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ORIGINAL ARTICLE

Geomorphologic impacts of the glacial lake outburst flood from Lake No. 513 (Peru)

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Abstract This article deals with the 2010 glacial lake outburst flood (GLOF) which happened in the Chucchún Valley in the Cordillera Blanca (Peru). The volume of the ice and rock fall from Mt. Hualcán was estimated to be about 500,000 m^3 and the detachment zone was identified between 5,450 and 5,600 m a.s.l. Basic landforms and processes (e.g. stream erosion, accumulation) were characterized by field investigation (2010 and 2011) as well as the rate of deglaciation using remotely sensed data (1948, 1962, 1970 and 2010). Two relatively independent parts of the Chucchún Valley were identified from the point of view of sediment flux: uppermost part of the catchment (4,192–3,575 m a.s.l.), where even fine-grained sediments were laid down, and the lower reaches up to the confluence (3,191–2,640 m a.s.l.), where valley bottom sediments were mobilised by the increased discharge. The comparison of field data and potential for erosion or sedimentation derived from the HEC-RAS model mostly showed conformity and discrepancy occurred in the valley segments where an extreme discharge during the 2010 GLOF laid down sediments after the gradient of the flow diminished. The rate of deglaciation is also described using historical remotely sensed data and unpublished reports and was set as 1,040 m in the last 62 years. We focused our attention also on the uppermost part of the catchment and applied a modified quantitative method for GLOF hazard evaluation—high topographical susceptibility for an icefall into the lake was calculated (0.92).

Keywords GLOF · Debris flow · Natural hazards · Deglaciation · Cordillera Blanca · Peru

Introduction

Most of the mountain glaciers worldwide have recorded retreat since the “Little Ice Age”, the most striking of which occurred during the last three decades in the tropical Andes (Rabatel et al. 2013). Due to global climate change, the rate of recession has been enhanced in recent time and rapid geomorphic changes are closely connected with the changing environment. The retreat of glaciers has given birth to numerous new lakes, among which are those located behind young and unstable frontal moraines (Chisolm et al. 2012; Emmer et al. 2014). In the case of existing proglacial lakes, an enlarged volume and areal extent have been recognized (Vilímek et al. 2005b). The ice coverage in the Cordillera Blanca during the Little Ice Age was estimated as being 850–900 km^2 (Georges 2004). The ice recession during the 20th century was concentrated into the periods (e.g. Ames and Francou 1995; Mark and Selzer 2005): 1930s–1940s and from the mid-1970s until the end of the century (the ice coverage in 1930 was 800–850 km^2; in 1970 was 660–680 km^2 and in 1990 was 620 km^2). For the Chucchún watershed, the glacial coverage shrunk by 24 % between LIA and 2003, while ELA (Equilibrium Line Altitude) increased by 130 m in the same period (Giraldéz et al. 2014).

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The glacial retreat is usually closely connected with threat of GLOFs—glacial lake outburst floods (Carey 2005) usually manifested as catastrophic flooding following dam failure or overflow. The discharge and destructive power of the flow is enormous (Neal 2007). Moraine dams from the Little Ice Age are considered to be among the most dangerous (e.g. Clague and Evans 2000) especially when flat or over deepened spaces form behind the moraines to host new lakes (Zapata 2002). GLOFs could be triggered by several processes; however, various types of slope movements belong to the most significant ones—e.g. rock and ice falls, landslides (Emmer and Cochachin 2013). This matter has been studied in different parts of the world, not only because of the raised seriousness of the natural risk in areas of growing population density and increased vulnerability, but also due to the fact that such lakes are an important source of water for local populations (e.g. Kershaw et al. 2005; Bajracharya et al. 2007; Bolch et al. 2008; Wang et al. 2008; Narama et al. 2010).

The situation of the Himalayan glaciers was described e.g. by Bajracharya and Mool (2009): “Although the number of lakes above 3,500 m a.s.l. has decreased, the overall area of moraine-dammed lakes is increasing”. Shrestha et al. (2010) stressed the fact that the knowledge of current GLOF risk in the area of the Hindu Kush-Himalayas is still incomplete, and they present a methodological approach to GLOF risk assessment. In Tien-Shan subsurface, drainage zones of Petrov Lake were identified in addition to strong glacier retreat (Janský et al. 2009). Natural hazards related to GLOFs were described from the Andes as well. Harrison et al. (2006) used lichenometry and dendrochronology as well as geomorphological mapping and sedimentology to assess the nature and timing of glacier recession in connection with GLOF in the Patagonian Andes. Also, in Europe, recent geomorphic processes have been described after a GLOF—for instance in Norway (Breien et al. 2008) or in the Swiss Alps (Haeberli et al. 2001).

GLOFs have to be considered not only from the point of view of natural hazards but also from the perspective of hazard management (e.g. Hegglin and Huggel 2008; Kattelmann 2003). Raising awareness of the impacts of climate change has been taken into consideration in national development agenda e.g. in Nepal (Rai and Gorung 2005). Glacial lake hazard assessment and mitigation from a Himalayan perspective were proposed by Reynolds et al. (1998) and prevention methods of GLOFs were performed by Grabs and Hanisch (1993).

