no current ice glaciers in the south (Jordan, 1998). The Bolivian Cordillera Oriental is estimated to host 98% of Bolivia's glaciers (Jordan, 1998).

Three climatically and topographically distinct regions were identified along the Bolivian Andes: the Cordillera Real (15°–16°S), Sajama (17°–18°S), and the Western Cordillera (18°–22°S) (Fig. 1, part b). Along the Cordillera Oriental, the first region, "Cordillera Real," is a glaciated mountain range situated close to La Paz (Fig. 1, part b). With the wettest climate of the Bolivian Andes, this region contains the highest density of glaciers in the Bolivian Andes. The second and third regions, "Sajama" and "Western Cordillera," are based along the Bolivia-Chile border in the mountain chain of the Cordillera Occidental. The Sajama region is situated around the isolated ice-capped volcanic mountains in the Sajama National Park (Fig. 1, part b). The Western Cordillera covers the area southward of Sajama, along the dry, barren mountain range of the Cordillera Occidental (Fig. 1, part b). Almost no ice glaciers exist in this region (Francou et al., 1999), as rainfall is very low. Annual precipitation here is estimated to be less than 250–300 mm on the summits (Vuille and Amman, 1997). With its dry climate, this area is the best example of arid high mountains in the inner tropics (Francou et al., 1999). Population densities differ in the three regions, with the Cordillera Real providing water for the cities of La Paz and El Alto (Vergara, 2009; Soruco, 2012). There are no cities located in close proximity for the other two regions, only mountain communities and towns. For all three regions, rock glacier volume and water equivalent were estimated and analyzed.

Estimating Water Stores

USING THE ROCK GLACIER INVENTORY

Prior to this study, the first Bolivian rock glacier inventory was produced using fine spatial resolution satellite data, available through the platform of Google Earth (version 7.1.1.18888, Google Inc.), supported by a field mapping and validation program undertaken in 2011 and 2012 (Rangecroft et al., 2014). Satellite data available through Google Earth ranged from 5 to 30 m spatial resolution imagery. Rock glaciers were identified and classified according to Baroni et al. (2004) (Rangecroft et al., 2014). The resulting inventory contained spatial data describing the location, shape, elevation, and surface area of the rock glaciers along the Andean mountain ranges of Bolivia, the Cordillera Oriental and the Cordillera Occidental (Fig. 1, part b). A full list of active rock glaciers and their coordinates are available in Table 1.

The calculated mean minimum altitude at rock glacier front (MAF) for active rock glaciers was 4983 m (±30 m) (Rangecroft et al., 2014). The majority (88%) of the active rock glaciers had a main direction of flow as southerly (SE, S, and SW) (Rangecroft et al., 2014). Average active rock glacier length was 550 m (Rangecroft et al., 2014) and average active rock glacier area was 0.13 km^2, with a minimum of 0.01 km^2 and a maximum of 0.79 km^2 (Table 1). Average rock glacier area for the Cordillera Real region was 0.07 km^2, 0.20 km^2 for Sajama, and 0.13 km^2 for the Western Cordillera (Table 1).

ESTIMATING ROCK GLACIER THICKNESS

Calculations of the water content of the rock glaciers were carried out, based on an estimation of the volume of ice contained in the rock glacier (e.g., Barsch, 1996; Brenning, 2005a; Azócar and Brenning, 2010). To generate a value for ice volume, estimates of rock glacier thickness and surface area were multiplied together. However, in this study, rock glacier thickness was an unknown variable because this cannot be measured from satellite- and airborne remote sensing instruments, and to-date there are no direct measurements of the thickness and average ice content of active rock glaciers in the Bolivian Andes. Existing studies elsewhere in the Andes have estimated the mean thickness of rock glacier ice-rich permafrost through an empirical rule established by Brenning (2005b) (Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011) (Equation 1; Table 2). However, it should be noted that more research is needed to improve the area-thickness relationship established by Brenning (2005b) for other regions.

$$\text{Mean rock glacier thickness}\,[m] = 50\ x\ (\text{rock glacier area}[Km^2])^{0.2} \qquad (1)$$

ESTIMATING ICE CONTENT AND WATER EQUIVALENTS OF ROCK GLACIERS

Once the thickness of a rock glacier was established, ice content was accounted for, as rock glacier permafrost is not composed of 100% ice. Ice content varies considerably within rock glaciers; therefore, the amount of water in rock glaciers is naturally dif-

TABLE 1

ID and coordinates of active rock glaciers identified in the Bolivian Andes, divided into three corresponding regions. Adapted from Rangecroft et al. (2014).

