GEOMORPHOLOGY AND NATURAL HAZARDS OF THE SELECTED GLACIAL VALLEYS, CORDILLERA BLANCA, PERU

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ABSTRACT

Field reconnaissance geomorphologic mapping and interpretation of satellite data was used to prepare geomorphological maps of the selected glacial valleys in the Cordillera Blanca Mts., Peru. The valleys are located about 5 km apart, but show important differences in geology and landforms presence and distribution. Above all, the presence of small glacial lakes near the ridge tops is typical for the Rajucolta Valley, whereas no such lakes occur in the Pumahuaganga Valley. Detailed field assessment of possible hazardous geomorphological processes on the slopes around the Rajucolta and Uruashraju Lakes was performed. Shallow landslides and debris flows often channeled by gullies are the main dangerous processes possibly affecting the glacial lakes. In the case of the Rajucolta Lake, evidences of shallow landslides were also found. Mapping showed that newly formed small glacial lakes and moraine accumulations located on the upper part of the valley slopes may be source of dangerous debris flows and outbursts floods in the future. In some cases, those processes may affect glacial lakes on the main valley floor, which often store considerable amount of water. Thus the possibility of triggering large glacial lake outburst flood should be carefully evaluated.

Key words: geomorphologic map, natural hazards, glacial lakes, Peru, Cordillera Blanca

1. Introduction

The study area is located in the department of Ancash within the Cordillera Blanca Mts. (Huascarán, 6768 m a.s.l.) elongated in the NW–SE direction. This mountain range runs for 170 km limited by the Santa River on its west side and Maraňón River on its east side (Figure 1). This mountain range is part of the Cordillera Occidental forming continental divide among Pacific (Santa River) and Atlantic Oceans (Maraňón River). Glaciers of the Cordillera Blanca Mts. represent world's largest glaciated region in the tropics. The Santa River valley has been subject to many natural hazards in the past (Zapata 2002) as well as during recent years (Vilímek et al. 2011). Many of them originated in the high parts of the mountains and caused damages and fatalities in the densely inhabited valley floors. Glacial lake outbursts floods (GLOFs, Vilímek et al. 2005; Carey et al., in print) and earthquake triggered slope movements (Klimeš et al. 2009) are the most dangerous types of natural hazards occurring in the Cordillera Blanca during last decades. The most devastating GLOF is the flood from the Palcacoccha Lake in 1941, which devastating large part of the province capital city of Huraz. The rock avalanche from the Huascarán Mt. from 1970 claimed between 5,000 (Evans et al. 2009) and 23,000 lives (Plafker et al. 1971) devastating towns of Yungay and Ranrahirca. Intensive research following those events showed that morphological properties of the moraine dams and old morphological features preserved in the relief provide basic and valuable information for landslide and GLOF susceptibility assessment.

Geomorphological map of two glacial valleys along with detailed expert assessment of hazards identified in the valley heads around glacial lakes is presented. Rajucolta Valley with large glacial lake is important for the safety of the regional capital city of Huaraz since it stores considerable amount of water (17,546,151 m^3 in 2004, personal communication N. Santillán, National Water Authority, Lima). The Pumahuaganga Valley located in the SE part of the mountain range has significantly different geological and geomorphological properties than the valleys in the north and central part of the Cordillera Blanca.