Similar forms of natural hazards have been described in the last decades in the Cordillera Blanca, forming part of the Western Cordillera (Lliboutry et al. 1977; Carey 2005; Hubbard et al. 2005; Vilímek et al. 2005a, b; Hegglin and Huggel 2008; Klimeš 2012; Emmer and Cochachin 2013; Emmer and Vilímek 2013; Haeberli 2013). The first ever historically mentioned aluviónes (sg. aluvión—local name for a debris flow, irrespective of its cause) in Cordillera Blanca (Fig. 1) are dated back to the beginning of the 18th Century (both events during 6 January, 1725) when one event hits the city of Huaraz and other destroyed Ancash village killing of about 1,500 persons (Zapata 2002). The latter aluvión originated from Mt. Huandoy and a lake situated at the head of the Ancash valley (Kinzl 1968). Several devastating events happened during the 20th century: an aluvión destroyed significant part of Huaráz city in 1941 (Zapata 2002; Vilímek et al. 2005b); another originated under Mt. Huantsán (6,395 m a.s.l.) in Huachescsa valley in 1945 or in the valley of Los Cedros from Jancarurish Lake in 1950 due to the combination of glacier calving and artificial adjustment of the lake outflow which temporarily weakened the dam (Zapata 2002). Mt. Hualcán itself was source of a natural hazard in recorded history only during the 1970 earthquake. During that time, an ice avalanche from the eastern wall of Mt. Hualcán crashed into a lake situated above Lake Librón (Huichajanca Valley in the Marañón River Basin), the moraine dam collapsed and the lake outburst into Lake Libron which is a bedrock-dammed lake. The following flood was absorbed by the large basin located further down in the valley (Zapata 2002). No collapses of natural dams were recorded on the western slopes of the Cordillera Blanca (catchment of the Santa River) during the 1970 earthquake (Lliboutry et al. 1977).

Lake No. 513 located under Mt. Hualcán (6,122 m a.s.l.) is a high-altitude bedrock-dammed lake with water level elevation of 4,431 m a.s.l. During Sunday 11 April, 2010 (7.40 a.m.), a large block of the glacier (together with rocks) crashed from the approximate elevation of 5,500 m a.s.l. into Lake No. 513 from the SW slope of Mt. Hualcán. Part of the lake water overflowed the dam which had a freeboard of about 20 m and created a glacial lake outburst flood in the Chucchún River valley (a right tributary to the Santa River).

Lake No. 513 has been considered to be dangerous since the beginning of 1970s (Oberti 1973); nevertheless, the first unpublished reports about the glacial retreat and lake control were written by Matellini (1965), Zavala (1966) and Caceres (1972). The overview of the Mt. Hualcán hazard as well as a small GLOF in 1991 was described by Carey et al. (2011). Suspicion about the ice-cored dam was confirmed in 1988 (Reynolds et al. 1998). After installation of siphons in 1988–89, the water level was reduced by 8 m. Furthermore, a 135 m long tunnel was drilled in 1993 to lower the lake level by another 20 m. A second, near-vertical, shaft was constructed for ventilation and proper access (Reynolds et al. 1998). This measure was considered to be sufficient with respect to the technical feasibilities,

Fig. 1 Location of the area

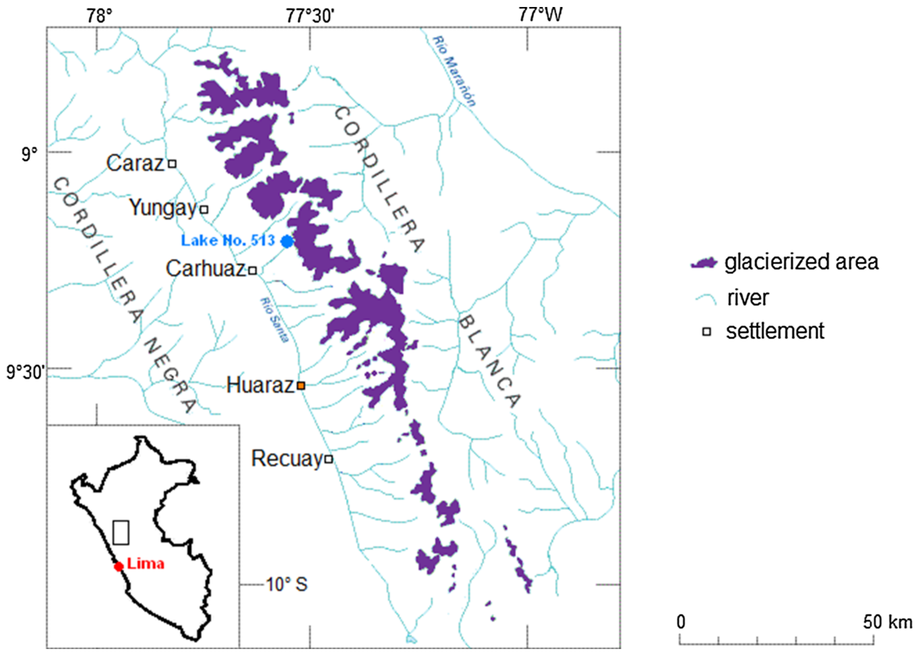

Fig. 2 An example of lateral erosion where part of the field was washed out. The largest block was only transported for a limited distance

financial possibilities and engineering–geological conditions. The total water level decrease of 28 m created a freeboard to contain possible displacement waves. In fact, the recent lake is located inside a rock depression of glacial origin and the frontal moraine is situated on the top of hard rocks. The recent water level does not reach the foot of the frontal moraine and is dammed behind bedrock with 20 m of freeboard (see Estudios de vulnerabilidad de recursos hidricos de alta montaña 1997, Unpublished report of Instituto Andino de Glaciologia y Geo Ambiente, Huaráz, Peru). The outburst flood from Lake No. 513 mostly mobilised material from the river bed and partly from river banks.