Cordillera Real				Sajama				Western Cordillera			
ID	Lat (S)	Long (W)	Size (km^2)	ID	Lat (S)	Long (W)	Size (km^2)	ID	Lat (S)	Long (W)	Size (km^2)
A1a	15.89611	68.51472	0.146	B50a	18.04361	69.04305	0.064	C84a	18.74944	68.96722	0.147
A2a	15.98944	68.43111	0.153	B54a*	18.11000	68.90666	0.103	C85a	18.75055	68.97055	0.039
A11a	16.09138	68.33361	0.058	B56a	18.12111	68.90222	0.150	C86a	18.89	68.9	0.118
A12a	16.09777	68.33972	0.036	B58a	18.13166	68.86888	0.180	C87a	18.90888	68.91083	0.518
A14a	16.12083	68.31416	0.089	B59a	18.12805	68.85833	0.213	C92a	19.12805	68.69722	0.185
A16a	16.16416	68.27277	0.107	B60a	18.12472	68.85416	0.266	C93a	19.15499	68.71305	0.124
A19a*	16.19305	68.26472	0.043	B62a*	18.14305	68.87055	0.024	C94a	19.1525	68.70805	0.115
A20a*	16.19666	68.25805	0.032	B68a	18.24111	69.05472	0.033	C95a	19.16527	68.70611	0.180
A21a*	16.1875	68.25333	0.011	B70a	18.24305	69.05027	0.057	C96a	19.15305	68.68083	0.117
A27a	16.27222	68.18305	0.039	B76a	18.43055	69.0325	0.669	C97a	19.15305	68.66694	0.211
A29a*	16.27861	68.17416	0.043	B77a	18.41583	69.02777	0.789	C101a	20.99333	68.05416	0.087
A34a*	16.33833	68.10138	0.046	B120a	18.13555	69.11111	0.196	C107a*	21.10250	67.85361	0.127
A37a*	16.36000	68.14638	0.047	B124a	18.74944	68.96722	0.126	C108a	21.1175	67.85222	0.052
A39a*	16.29861	68.15138	0.145	B134a	18.41583	69.03305	0.061	C109a	21.30361	67.96138	0.093
A40a*	16.62888	67.82388	0.034	B135a	18.42166	69.03194	0.043	C110a	21.49777	67.91833	0.206
A42a*	16.63305	67.82305	0.038					C111a	21.49916	67.92111	0.050
								C113a	21.56916	67.84583	0.035
								C114a	21.61666	67.9475	0.078
								C115a	21.62916	67.92916	0.134
								C116a	21.62805	67.93361	0.037
								C126a	19.015	68.82694	0.131
								C128a	19.01888	68.82305	0.079
								C130a	19.07694	68.70222	0.016

*Indicates rock glaciers that were visited for field validation.

ficult to estimate due to the inherent variability and difficulty in determining exact genesis and subsequent depth and distribution of ice (Seligman, 2009). Currently, the worldwide estimates for ice content within rock glaciers ranges between 40% and 60% by volume (Barsch, 1996; Haeberli et al., 1998; Arenson et al., 2002; Hausmann et al., 2007; Brenning, 2008; Krainer and Ribis, 2012). A lack of studies investigating the ice content of rock glaciers in the Andes does not help to reduce this large range of uncertainty.

First attempts to quantify ice content in the Andes were established by Croce and Milana (2002), who found an average ice content of 55.7% for an Argentinean rock glacier. More recently, Arenson et al. (2010) working in Argentina showed that test pits dug in rock glaciers contained over 50% ice content. Similarly, Perucca and Esper Angillieri (2011) used the estimate of 50% ice content by volume for calculating water equivalents of rock glaciers at 28°S in the Argentinean Andes. Monnier and Kinnard (2013) found a much lower range of ice content in a small rock glacier in Chile (15%–30%); however, there are some limitations about the coring technique utilized, and they concluded that the rock glacier was degrading. Therefore, due to the lack of ice content studies in the semi-arid Andes, it can be argued that using the range 40%–60% ice content offers the best estimate currently available and allows a lower and an upper estimate of ice content to be calculated. From this, water content can be determined using the conversion factors for the density of ice and density of water shown in Table 2. An ice density of 0.9 g cm^{-3} (≡ 900 kg m^{-3}) was used to convert ice volume into a water equivalent (Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011).

