Science of the Total Environment 579 (2017) 272–282

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Hydrological and depositional processes associated with recent glacier recession in Yanamarey catchment, Cordillera Blanca (Peru)

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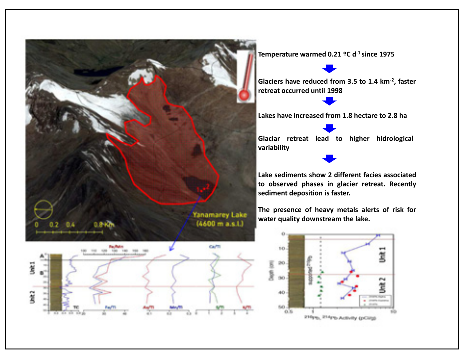
HIGHLIGHTS

- Climate warming has led to a reduction of the glaciers to one-third of that in 1975.
- New small lakes formed very rapidly in the deglaciated areas.
- Temperature closely control lake intake during the dry season
- Lake sediments reveal two different facies related to glacier retreat since 1975.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 15 November 2016
Accepted 16 November 2016
Available online 24 November 2016

Editor: D. Barcelo

Keywords:
Glacier recession
Climate change
Glacier hydrology
Proglacial lakes
Heavy metals
Cordillera Blanca
Peru

ABSTRACT

In this study, we investigate changes in the glaciated surface and the formation of lakes in the headwater of the Querococha watershed in Cordillera Blanca (Peru) using 24 Landsat images from 1975 to 2014. Information of glacier retreat was integrated with available climate data, the first survey of recent depositional dynamics in proglacial Yanamarey Lake (4600 m a.s.l.), and a relatively short hydrological record (2002–2014) at the outlet of Yanamarey Lake. A statistically significant temperature warming (0.21 °C $decade^{-1}$ for mean annual temperature) has been detected in the region, and it caused a reduction of the glacierized area since 1975 from 3.5 to 1.4 km^{-2}. New small lakes formed in the deglaciated areas, increasing the flooded area from1.8 ha in 1976 to 2.8 ha in 2014. A positive correlation between annual rates of glacier recession and runoff was found. Sediment cores revealed a high sedimentation rate (>1 cm yr^{-1}) and two contrasted facies, suggesting a shift toward a reduction of meltwater inputs and higher hydrological variability likely due to an increasing role of precipitation on runoff during the last decades. Despite the age control uncertainties, the main transition likely occurred around 1998–2000, correlating with the end of the phase with maximum warming rates and glacier retreat during the 1980s and 1990s, and the slowing down of expansion of surface lake-covered surface. With this hydrological - paleolimnological approach we have documented the association between recent climate variability and glacier recession and the rapid transfer of hydroclimate signal to depositional and geochemical processes in high

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http://dx.doi.org/10.1016/j.scitotenv.2016.11.107

elevation Andean environments. This, study also alerts about water quality risks as proglacial lakes act as secondary reservoirs that trap trace and minor elements in high altitude basins.

1. Introduction

The almost worldwide increase in air temperature during the last century has caused a reduction in the extent and volume of ice in the majority of the world's mountain areas (Oerlemans, 2005; Vincent et al., 2013; Marshall, 2014). A common process associated with glacier retreat is the formation of new lakes in the over-excavated basins, and an increase in water levels in existing lakes. As hydrological (runoff and glacier meltwater) and geomorphological (glacier deposits) processes in watersheds affected by recent deglaciation are very active, and the landscapes are very often carved in very unstable terrain (Benn and Evans, 2010), glacial lake outburst floods (GLOFs) pose a great risk to populations in their drainage areas (Carrivick and Tweed, 2013).

The Andes, in particular the Peruvian mountains, are a showcase for these hazards. There have been many reports of dramatic glacier recession in the Cordillera Blanca (Kaser et al., 2003; Mark and Seltzer, 2005; Vuille et al., 2003, 2008) and other mountain areas including the Cordillera Huayhuash (McFadden et al., 2011), Cordillera Vilcanota (Salzmann et al., 2013), Coropuna (Racoviteanu et al., 2007) and Huaytapallana (López-Moreno et al., 2014). Glacier recession accelerated in the Peruvian Andes over the three last decades of the 20th century (Kaser and Georges, 1999; Francou and Vincent, 2007; Raup et al., 2007; Burns and Nolin, 2014). Thus, from 1970 to 1997 the glacier coverage in Peru declined by >20% (Bury et al., 2011; Fraser, 2012), and this has been associated with higher lake levels and a marked increase in landslides, flash floods and mud flows, often with dramatic consequences (Portocarrero, 1995; Carey, 2005; Carey et al., 2012). However, because of a relative lack of data, the hydrological response in terms of total water available and changing seasonal patterns associated with this recession has been less studied, even though in some catchments 50% of the net runoff is from glacier melting, and can constitute almost 100% during the dry season (Bury et al., 2011; Baraer et al., 2012). Available information has provided evidence that glacier recession is leading to an increase in interannual variability in runoff in Cordillera Blanca (Kaser et al., 2003). Bury et al. (2011) reported that glacier retreat in some catchments of Cordillera Blanca has caused an increase in runoff, although this may be temporary and will be probably be followed by a decrease in water yield as the glaciers become smaller. They also suggested possible shifts in the seasonality of stream hydrographs. Such results were later supported by Baraer et al. (2012) confirming a transition during the 1970s in the discharge parameters of many rivers draining the Cordillera Blanca, including the Querecocha watershed, resulting in a decline in dry-season surface water availability after a period characterized by increasing runoff.