The alarming reports about missing people published e.g. by www.larepublica.pe or www.peruviantimes.pe later proved to be false. The whole disaster claimed no fatalities; nevertheless, some houses, roads, bridges and an important water treatment facility were destroyed. The rather low extent of damage is due to the fact that the valley is not densely populated and some villages were left out of the reach of the debris flow. It was a considerable event due to the large amount of material transported down the valley; lateral erosion was documented inside the valley and the processes occurred very quickly. As an example, we could mention the case of one farmer, who lost part of his field together with his cattle (!)—see also Fig. 2.

The main aim of this paper was to identify and map the geomorphological response of the Chucchún Valley to the 2010 GLOF. To do so, a geomorphological map was prepared and the main fluvial processes as well as their spatial distribution were indentified. This information was compared with the erosion and accumulation potentials calculated by the HEC-RAS model. The GLOF susceptibility evaluation was set up using an adjusted quantitative method of Wang et al. (2011) and information about the deglaciation process.

Study area, geological and geomorphological setting

In general, the SW slopes of the Cordillera Blanca, which is facing the main Santa River valley, are accompanied by normal faults and according to their origin could be classified as fault slopes. At the foothill, fluvioglacial deposits are located with moraine ridges (lateral, front moraines) which were dated at around 10–11,000 BP (Giraldéz 2011). To depict the detailed geological and geomorphological characteristics of the area, they are described from the upper to lower parts of the catchment. The catchment of the Chucchún River (a right tributary of Santa River) stretches from the NE to SW across three different zones (upper, central and lower parts of the Chucchún Valley) which vary according to their geological as well as geomorphological character.

The upper part of the valley consists of intrusive rocks: coarse-grained granodiorites and tonalites (Wilson et al. 1995). This area is formed into sharp modelled and glaciated peaks and crests. Lake No. 513 is located below Mt. Hualcán (6,122 m a.s.l) in a glacial cirque. It was originally located behind the frontal moraine, but after the water level was artificially lowered the lake is now bedrock-dammed. Nevertheless, other, older moraines reached an elevation of 3,500 m a.s.l. The ancient lake located here has completely filled with fluvial sediments (its local name is Pampa Shonquil).

The central part of the Chucchún River valley has been developed in various sediments of the Mesozoic era. Formation of “Carhuaz”, “Santa” and “Chimu” was described from this area by Wilson et al. (1995). For the Chimu formation, the occurrence of quartzite, sandstone and claystone is typical in a thickness of hundreds of metres (150–400 m). Layers of limestone and claystone in a total thickness of 100–380 m were described by Wilson et al. (1995) under the Santa formation. The deposition of the Carhuaz formation with a thickness of around 500 m (sandstone and claystone) shows signs of discordance contrary to Santa strata. The Chucchún River is deeply cut in the Mesozoic sediments compared to other parts of the valley. In addition to the Mesozoic sediments, significant layers (150 m) of pyroclastics from the Neogen are located in the central part of the Chucchún River catchment. This formation bears the local stratigraphic name of “Yungay”.

The lower part of the valley, near the confluence with the Santa River, is compounded by alluvial sediments forming a large and flat (average slope inclination of 3°) alluvial cone. GLOFs like the one described in this paper contribute to a build-up of this accumulation. Nevertheless, the 2010 event was only a very small contribution with respect to the overall size of the dejection cone.

Methodology

Field research

During the field research, we searched for enormous lateral erosion and levees not only to have a feeling about the intensity and extent of the natural processes but also especially to identify segments of the Chucchún River valley where the erosion and/or sedimentation play a leading role. The first field research took place shortly after the GLOF event during June 2010 when especially the direct impacts of the GLOF were documented. Interviews with local people were important for an estimation of the velocity and character of the flow. The final field trip in September 2011 was oriented mainly towards creating topographic cross profiles describing river channel and overbank areas. The cross sections were measured using a handheld laser range finder (Laser Ace 1,000) with submetre accuracy of measurements at a distance of about 100 m. The profiles were localized with a Garmin GPSmap 60CS. Topographic characteristics of the defined valley segments were calculated using an 8 m DEM derived from spring 2012 WorldView images (Schneider et al. 2014).

Sediment transport analysis

Sediment transport analysis was performed by the HEC-RAS model compiled on the basis of field data measured after the flood event (see also Klimeš et al. 2014). Sediment analysis is sensitive to the input data and is used mainly for predicting regional, long-term trends. For modelling, the right definition of bed gradation, setting of appropriate computing functions and also the boundary conditions are crucial. Three different computing approaches were taken and the results were compared to obtain the most suitable results. The whole concept of the computation is based on a sediment continuity equation that compares inflowing and outflowing loads of sediment in each cross section. Because of the above-mentioned limits, we used this sediment transport analysis only (!) as a potential for erosion and sedimentation which we compared in this paper with the field data. We suppose that it may be important to know how a single event (2010 GLOF) fits (or doesn’t fit) with the long-term valley evolution from a geomorphological point of view.

Remote sensing data and hazard evaluation

The remote sensing data were useful for geomorphological research even though we carried out the field campaigns. They also have a great importance for hazard evaluation. Four sets of images were studied in detail to reveal the intensity of deglaciation in the uppermost part of the Chucchún River catchment. The aerial photos dated back to 1948, 1962 and 1970; and the satellite image (Google Earth Digital Globe 2013) represents the recent situation (2010). This time span enables us to cover a period of 62 years. Other morphometric data were used for the modified quantitative method presented later in this chapter.

For the hazard associated with GLOF, it is important to describe glacial lake typology and selected characteristics of the surrounding of the lake—aspects of stability with respect to the possibility of producing a dangerous event. They may increase or decrease the potential instability causing an outburst (or overflow). The aspects of stability include more than twenty characteristics (e.g. Grabs and Hanisch 1993; Huggel et al. 2002; McKillop and Clague 2007).