ESTIMATING THICKNESS AND WATER EQUIVALENTS OF ICE GLACIERS

One of the aims of this work was to compare the water equivalent storage of rock glaciers to that of ice glaciers. In order to make this comparison, it was first necessary to establish current ice glacier coverage of the Bolivian Andes. Recent data describing the distribution of ice glaciers across the whole of Bolivia were not available, so it was necessary to use data from Ram-

TABLE 2

Values used to calculate estimates of permafrost thickness, ice content, and water volume in rock glaciers and ice glacier thickness and their sources.

Characteristic	Values	References
Rock glacier permafrost thickness	$50 \times$ (surface area)$^{0.2}$	Brenning, 2005b, p. 24; Azócar and Brenning, 2010, table 1
Percentage of rock glacier volume as ice	40–60%	Barsch, 1996; Haeberli et al., 1998; Arenson et al., 2002; Hausmann et al., 2007; Brenning, 2008; Krainer and Ribis, 2012
Ice glacier thickness	$28.5 \times$ (surface area)$^{0.357}$	Chen and Ohmura, 1990, p. 128
Density of ice	0.9 kg m^{-3}	Azócar and Brenning, 2010, p. 45

irez et al. (2012) for the Cordillera Real and Jordan (1998) for the Cordillera Occidental. For the Cordillera Real only, we were able to use a recent inventory by Ramirez et al. (2012) in which they estimated ice glacier coverage of 185.5 km^2 (Ramirez et al., 2012). Along the Cordillera Occidental, the only ice glaciers existing are those in the Sajama region, which Jordan (1998; Jordan et al., 1980) estimated to cover 10 km^2. South of this region, ice glaciers are absent (Jordan et al., 1980; Jordan, 1998).

Using the empirical relationship established by Chen and Ohmura (1990) used by Azócar and Brenning (2010) and Perucca and Esper Angillieri (2011), ice glacier thickness (and subsequent water equivalent assuming 100% ice content) was estimated using Equation 2:

$$\textit{Mean ice glacier thickness}\,[m] = 28.5x(\text{ice glacier area}[km^2])^{0.357} \quad (2)$$

Ice glacier thickness had to be calculated on an individual basis to be comparable with the rock glacier estimates. However, data on all individual ice glacier sizes were not available; therefore an estimate of average ice glacier size was established using known total surface area and number of ice glaciers. For the Cordillera Real, the total number of ice glaciers within the inventory of Ramirez et al. (2012) was 476, giving an average ice glacier size of 0.39 km^2. Using this average, the mean ice glacier thickness equation could be applied and multiplied by the number of ice glaciers to find total ice volume and water equivalent. For the Sajama region, the 10 km^2 coverage was known to be composed of the glaciated cone of Sajama (4 km^2), Payachata (4 km^2), and Quimsachata (2 km^2) (Jordan et al., 1980; Jordan, 1998).

To directly compare the water equivalents of ice glaciers and rock glaciers (as a ratio), the average ice content of 50% was used as a midrange between the lowest (40%) and the highest (60%) bounds of rock glacier ice contents.

FIELD WORK

To investigate the internal composition of rock glaciers, direct and indirect methods can be applied. Direct methods (e.g., coring, drilling, test pits) are labor- and time-intensive, whereas indirect methods (e.g., geophysical surveys) allow relatively rapid and inexpensive acquisition of data. Fieldwork was conducted on the Chiguana active rock glacier (21°06′09S, 67°51′13W) in the Western Cordillera region as this is a representative active rock glacier for the Bolivian Western Cordillera. Electrical resistivity surveys and test pits were conducted on lower parts of the rock glacier, close to the snout of the rock glacier. Electrical resistivity surveying used a Geo-receiver (JP), Geo-transmitter (JP-600), and electrodes to perform the vertical electrical sounding (SEV) method.