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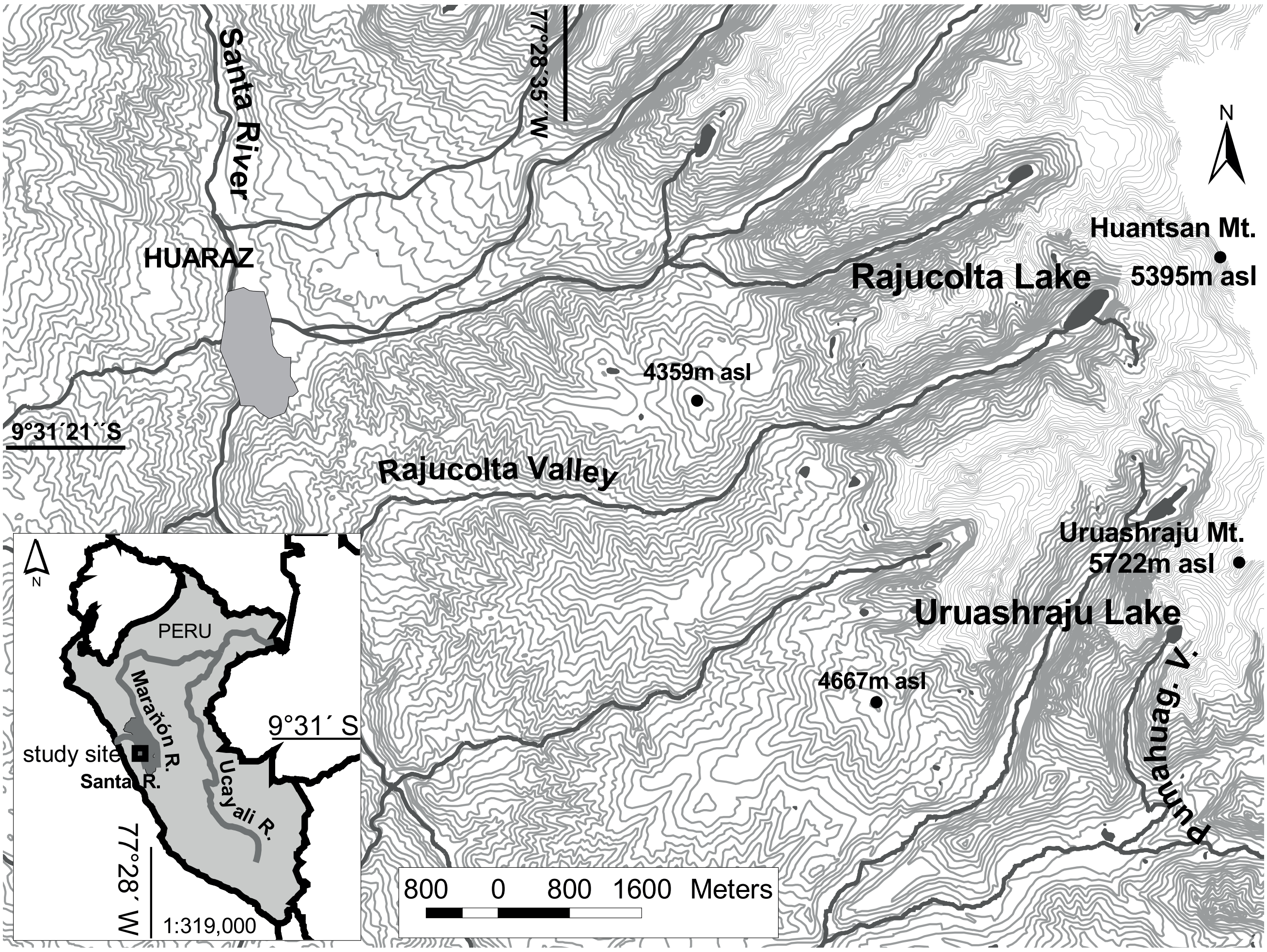

Fig. 1 Orientation map of the study area

1.1 Geology

Major part of the Cordillera Blanca Mt. constitutes of the batholith with total length of 200 km and width between 12 and 15 km. It is predominantly made of coarse grained granodiorite and tonality rocks (Figure 2) which are strongly foliated. In certain locations of the batholith, intrusive rocks gradually change to amphibolites. Dikes and sills of quartz-porphyry occur frequently in many locations of the batholith which is in contrast to the scare occurrence of the basic rocks dikes. The age of the batholith is estimated shortly after Paleogene volcanism or in the Mio-Pliocene Era with K/Ar age calculated 16 to 2.7 ± 0.4 M.A. (Wilson et al. 1995).

The highest summits of the SE section of the Cordillera Blanca Mt. are overlaid by sedimentary (sandstones and shale) and extrusive volcanic rocks (dacitic, andesitic and basaltic lavas, tuffs and breccias). They represent erosive remnants of sedimentary rocks (Mesozoic to Tertiary age), which primarily overlaid the Cordillera Blanca batholith (Morales 1967) and form area around it.

Main structural features of the batholith are controlled by pronounced foliation and system of vertical fractures. Two main directions of fractures are NW–SE and NE–SW. The third fracture system is sub horizontal. Evidences of tectonic movements can be found on many faults and show apparent striations. The main regional fault is the Cordillera Blanca normal fault running for some 210 km along west margin of the batholith. Estimations of its slip rate vary depending on exact location from 0.86 mm up to 3 mm/year (Wise and Noble 2003). Some authors also describe left lateral component of its movement (Wise and Noble 2003), which has been also detected by direct movement measurements (Košťák et al. 2002).

Variety of metallic and non-metallic raw deposits is located within the Cordillera Blanca Mt. They have been known and used since colonial times (Wilson et al. 1995). Polymetallic-wolfram-molybdenum zone of the Cordillera Blanca is found on the contact between igneous rocks of the batholith and overlying older formations along the NW slopes.