For the evaluation of the hazard, it is generally considered necessary to include two groups of characteristics to accurately assess the possibility of a sudden release of water from any type of a lake. These are: (1) dam stability (possibility of its failure—breach or rupture); and (2) potential trigger (external factor whose consequences may cause a sudden release of water from a lake) (e.g. Richardson and Reynolds 2000). The solid bedrock dam of Lake No. 513 and the excavated tunnels are considered as being stable even in the case of large earthquake; thus, the only mechanism of sudden water release is dam overflow by a displacement wave(s) following mass movement into the lake including fast slope movements (e.g. icefalls, rockfalls, landslides) and a flood wave(s) from a lake situated upstream. Dam overflow by a displacement wave(s) following mass movement into the lake is highly complex and difficult to quantify question, which is generally controlled by: (i) volume, character and speed of transported material which enters the lake; (ii) lake depth, volume and lake bottom morphology (breakwater effect); and (iii) dam freeboard and geometry. Modelling of landslide generated water waves is not a matter of this paper (e.g. Biscarini 2010 used detailed computational fluid dynamics to simulate the formation of waves generated by landslides). The first group of above-mentioned variables is predictable with difficulty and a detailed glaciological field study needs to be performed to be able to quantify them accurately; the second and third groups of characteristics are quite well known in the case of Lake No. 513. Although the dam freeboard reaches 20 m (Carey et al. 2011), the 2010 event showed that a sudden water release following dam overflow is a possible scenario for this lake.

With the background of the complexity of GLOF hazards (mentioned in the last two paragraphs) and the knowledge of various methods for hazard evaluation (see also Emmer and Vilímek 2013), we choose the quantitative method according to Wang et al. (2011), which we slightly modified with respect to the specifics of Lake No. 513.

The modified method presented by Wang et al. (2011), originally used for identification potentially dangerous moraine-dammed lakes in Nepal, is used for evaluating the topographical susceptibility for an icefall into the lake in this study. In the original methodology, five characteristics including the mean slope of the moraine dam are assessed. For the purpose of Lake No. 513, this characteristic was omitted and its weight was divided among the remaining four characteristics (Table 1). Topographical susceptibility for an icefall into the lake was then expressed as follows:

$$P = \sum_{i=1}^{4} w_i V_i \tag{1}$$

where w_i is the recounted weight of the characteristic and V_i the respective danger value. The result of this calculation is expressed on a scale from 0.25 (icefall into the lake is not a likely scenario) to 1 (icefall into the lake is a highly possible scenario). The input data for this calculation were gained from the 2011 field study and from remotely sensed photographs (Google Earth Digital Globe 2013). The determined values for the calculation are highlighted in Table 1.

Results

The 2010 GLOF event characteristics

The intensity of deglaciation is rather strong in this area. From the comparison of images from 1948, 1962, 1970 and 2010, it is clear that the glacier has retreated 1,040 m in 62 years (in the place where the lake was formed). The annual rate of glacial retreat is almost 17 m, but it was not uniform throughout the whole period (see Fig. 3). At present, there is no direct contact between the glacier and the lake. Moreover, the buried ice in the frontal moraine does not play such an important role as it did before 1988.

The rock–ice avalanche involving bedrock material detached at an elevation of between 5,450 and 5,600 m a.s.l. and transported over the steep surface of Glacier No. 513 for 1.7 km into the Lake No. 513. Before reaching the lake, the avalanche had to cross a 190 m high rock step (Klimeš et al. 2014). The crash into the lake induced a displacement wave (series of waves). The hydrodynamics of the lake surface are unclear because we do not know the exact volume and precise content of the ice–rock avalanche. We estimate that the volume of material that crashed into the lake is about 500,000 m^3.

The induced displacement wave overflowed the dam freeboard (20 metres) and partly eroded the moraine wall in the former outlet and a 5–6 m high wave flowed into the Chucchún River. People in Acopampa village recognized

Table 1 Modified method for evaluating topographical susceptibility for an icefall into Lake No. 513

Interval	I	II	III	IV	Original weight	Recounted weight (*w*)
Danger value (*V*)	0.25	0.5	0.75	1		
Mother glacier area (km^2)	<0.5	0.5–1	1–2.5	**>2.5**	0.07	0.09
Distance between lake and glacier (m)	>600	300–600	**80–300**	<80	0.27	0.34
Slope between lake and glacier (°)	<12	12–17	17–21	**>21**	0.22	0.27
Mother glacier snout steepness (°)	<14	14–19	19–26	**>26**	0.245	0.30
Mean slope of moraine dam (°)	<10	10–14	14–22	>22	0.195	Omitted

