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Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes

Fabian Drenkhan[a,b,*], Lucía Guardamino[b], Christian Huggel[a], Holger Frey[a]

[a] Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zurich, Switzerland
[b] Department of Humanities, Pontifical Catholic University of Peru, Av. Universitaria 1801, Lima 32, Peru

ABSTRACT

Glacier shrinkage is a strong driver of change for mountain hydrology and landscape development and bears multiple risks as well as new options for human livelihoods. In the tropical Andes, current rates of glacier loss are investigated to some point but associated future extent of both vanishing glacier and forming lake areas and volumes are poorly explored. This study combines an analysis of current (1988–2016) and future (2050/2100) glacier and lake development in the Vilcanota-Urubamba basin (Cusco, Southern Peru). Total glacier area (volume) decreased by 37.3% (20.5%) from 226.1 km^2 (8.122 km^3) in 1988 to 141.7 km^2 (6.457 km^3) in 2016. Adjacent lakes increased in area (number) by 15.5% (18.3%) from 23.3 km^2 (460 lakes) in 1988 to 26.9 km^2 (544 lakes) in 2016 while corresponding lake volume has grown by 9.7% from 0.637 km^3 to 0.699 km^3, respectively. High spatiotemporal variability can be observed in the basin, with strongest glacier shrinkage in the lower lying northwest (Cordilleras Urubamba and Vilcabamba) and highest growth and lake extent in the Altiplano region of the southeast (Cordillera Vilcanota and Quelccaya ice cap). Future glacier areas could substantially decrease between 40.7% (RCP2.6) and 44.9% (RCP8.5) within the next decades (2031–2060) and between 41.4% and 92.7%, respectively, within this century (2071–2100). Hence, Andean landscapes would transform into mostly glacier-free areas with some remaining ice-covered summits over ~6000 m asl. and this would imply a loss of permanently stored water of several km^3. Until the end of this century, important future lake areas could develop and continue to grow between 3.2% (RCP 2.6) and 6.0% (RCP8.5) with an associated volume increase of 0.032 km^3 (4.6%) and 0.041 km^3 (5.9%), respectively. Our current baseline and future projections suggest that a decrease of glacier shrinkage is also followed by a slowdown in lake formation and particularly volume growth which might have already developed or occur in the near-future. Under the depicted scenarios of change, strong emphasis needs to be promptly put on feasible water management and storage options as robust adaptation measures tackling high uncertainties, risks and complex hydroclimatic and socioenvironmental intertwining.

1. Introduction

As with other high mountain regions, the tropical Andes are adversely affected by strong hydroclimatic and socioeconomic impacts in the context of global change (Baraer et al., 2012; Buytaert and De Bièvre, 2012; IPCC, 2014; Urrutia and Vuille, 2009; Vuille et al., 2008a). In the Andes of Peru, allover glacier shrinkage corresponding to an area loss of approximately 43% between 1970 and 2010 (ANA, 2014a), has uncovered many glaciated areas below 5000 m asl. (López-Moreno et al., 2014; Mark and Seltzer, 2005; Rabatel et al., 2013; Salzmann et al., 2013). In combination with permafrost degradation (> 5000 m asl.), this development bears multiple consequences, such as emerging hazards from unstable moraines, ice and rocks (Haeberli et al., 2017), changes in erosion and sedimentation rates (López-Moreno et al., 2017), as well as spatiotemporal alterations in both quantity and quality of mountain water resources (Drenkhan et al., 2015; Stark et al., 2012). As a result of glacier shrinkage, many high mountain lakes are currently developing in Peru (Colonia et al., 2017; Drenkhan et al., 2015; Emmer et al., 2016) and other glaciated mountain regions, such as the Alps (Haeberli et al., 2016a) and Himalayas (Gardelle et al., 2011; Kapitsa et al., 2017). These new and growing lakes imply several risks, such as Glacier Lake Outburst Floods (GLOF), water storage potentials as well as open administration and water management questions (Allen et al., 2016; Haeberli et al., 2016a; Terrier et al., 2011). Anticipating both current and future risks as well as new options for water use linked to deglaciation processes and lake formation and growth, are therefore crucial. In the Andes of Peru, glacier lake growth has only been assessed for a few catchments in the Ancash (Santa river) (Emmer et al., 2016) and Cusco (Vilcanota-Urubamba river) (Guardamino and Drenkhan, 2016; Hanshaw and Bookhagen, 2014) regions. A comprehensive lake inventory for all 19 glaciated mountain ranges in Peru was compiled for the period 1970–2010 (ANA, 2014b). Recently, efforts have been made to build a nation-wide inventory of potential future lakes (Colonia et al., 2017) which is about to be published with additional material for stakeholders. This represents a first comprehensive approach for the Peruvian Andes, and, to our knowledge, other tropical mountain regions, to project and quantify future lake development and associated water volumes.