Electrical resistivity is one of the most commonly used geophysical methods to investigate permafrost and rock glacier internal content and structure (Croce and Milana, 2002; Bucki et al., 2004) as the equipment is light and easy to use (Croce and Milana, 2002). Refraction seismics can provide detailed information on the structure of the upper layers, and when complemented with geoelectric methods, deeper information can be gained, such as permafrost thickness estimates (Croce and Milana, 2002). Additional geophysical methods should be applied to reduce ambiguities if possible. Geophysical surveys require verification by coring/drilling or other direct methods (Degenhardt and Giardino, 2003) such as test pits. Well drilling combined with high-resolution reflection seismics is usually viewed as the best option for rock glacier investigation (Kääb et al., 1997), but is usually expensive.

Results of Rock Glacier Water Content Calculations

ROCK GLACIER PERMAFROST THICKNESS AND ICE VOLUME

Rock glacier permafrost thickness estimates ranged between 20 and 48 m (Table 2). Overall, these calculations resulted in an estimated total ice volume of 0.23 to 37.60 million cubic meters (Table 3).

ROCK GLACIER WATER EQUIVALENT CALCULATIONS

Results in Table 3 show that throughout the Bolivian Andes active rock glaciers are estimated to contain a total water volume equivalent of between 0.01 and 0.13 km^3 of water. Regionally, rock glaciers of the Cordillera Real (15°–16°S) have been estimated to store the smallest amount of water, containing between 0.01 and 0.02 km^3 of water (Table 3). Sajama (17°–18°S) and Western Cordillera (18°–22°S) have been estimated to hold triple this water equivalent each (Table 3). In Sajama, rock glaciers are estimated to hold 0.04 and 0.06 km^3 of water (Table 3). In the Western Cordillera, rock glaciers contained between 0.04 and 0.05 km^3 of water (Table 3).

RATIOS OF ROCK GLACIER TO ICE GLACIER WATER EQUIVALENTS

On average, the 1.07 km^2 of rock glaciers in the Cordillera Real were estimated to contain 0.01 km^3 water, yet the 185.5 km^2 of ice glaciers (Ramirez et al., 2012) were estimated to contain

TABLE 3

Table of ice volume (km³) and corresponding water volume (km³) equivalents for Bolivian rock glaciers, regionally and nationally (total). These calculations cover a range of ice content estimates with a lower (40%), average (50%), and upper (60%) bound. Rock glacier surface areas were taken from Rangecroft et al. (2014).

Region	Rock glacier total surface area (km^2)	Ice content estimate		Ice volume (km^3)	Water volume equivalent (km^3)
Cordillera Real (15°–16°S)	1.07	Lower	40%	0.01	0.01
		Average	50%	0.02	0.01
		Upper	60%	0.02	0.02
Sajama (17°–18°S)	2.98	Lower	40%	0.05	0.04
		Average	50%	0.06	0.05
		Upper	60%	0.07	0.06
Western Cordillera (18°–22°S)	2.88	Lower	40%	0.04	0.04
		Average	50%	0.05	0.05
		Upper	60%	0.06	0.05
Total	**6.93**	Lower	40%	0.10	0.09
		Average	50%	0.13	0.11
		Upper	60%	0.15	0.14

3.34 km^3 of water (Table 4). This resulted in a ratio of rock glacier to ice glacier water equivalence of 1:228, implying that ice glaciers contained a store of water 228 times bigger than that of the rock glaciers in the same region. In Sajama (17°–18°S), the 2.98 km^2 of rock glaciers were estimated to contained an average of 0.05 km^3 of water, with 10 km^2 of ice glaciers in the same region, which equated to 0.39 km^3 of water (Jordan, 1998) resulting in a ratio of rock glacier to ice glacier water equivalence of 1:7 (Table 4). In the Western Cordillera (18°–22°S), there are no ice glaciers due to limited precipitation (Jordan, 1998; Vuille, 2007), yet the 2.88 km^2 of rock glaciers in this region contained an estimated 0.05 km^3 of water, indicating a hydrological store in the absence of ice glaciers. However, this regional water store is for the largest region analyzed (Table 4; Fig. 1, part b).