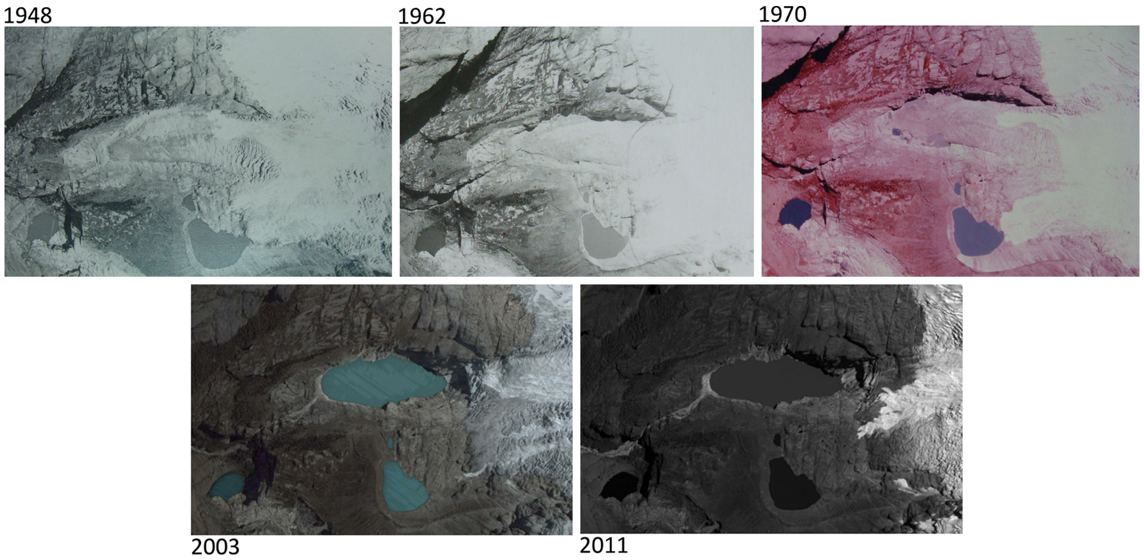

Fig. 3 Glacial retreat in the surroundings of Lake No. 513 (between 1948 and 2011)

the rising discharge at around 8.40 a.m.–1 h after the ice–rock fall. The second wave came around 35 min later. This could be explained by a partial and temporary blockage somewhere in the Chucchún Valley. According to our field investigations such a place might be located in the upper part of the valley where the valley is blocked by an extremely large boulder (15 × 12 × 10 m); another possible explanation may be that two waves overtopped the lake dam (e.g. due to two subsequent avalanches from the Mt. Hualcán—nevertheless, there are no eye witnesses to corroborate this statement).

Analysis of erosion and accumulation phases of the evolution of the Chucchún Valley

The Chucchún Valley can be distinguished into segments according to prevailing erosional and accumulation processes (Table 2; Fig. 4). We have defined an erosional section in hard rock or in sediment cover, and also segments with fine-grained or coarse accumulation, starting from Lake No. 513 down to the confluence with the Santa River. General characteristics such as altitude, and longitude and vertical distance are clear from Table 2.

The outflow of the Chucchún River from Lake No. 513 represents a cut way in the frontal moraine and deepward erosion into hard rocks (segment I in Fig. 4). For this segment, we do not have data from HEC-RAS model. The moraine sediments adjacent to the river outflow were washed away in a belt of about 30 m wide what is probably a result of repeated high discharges from the lake. The river continues through the not very deep erosion channel in the 260 m high rock face to its second part (II in Fig. 4) where erosion in sediments of a different origin takes place (moraine material, deluvium and glaciofluvial sediments). Sediments are transported to the next part of the river because of the high gradient of the flow (20°) and its transport capability. The U-shaped valley profile is still dominant. The belt of recent erosion is only 20 m wide (comp. with the width of the eroded moraine).

An accumulation of boulders evolved at the beginning of the third segment (III) where the gradient of the Chucchún River sharply decreases from 20° to 6° (see Table 2; Fig. 5). The "lowering" of the gradient is important for the presence of boulder accumulations. The second important factor is that this river section follows after a part with high stream power (and sediment inputs). Conditions for the

Table 2 Segments of the Chucchún River distinguished according to the gradient and prevailing geomorphological processes (erosion/accumulation)

Valley section	Dominant process	Length (m)	Max alt. (m a.s.l.)	Min. alt. (m a.s.l.)	Vertical distance (m)	Gradient (°)
I	Erosion in hard rocks	544	4,462	4,210	252	25
II	Erosion in sediments	1,165	4,210	3,775	435	20
III	Bolder accumulation	1,188	3,775	3,644	131	6
IV	Lateral erosion	925	3,644	3,606	38	2
V	Fine-grained accumulation	623	3,606	3,589	17	1
VI	Deepward erosion	2,590	3,589	3,194	395	9
VII	Bolder accumulation	1,289	3,194	3,059	135	6
VIII	Erosion (+boulder accum.)	1,624	3,059	2,917	142	5
IX	Accum. (+lateral erosion)	2,237	2,917	2,771	146	4
X	Bolder accumulation	1,282	2,771	2,701	70	3
XI	Fine-grained accumulation	1,037	2,701	2,665	36	2
XII	Deepward erosion	121	2,665	2,656	9	4

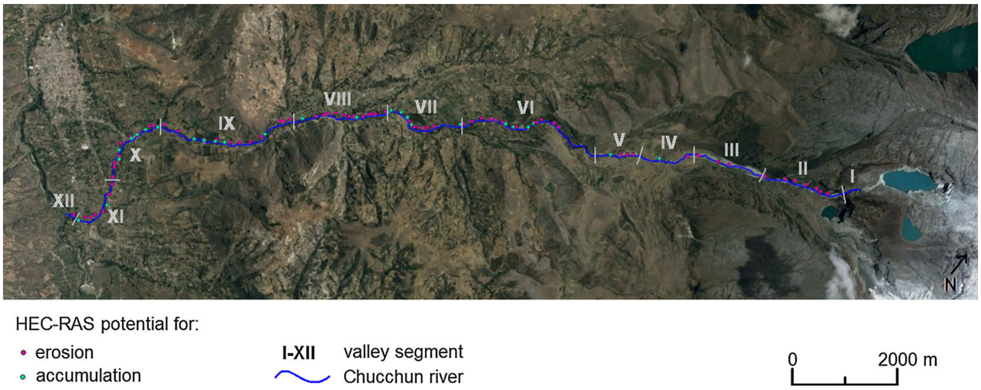

Fig. 4 Erosion and accumulation processes derived from the HEC-RAS model; segments I-XII according to the Table 2 (source: Google Earth Digital Globe 2013)

existence of an anastomosing stream are fulfilled. The derivatives from the HEC-RAS model suggested erosion in this segment, which is in contrary to the above-mentioned accumulation of boulders. Nevertheless, the 2010 GLOF represents an extreme discharge (Klimeš et al. 2014) compared to the "normal" erosional evolution of the valley, and transported sediments had to deposit in the first suitable locality, where the valley widened and the gradient lowered.