* Corresponding author at: Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zurich, Switzerland.
E-mail address: fabian.drenkhan@geo.uzh.ch (F. Drenkhan).

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Nonetheless, there are no studies yet which comprehensively assess past, present and future glacier and lake development under scenarios of climate change and which put them into a broader context of future water management. Here, we address this gap by presenting three main aspects for the upper Vilcanota-Urubamba basin (hereafter: 'VUB') in Southern Peru: i) a multi-temporal analysis (1988–2016) of recent glacier and lake development, ii) an assessment of scenario-based future glacier extension and developing lakes until 2050 and 2100, and, iii) related glacier and lake volume estimations. The objective of this study is to identify current and potential future glacier and lakes trend changes and to discuss associated uncertainties. Beyond our study region, the achieved results bear relevance within a global context of glacier shrinkage, lake development and associated challenges and options for long-term risk and water management.

2. Regional setting

The study area is situated between the Central and Eastern Andes at the transition towards the Peruvian-Bolivian Altiplano in the region of Cusco, Southern Peru and comprises the entire extent of the upper VUB including the Vilcanota-Urubamba rivers (Fig. 1). We defined the outlet of the basin around 400 km northwest from its origin at Abra La Raya (5443 m asl.), where the Huamanmarca tributary diverts into the Upper Urubamba river at Santa María (1180 m asl.). The whole basin area covers 11,048 km^2 and includes a large glacier extent of, listed in downstream running order, the Cordillera Vilcanota (66.0 km^2), Quelccaya ice cap (18.4 km^2), Cordillera Urubamba (18.1 km^2) and Cordillera Vilcabamba (39.2 km^2). The southernmost glacier fragment corresponds to Cordillera La Raya, but due to its insignificance as mountain range in the basin (total area $< 2\,km^2$) it has been considered as part of the Cordillera Vilcanota. Total glacier area fraction in the VUB is about 1.3% which strongly varies at catchment scale from 0% to 5.5%.

The complex topographic and hydroclimatic situation of the study area is characterized by outer- and subtropical features including strong westerlies during the pronounced dry season (austral winter) and prevailing easterlies transporting moisture during the wet season (austral summer) (Garreaud et al., 2009; Salzmann et al., 2013). The region is particularly influenced by interannual anomalies of El Niño Southern Oscillation (ENSO) with increased easterly moisture transport during El Niño and with enhanced dry westerly flow regimes during La Niña (Perry et al., 2014). These anomalies have an impact in glacier mass balance in the Peruvian Andes with potentially strong melting due to enhanced ablation during El Niño and more stable or even positive mass balance during La Niña. Nonetheless, ENSO signal and magnitude on glaciers are not always clear and discriminable from other important climatic features (cf. Vuille et al., 2008b). However, for the upper VUB and within our study period, Thompson et al. (2017) identified a consistent relationship of negative mass balance related to e. g. the last El Niño 2015/16. Generally, positive temperature trends at a magnitude of approximately 0.1–0.4 °C/decade (1965–2009) are observed in the VUB from both station (SENAMHI, 2009) and NCEP/NCAR reanalysis data (Salzmann et al., 2013). In the same period, precipitation series also indicate (slightly) positive values in the order of 0.2–2.2 mm/year but particularly from the 2000s a decrease of this trend has been observed (Avalos et al., 2012) which was partially confirmed by (Salzmann et al., 2013). This could already be an indicator for a future 'aridification' of the Altiplano and, hence, the VUB which was also described by the IPCC (2014). Additionally, Neukom et al. (2015) found potential precipitation reductions in the order of 19–33% during the wet season in austral summer (DJF) until 2100.