ELECTRICAL RESISTIVITY

From fieldwork conducted in the Bolivian Andes, the presence of ice was confirmed within the Chiguana active rock glacier (Fig. 2, parts a and b). Test pits confirmed the presence of ice (Fig. 2, part c). However, these surveys did not extend deeper than 5 m, therefore ice content values through the entire depth of the rock glacier were not established. Previous research suggests that resistivity readings greater than 20,000 Ω represent an ice-rich layer (e.g., Francou et al., 1999). Survey site 1 (Fig. 2, part d) (21°06′06.93S, 67°51′17.95W) showed that within the first meter readings were characteristic of an ice-rich layer (19,817 Ω at 0.89 m), followed by a layer characteristic of substrate without ice (2,003 Ω) until a depth of 5.22 m. Below this resistivity, values of 31,640 Ω were measured, implying ice underneath an active layer of ~5 m. Site 2 (Fig. 2, part e) (21°06′06.46S, 67°51′19.44W) showed a similar pattern; an ice-rich layer at 1 m depth (512,580 Ω between 0.14 and 0.79 m), then a zone of substrate without ice (220 Ω) followed by an ice-rich layer below this at 2.39 m (Fig 2, part e). These results from the SEV surveys at Chiguana rock glacier in Bolivia (Fig. 2, parts d and e) demonstrated a similar pattern found by Croce and Milana (2002) for a rock glacier in the Argentinean Andes. Resistivity values greater than 20,000 Ω were found within the few meters of the survey sites in Argentina, and then again below what could be considered the active layer (the first 1–5 m), implying an upper dry deposit layer was found over a second wet debris layer with poor conductivity (2–5 m thick) followed by a highly resistive layer of frozen debris (permafrost) (Croce and Milana, 2002).

Discussion

ROCK GLACIER WATER CONTENT

In comparison to the limited number of studies on rock glacier water stores, Bolivian rock glaciers contained far less water than those of the Chilean Andes (Azócar and Brenning, 2010) and the Argentinean Andes (Perucca and Esper Angillieri, 2011). Azócar and Brenning (2010) found 147.5 km^2 of rock glaciers in Chile (27°–33°S), which they estimated to hold the water equivalent of 2.37 km^3. Therefore the hydrological store of rock glaciers is much greater farther south in the Andes (27°–33°S) than Bolivia (15°–22°S). Our results are more comparable to those of Perucca and Esper Angillieri (2011) in Argentina who calculated a water equivalent of 0.12 km^3 for 6 km^2 of rock glaciers in a 1 degree region at 28°S. This result is a similar estimate to that stored in Bolivian rock glaciers but covering a much smaller area. Overall, rock glaciers are relatively more important as water stores in Bolivia with a national ratio of 1:33 rock glacier to ice glacier water equivalent (Table 4) than they are in the European (Swiss) Alps, where their ratio is calculated to be ~1:83 (Brenning, 2005b).

However, it is the regional impact of these water resources that is important to consider when evaluating the absolute values, and their presence in comparison to other water stores (such as ice glaciers). For example, Table 3 shows that there are noticeable differences in rock glacier water content when viewed regionally. Rock glaciers of the Sajama region contained the largest amount of ice covering the smallest regional area (Table 4) and therefore have the greatest potential as water sources. Conversely, the Cordillera Real's rock glaciers contained the least amount. Exploring these regional differences in the context of population pressures and other water stores (e.g., glacial ice) is important if the significance of the rock glacier water storage is to be understood.

HYDROLOGICAL IMPORTANCE OF ROCK GLACIERS

Rock glaciers of the Cordillera Real stored the lowest amount of water out of the three regions (corresponding to the smallest surface area) (Table 3), yet this region of Bolivia is the most densely populated region, with the basins of the Cordillera Real supplying water for around 2.3 million people living in La Paz and El Alto (Vergara, 2009; WMO, 2011). From the comparison of rock glacier to ice glacier water equivalent in Table 4 it is clear that rock glaciers contribute less to regional water supply in the Cordillera Real, where ice glaciers dominate. However, with rapid ice glacier

TABLE 4

Regional and total area (km²) and corresponding water equivalents (m³) for Bolivian rock glaciers and ice glaciers, with a final column comparing these water equivalents directly as a ratio. Values are reported to two decimal places. Rock glacier water equivalents use the 50% ice content (average ice content).