The next segment IV represents an alluvial plain of an old lake behind Younger Dryas moraine (Giraldéz et al. 2014) filled by fine-grained sediments (Fig. 5). Lateral erosion has been underway in recent times leading to the creation of meanders.

The following section V is distinguished by the lowest stream gradient (Table 2; Fig. 5) together with the alluvial fan just before the confluence with the Santa River and the segment IV. Only fine-grained sediments were left behind here after the 2010 GLOFs, which also filled and blocked the drinking water supply intake facility. This area (known locally as Pampa Shonquil) is in fact the local base level for the erosion which takes place in the uppermost part of the catchment. Both types of sediment (boulder and fine-grained) are trapped in the territory of segments 3–5. Only the water itself and the sediments carried in suspension continue to the central part of the Chucchún River valley where transported material is entrained by both deepward and lateral erosion.

Fig. 5 The Pampa Shonquil is the location of a former glacial lake now filled by sediments. Fine-grained sediments from the 2010 GLOF were laid down here (segment V) while larger boulders reached "only" the mouth of the glacial valley (segment III)

In the section VI, the erosion becomes a dominant factor from the viewpoint of the valley evolution. Locally, undercut slopes evolved as well as small landslides which contribute to the flood sediment load. This part turns slowly to section VII, where block accumulation prevails (some of them 1.5 m in diameter).

A wide, erosion valley part (section VIII) evolved in the Neogene pyroclastics (Yungay formation). Deepward erosion dominates, although lateral erosion is also documented (the lateral erosion is mostly evolved in places with little bit lower gradient). A local decrease in the river gradient is usually marked by block accumulation which was left here when the stream power declined. Lateral erosion prevails over downward cutting in this part of the Chucchún valley (section IX). The valley is also more open.

The common feature of the following two sections is their accumulation and significant boulder accumulation was distinguished (section X). From the point of view of geomorphology, this area belongs to the upper part of the alluvial fan, where varying generations of sediments contribute to the creation of a large accumulation at the confluence with the Santa River. During the "normal" valley evolution (without extreme discharges), the HEC-RAS model suggests potential to erosion in both segments X and XI. In our opinion, based on the field investigation, the flow lowered the velocity in this area which deposited the sediment (similar to segment III).

The finest material has accumulated after the lowering of the gradient (section XI). From a paleogeomorphological point of view, several larger events have occurred in this area in the past, which can be determined from the size of the alluvial fan in Carhuaz (unfortunately we do not have any dating).

A short erosion valley (section XII), in agreement with the "potential" derived from the HEC-RAS model, has been created just before the right-side confluence of the Chucchún River with the Santa River.

Influence of geomorphological processes on society and man-made structures

During the 2010 event, both erosion and accumulation processes had an effect in some way on society—in fact all of the bridges were destroyed or partly influenced. The water treatment plant in Pampa Shonquil (Photo 2) was destroyed by the accumulation of fine-grained material (segment III). The most vulnerable area for inhabitants and infrastructure where the bank accumulation significantly changed the near surroundings in a belt of 20–30 m along the Chuchún River was identified in segment X. Most of the alluvial fans in the Cordillera Blanca are usually heavily settled because the flat areas offer good construction conditions. In this case, the city of Carhuaz is located on the alluvial fan as well. From a paleogeomorphological point of view, several larger events have occurred in this area in the geological past, which can be determined from the size of the alluvial fan in Carhuaz (unfortunately we do not have any dating). Lateral erosion strongly influenced a village in segment VII, where part of a field was completely washed away and one or two houses are located close to the river bank. In the case of a larger event, these two houses would be close to the erosional edge of the river.

GLOF susceptibility evaluation

Based on the 2011 field study and remotely sensed photographs, we identified two potential triggers for future sudden water release (outburst flood) from Lake No. 513. These are: (1) icefall/ice–bedrock avalanche/snow avalanche from the western slopes of Mt. Hualcán into the lake; (2) flood wave/debris flow from the remediated moraine-dammed Lake Cochca situated upstream on the left bank.

Ongoing deglaciation of Mt. Hualcán is probably connected with direct dynamic slope movements such as icefalls and avalanches. Paths of recent ice avalanches from the overhanging parts of the glacier are clearly visible in the lower parts of the glacier (Fig. 6a). From the point of view of their size, there are three significant overhanging blocks of glacier on the western slopes of the Hualcán massif, which seem to be susceptible to fall within a short