In addition, based on available hydrological records and isotopic analysis of water samples, Mark et al. (2010) reported a continuous decrease in the specific discharge from the most glaciated catchments of Cordillera Blanca, and a relatively higher proportion of water originating from glacier melt (a decreasing $\delta^{18}O$ trend).

Although an intensification of geomorphic processes parallels deglaciation, changes in the depositional processes in the deglaciated watersheds (sediment transport and rates of delivery) have not been investigated so far in the most recently deglaciated areas of the Andes. Newly formed lakes offer a unique opportunity to study how hydrological and depositional processes interact in these new basins, and so help to evaluate associated hazards (Michelutti et al., 2015). Indeed, previous studies demonstrated that lake sediment records from the tropical Andes can be used to identify changes in the extent of climate mediated up-valley ice cover (Rodbell et al., 2008; Stansell et al., 2013, 2014), and the possible content of pollutants on ice and sediments of Andean glaciers and lakes respectively (Cooke et al., 2009; Pavlova et al., 2014; Eichler et al., 2015).

In this study we investigated the recent evolution of the Yanamarey glacier and the Querococha watershed, which is one of the most studied glacier hydrology sites in the Peruvian Cordillera Blanca. Regular observations of glacier extent and climate variables associated with hydropower production, recorded since the 1970s by the Huaraz-based Peruvian Office of Glaciology and Lake Security (Carey, 2005; Mark and Seltzer, 2005; Mark and Seltzer, 2005; Bury et al., 2011), include reports of changes in glacier extent, the retreat of glacier fronts, and direct measurements and estimates of the evolution of the mass balance. We used Landsat TM images at an almost annual resolution to study the evolution of glacier surfaces in the two glaciated sectors of the Querococha catchment, providing the most detailed and updated report of glacier retreat in the catchment and the first assessment of the increasing surface covered by lakes in the region. Short sediment cores from Yanamarey Lake, in the headwater of the Querococha watershed, were used to investigate the evolution of lake depositional processes since the mid of the 20th century. Data on runoff from Yanamarey Lake has previously been used to characterize the water balance of these headwater areas (Baraer et al., 2012); these data were updated (2002–2014) and related to the evolution of climate and the glaciers. This is the first survey of a newly formed proglacial lake including sediment cores in the Andean region. Our approach relies on the fact that the hydrology of proglacial lakes is closely related to the fluctuations in glacier retreat velocity occurring upstream, and it will also affect the erosional and depositional processes in foreland areas, as well as the transport and deposition of heavy metals that may strongly impact downstream water quality. This topic is addressed through the integration of available climatological, hydrological and remote sensing data with lake sediment analyses. It improves the reconstruction of the glacier retreat evolution, its relationship to climate, and the impacts on the hydrology and sediment dynamics (erosion and deposition) in the catchment.

2. Study area

Yanamarey Lake (9°40′S; 77°15′W) is at approximately 4600 m a.s.l., has a drainage surface area of 3.5 km^2 (Fig. 1), and partially covered by glaciers (1.4 km^2). The Yanamarey Lake occupies an over-excavated basin in the bedrock, bounded by young lateral moraines on both margins and a terminal moraine that were probably deposited during the last period of maximum ice extent (the Little Ice Age: LIA). Up to the 1960s the recent lake basin was completely occupied by the glacier, and the Landsat images show it was completely free of ice at some time between 1975 and 1985. The highest mountain in the catchment is Yanamarey Peak (5192 m a.s.l.). The catchment is representative of small glacierized areas in the Cordillera Blanca (Gomez, 2004). The bedrock in the region is composed of metamorphic rocks (quartzite and hornfels) above the central granodioritic batholith that forms the core of the Cordillera Blanca (Wilson et al., 1967). The vegetation cover (mosses and grasses) is sparse, and the soils are poorly developed over the loosely consolidated alluvium and till. Glacier meltwater entering the lake is transmitted directly to the outlet stream without a significant lag resulting from lake storage. Mark et al. (2010) estimated a mean residence time of approximately 11 days. Runoff from the catchment is mixed with non-glacier streams that flow into Lake Querococha, defining a larger watershed (58 km^2, 3.4% glaciated) that drains to the Rio Santa (Mark et al., 2010).