In the VUB, rural communities prevail with traditional livelihoods, mostly low socioeconomic and high poverty levels (INEI, 2017a) and, hence, high vulnerabilities towards adverse effects of climate change (Buytaert et al., 2017; Orlowsky et al., 2016; Postigo et al., 2008). Glaciers represent an important cultural value within the indigenous Andean cosmovision (Bolin, 2009; Drenkhan et al., 2015) including mountain deities, offerings and pilgrimage activities. The above mentioned changes in the climatic regime would severely affect glaciers and livelihoods for the majority of 838,500 people inhabiting the VUB (INEI, 2017b), by combining long-term effects of less accumulation and enhanced ablation rates (Kronenberg et al., 2016). With a total area of $\sim$260 km^2, the Cordillera Vilcanota includes the second-largest tropical glacier extent worldwide and provides crucial water supply for multiple water users and ecosystem services. Continued glacier shrinkage coupled with growing irrigated agriculture (currently $> 2087\,km^2$) and hydropower demand ($>$ 290 MW installed capacity) might therefore strongly affect water availability for socioenvironmental systems, particularly in the dry season and upstream areas (Drenkhan et al., 2015; INEI, 2013; Kronenberg et al., 2016; Orlowsky et al., 2016). Furthermore, landslides and GLOF can pose severe risks for local livelihoods and the sensitive tourism sector (Cusco and Machu Picchu) including losses of infrastructure and lives. Large GLOF events at Salcantay-Yanatile/Santa Teresa (Cordillera Vilcabamba) in 1996/1998 (Carlotto et al., 2007; Frey et al., 2016) or at Chicon-Urubamba (Cordillera Urubamba) in 2010 (Portocarrero, 2014) illustrate their damage potential. On the other hand, rapid changes in this high mountain environment also bear some new options and co-benefits as new lakes could be used for local water storage, as tourism attractions as well as additional routes for Andean mountaineering in recently deglaciated areas (Vuille et al., 2017).

Nonetheless, data about current glacier shrinkage, related processes and risks are scarce in the region. Only a few studies have quantified multi-temporal glacier shrinkage for (parts) of the Cordillera Vilcanota (Hanshaw and Bookhagen, 2014; Salzmann et al., 2013; Veettil et al., 2017; Veettil and de Souza, 2017) and Vilcabamba (Guardamino and Drenkhan, 2016), some of them including lakes assessments. The Glaciology and Water Resources Unit (UGRH) of the National Water Authority (ANA) in Peru has compiled comprehensive inventories of glacier and lake extents for the Cordilleras Vilcanota, Urubamba and Vilcabamba until 2009 (ANA, 2014b; 2014a) which are currently updated. The recent inventory of future lakes under the scenario of overall disappearance of Peruvian glaciers by Colonia et al. (2017) is particularly important for both future risk and water management assessments.

3. Data and methods

This study uses free multi-spectral optical satellite data from five points in time between 1988 and 2016, separated by 6-year intervals (except for 1988–1998). Therefore, radiometrically and geometrically corrected L1T and L1C products from Landsat 5 TM (1988, 1998, 2004 and 2010) and Sentinel-2 MSI (2016) were downloaded from USGS Earth Explorer and ESA Copernicus Open Access Hub, respectively (Table 1). All scenes were acquired in the dry season between June and September (austral winter) in order to minimize potential misclassification due to temporal snow cover. Generally, temporal snow cover extent is low or negligible in tropical glacier areas and therefore less determinant for a correct ice classification, only in the scenes 2004–2016 limited snow cover is present in some regions. Digital Elevation Model (DEM) data comes from an adapted version of the global Shuttle Radar Topographic Mission (SRTM) 1° provided by Alaska Satellite Facility (ASF), University of Alaska Fairbanks which was developed for ALOS PALSAR imagery correction. This DEM (hereafter: 'SRTM AP') is freely distributed since 2015, artifact- and void-corrected and upscaled from originally 30 m to 12.5 m spatial resolution (ASF, 2015). Accuracy has not been specifically assessed but probably lies within the order of the source SRTM 30 m with $\leq$16 m absolute vertical and $\leq$20 m absolute horizontal circular accuracy.