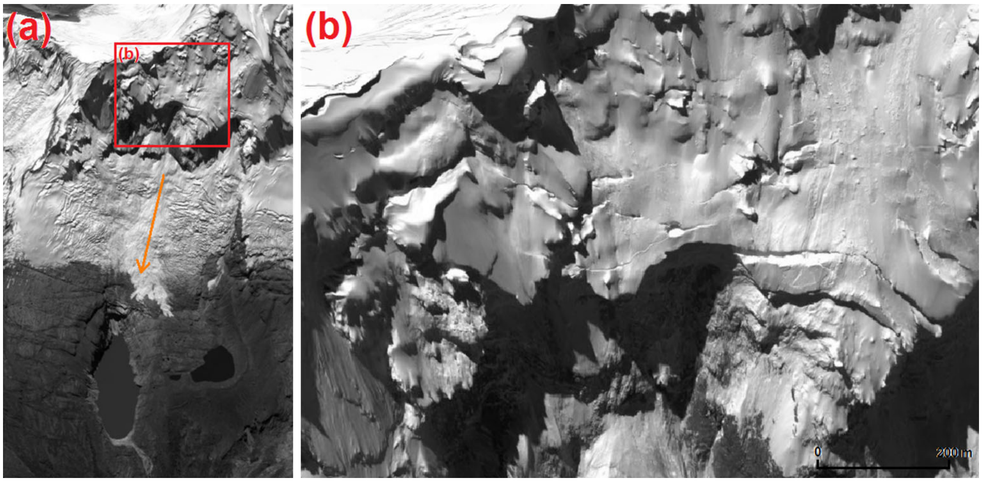

Fig. 6 Satellite imagine of the surroundings of Lake No. 513 (source: Google Earth Digital Globe 2013). **a** shows a view of Mt. Hualcán and lakes No. 513 and Cochca from the SW in May 2011. The *orange arrow* highlights the ice avalanche paths (*lighter colour*). **b** Detailed view of the western slopes of the Hualcán massif at an altitude of between 5,250 and 5,750 m a.s.l. Three blocks of the overhanging part of the glacier are clearly visible in centre of this picture

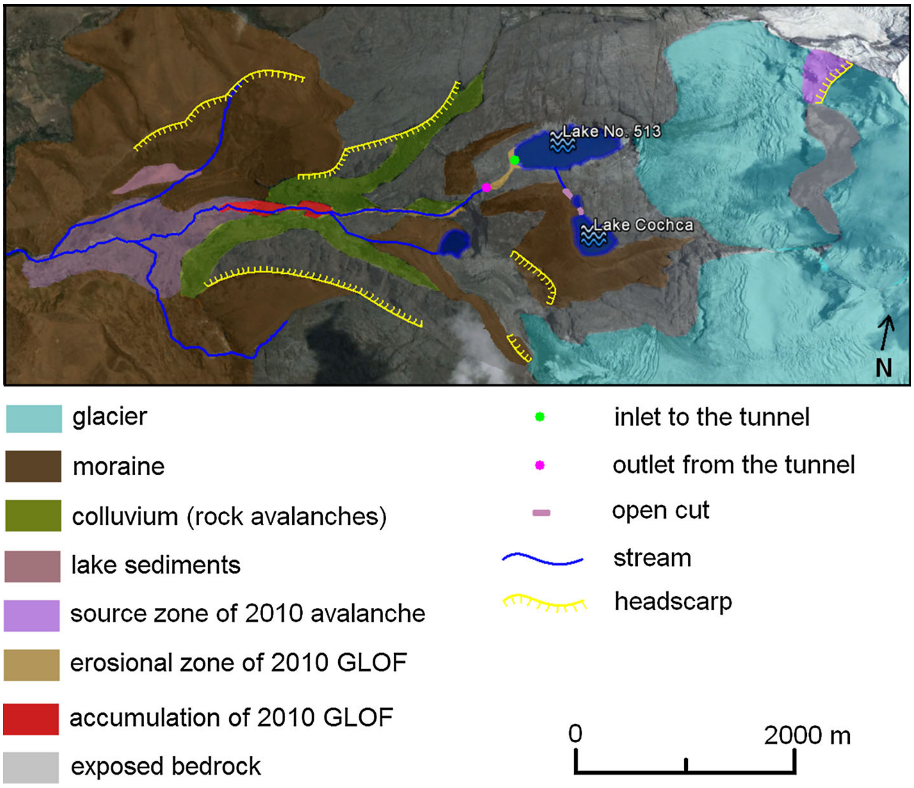

Fig. 7 Geomorphological map of the upper part of Chucchún Valley (*background image* Google Earth Digital Globe 2014 CNES/Astrium image, 8/20/2013)

period of time (Figs. 6b, 7). These blocks are between 200 and 300 m wide and 70–130 m high, and are situated at an altitude of about 5,500 m a.s.l. The thickness of blocks is not exactly known from the remotely sensed photographs, but we estimate the thickness to be in the order of tens of metres; thus, the volume of each block is estimated to be about 200,000– 800,000 m^3 (the volume of avalanche which entered the lake and caused the 2010 event was estimated to be 500,000 m^3). Therefore, we suppose that there is a potential for another GLOF event in the near future following a significant icefall into the lake. This conclusion corresponds with the result of a calculation according to the modified method presented by Wang et al. (2011):

$$P = 0.09 \times 1 + 0.34 \times 0.75 + 0.27 \times 1 + 0.30 \times 1 = 0.92$$

The calculated value of 0.92 represents high topographical susceptibility for an icefall into the lake.

Discussion

Remedial works related to glacial lake safety are in progress much more in the Cordillera Blanca than e.g. in Nepal (see also Kattelmann 2003), because they began in the 1950s (Carey 2010). Lake No. 513 was considered to be safe after 1994 when the safety project was completed (Carey et al. 2011). Nevertheless, the GLOF from April 2010 showed that the hazard has not been reduced to zero. This, along with the ongoing deglaciation over past few decades, suggests that a revision of hazard levels of glacial lakes in the Cordillera Blanca should be performed—especially in areas with intensive settlement development.