		Rock glacier		Ice glacier		Ratio
Region	Region area (km²)	Area (km²)	Water equivalent (km³)	Area (km²)	Water equivalent (km³)	Rock glacier: Ice glacier water equivalent
Cordillera Real (15°–16°S)	~ 7050	1.07	0.01	185.5 (Ramirez et al., 2012)	3.34	1: 228
Sajama (17°–18°S)	~ 4000	2.98	0.05	10.00 (Jordan, 1998)	0.40	1: 7
Western Cordillera (18°–22°S)	~2500	2.88	0.05	0 (Jordan, 1998; Vuille, 2007)	0	∞
Total	**36,050**	**6.93**	**0.11**	**195.5**	**3.73**	**1: 33**

recession evident in this region (Soruco et al., 2009; Ramirez et al., 2012), we hypothesize that the relative importance of rock glaciers to ice glaciers will increase. The ice in rock glaciers is protected from small thermal changes by an insulating debris layer, resulting in a longer lag time than ice glaciers in their response to climate change, which is known to be on decadal time scales (Schrott, 1996; Haeberli et al., 2006). This makes rock glaciers more resilient water stores (Millar and Westfall, 2008), so it is likely that rock glaciers will persist as longer-term stores of water in mountain regions, even when ice glaciers have retreated or disappeared. It is important to note that response to climatic change is a size dependent process, with smaller rock glaciers being more susceptible to thawing. However, we also argue that, given appropriate conditions, retreating ice glaciers may also begin to incorporate significant debris cover and, over time, may undergo a transition to rock glacier forms.

In Sajama, rock glaciers have a higher relative importance as water stores in comparison to ice glaciers than in the Cordillera Real region, with a ratio of 1:7 rock glacier to ice glacier water equivalence (Table 4). This ratio is similar to that of the Andes of Santiago, Chile, which is also 1:7 (Brenning, 2005b), but of lower importance than that of the Arid Chilean Andes between 27°S and 29°S, where ratios are 1:2.7 (Azócar and Brenning, 2010), and between 29°S and 32°S, where rock glaciers dominate with a ratio of 3:1 (Azócar and Brenning, 2010). It can be noted that with recent glacier recession the ice coverage of the Sajama region is likely to be currently less than 10 km², especially given glacier recession trends in the Cordillera Real; however, there is a lack of published data for this region. Also, similarly to the Cordillera Real, the estimated rock glacier reserve of Sajama will increase in relative importance with projected glacier recession in Sajama.

In the Western Cordillera (18°–22°S), without the contribution of ice glaciers to the hydrological cycle in this region, and with the very limited rainfall (<300 mm a^{-1}), here potentially rock glaciers may act as an important water store. However, rock glaciers are still sparse in this region in comparison to those of the Chilean Andes (Azócar and Brenning, 2010), and population levels along the Western Cordillera are low.

FUTURE RESEARCH

Rock glaciers are long-term stores of frozen water, but the total water stores calculated in this research may not represent water that is readily available for release for human consumption. Research and data on rock glacier and ice glacier discharge are crucial for improving scientific understanding of local cryospheric reserves and their importance to the hydrological cycle and for future water resources management. It is also clear from this paper that more recent data on ice glaciers across the whole of the Bolivian Andes are needed and that field studies on ice content of Bolivian rock glaciers is necessary to improve and refine our understanding and the information established here. Furthermore, research on the impacts of future temperature and precipitation changes on the hydrological function of rock glaciers is needed to fully implement the information provided here in a future context. As rock glaciers are known to exist close to the mean annual air temperature 0 °C isotherm (Payne, 1998; Avian and Kellerer-Pirklbauer, 2012), it is important to investigate the potential implications of projected climate change for rock glaciers and their water stores.