The detachment zone of the 2010 ice and rock fall from Mt. Hualcán, which was identified at an elevation of between 5,450 and 5,600 m a.s.l., is slightly above the zone (4,600–5,000 m a.s.l.) where new glacial lakes were recognized within the Cordillera Blanca (Emmer et al. 2014). This zone is very sensitive to any changes in temperature and precipitation distribution.

The erosion in the last segment (XII) could be explained in several ways which are out of the scope of the present paper. It could be explained by neotectonic uplift of the Cordillera Blanca and the effect of backward erosion or recent lowering of the base level of erosion within the Santa River and following influence on Santa River tributaries. To identify one of the reasons, a study of a much larger area has to be carried on.

The moraine-dammed Lake Cochca, situated upstream from Lake No. 513 on the left bank, represents another potential trigger for an outburst flood from Lake No. 513. The dam of this lake was remediated in 1953 by an open cut and the lake volume was lowered to $\sim 10^6$ m^3 (Reynolds 2003). Concrete lake outlet is considered to be resistible against erosion. The most frequent cause of GLOFs from moraine-dammed lakes within the Cordillera Blanca is dynamic slope movement into the lake with an 80 % share, of which 45 % represent icefalls or avalanches and 35 % rockfalls or landslides into the lake (Emmer and Cochachin 2013). Lake Cochca (Fig. 6) is about 400 m away from the current glacier extent (Fig. 5a); the mean gradient of the slope between the lake and the glacier is relatively gentle (10°) and there is no apparent evidence of slope movements on the moraines surrounding the lake. Therefore, there is no immediate threat of a GLOF following fast slope movement into Lake Cochca. Nevertheless, we also calculated the value of topographical susceptibility for Lake Cochca (the same as for Lake No. 513 before; see also Table 3):

$$P = 0.09 \times 1 + 0.34 \times 0.50 + 0.27 \times 0.25 + 0.30 \times 1 = 0.63$$

On the other hand, the dam freeboard is 0 m (surface outflow), thus any flood wave caused by fast slope movement into the lake would instantly overflow into Lake No. 513. Yet, it is not wholly clear whether a sudden release of (part) of the accumulated water from Lake Cochca into Lake No. 513 would be absorbed, or if it would consequently cause a GLOF event also from Lake No. 513. We assume that a dam overflow following an icefall from overhanging parts of the glacier on the western slopes of the Hualcán massif into Lake No. 513 is a more probable trigger for a future GLOF from this lake than a flood wave from Lake Cochca.

Conclusion

Various segments of the Chucchún Valley were distinguished according to prevailing erosion or accumulation processes. Two relatively independent parts of the Chucchún Valley were identified (segments I to V and VI to XII). In the upper part, all three main geomorphological processes of erosion, transport and sedimentation took place. Even the fine-grained sediments were laid down in the fifth segment but water continues to flow down the valley where new sediments were trapped in the stream due

Table 3 Modified method for evaluating topographical susceptibility for an icefall into Lake Cochca

Interval	I	II	III	IV	Original weight	Recounted weight (*w*)
Danger value (*V*)	0.25	0.5	0.75	1		
Mother glacier area (km^2)	<0.5	0.5–1	1–2.5	**>2.5**	0.07	0.09
Distance between lake and glacier (m)	>600	**300–600**	80–300	<80	0.27	0.34
Slope between lake and glacier (°)	**<12**	12–17	17–21	>21	0.22	0.27
Mother glacier snout steepness (°)	<14	14–19	19–26	**>26**	0.245	0.30
Mean slope of moraine dam (°)	<10	10–14	14–22	>22	0.195	Omitted

to intensive erosion and mobilisation of older valley sediments.

Geomorphological processes in the central part of the valley (segments VI to IX) are controlled both by the stream gradient and lithological conditions. The lowering of the gradient in the longitudinal profile is interrupted by segments of temporal gradient increase.

The comparison of "potential to erosion or accumulation" derived from the HEC-RAS model with the real situation after the single GLOF event showed conformity in erosion in the uppermost and lowermost parts in general (in detail: segments II, XII and partly VIII). The discrepancy we indentified in segments III, V, X and XI where an extreme discharge during the 2010 GLOF laid down sediments after the gradient of the flow diminished, while the HEC-RAS model showed potential to erosion. In some segments (VI, VII and IX), it was hard to set-up the conformity or discrepancy because these segments are rather long and the landscape rather variable (small local accumulations and changing deepward and lateral erosion types). Nevertheless, we mostly found conformity and if not it was possible to explain it.

Due to the general neotectonic uplift of the Cordillera Blanca, rivers are carved down the alluvial fans and the finest accumulation usually only influences the close surroundings of the river. But in the upper part of the fan, meandering of the stream is common and during huge debris flow, a new alluvial channel could be created and the endangered zone might shift inside the alluvial fan.

From the point of view of the society, the upper part of the valley (segments I to V) is free of man-made objects (above the inhabited zone); nevertheless, the water treatment plant is located there (!). There are two villages partly endangered by erosion/accumulation processes in the central part of the Chucchún Valley (valley segments No. VII and X). Finally, the city of Carhuaz is situated on the alluvial fan, where most of the fine-grained material is settled.

According to the modified method presented originally by Wang et al. (2011), high topographical susceptibility for an icefall into the lake was calculated (0.92) for Lake No. 513. There is another glacial lake situated above Lake No. 513—moraine-dammed Lake Cochca (calculated topographical susceptibility 0.63). Although no immediate slope movement hazard has been identified in the surroundings of Lake Cochca, it is necessary to stress that this lake does not have any dam freeboard and after any slope movement into Lake Cochca all of the water will flow out into Lake No. 513.

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