Conclusions

Currently, little is known about Bolivian rock glacier water resources and their hydrological importance at local, regional, and national scales. This is the first time the water equivalents of Bolivian rock glaciers have been estimated and assessed in comparison to ice glaciers in the region. Although rock glaciers are of a similar size to other regions such as the Chilean Andes, their coverage is sparser along the Bolivian Andes, resulting in a much smaller total coverage than other regions of the Andes, and therefore overall their role in the hydrological cycle in general is less significant. However, rock glaciers in the Bolivian Andes can be considered as relatively locally important water stores in re-

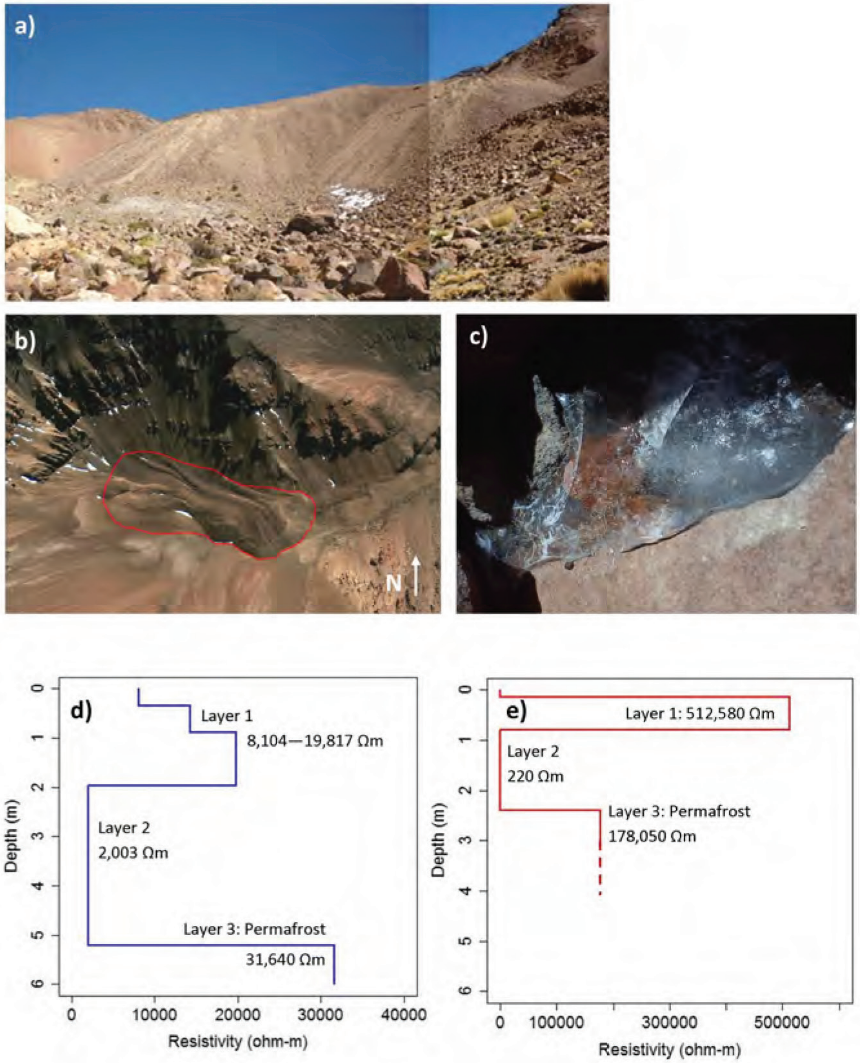

FIGURE 2. Electrical resistivity surveys and test pits conducted on the Chiguana rock glacier (21°06′09″S, 67°51′13″W) in August 2012. (a) High resolution Google Earth image of Chiguana rock glacier. (b) Ice was present within a meter from the surface in the areas surveyed. Photo by S. Rangecroft, August 2012). (c) Photograph of the rock glacier front (snout). Photo by S. Rangecroft. (d) Geoelectrical model for survey site 1 (21°06′06.93″S, 67°51′17.95″W). (e) Geoelectrical model for survey site 2 (21°06′06.46″S, 67°51′19.44″W).

gions of limited or no ice glacier coverage, such as in the Western Cordillera and Sajama. Relative importance of rock glacier stores compared to ice glaciers along the Bolivian Western Cordillera mountain range is similar to regions of the Chilean Andes, yet in the Cordillera Real ice glaciers dominate as hydrological stores. With projected ice glacier recession, this relative importance of rock glaciers in the Cordillera Real may increase. This work has improved knowledge and understanding of rock glaciers in the Bolivian Andes, contributing to the first step of sustainable water management: mapping and gathering information on current water resources. However, more research is required regarding rock glacier discharge data and impacts of future projections on rock glaciers and their water stores.

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