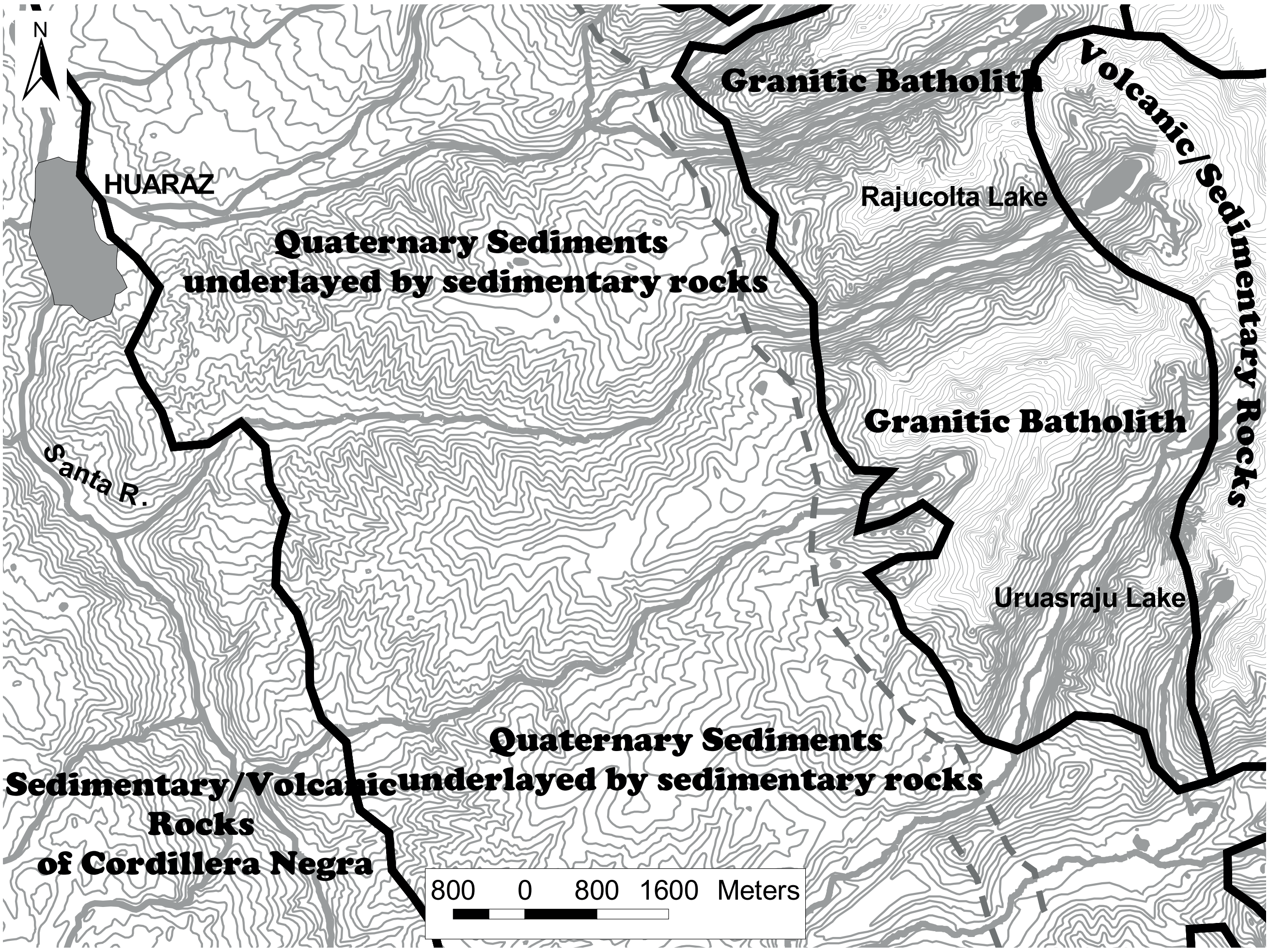

Fig. 2 Geology of the study area. Limits of the geological units are in black solid line, gray dashed line shows Cordillera Blanca normal fault

1.2 Geomorphology

Cordillera Blanca has the average altitude of over 4000 m with several peaks exceeding 6000 m (e. g. Huascaran 6768 m a.s.l., Huandoy 6395 m a.s.l.). Highest parts of the mountains are covered by mountain glaciers which reached extend of 721 km^2 in 1970, but retreated to 600 ± 61 km^2 in 1996 (Silverio and Jaquet 2005). There were 402 glacier lakes known in 1970 (Ames ed. 1989), but it is expected that its number increased due to glacier retreat, which is often accompanied with lake formations. Along the west limit of the mountains, lay undulating, deeply dissected foothills formed in glacial or fluvioglacial sediments underlay by Mesozoic and Tertiary rocks. The foothills are situated in the altitude between 3050 m and 3850 m forming belt 3 to 12 km wide. The glacial sediments consist of gravel and sand layers which may contain also isolated blocks of rocks up to several tens of meters of size. Massive lateral and terminal moraines extends from the glacial valleys to this area.

The Santa River Valley is located between the foothills of the Cordillera Blanca on east and the Cordillera Negra Mt. range on the west. Upper part of this graben valley (Wise and Noble 2003) is wide and opened with gradient between 0.9% and 1.6%. Whereas, its lower course is rather narrow with gradient not smaller than 3.5%. In the place where the river changes abruptly its direction from NW to WSW, very narrow canon formed leading its waters to the Pacific shore.

The Cordillera Negra Mts. lays west of the Santa River. Its highest altitudes are about 5000 m a.s.l. and it is intersected with many deep and narrow valleys formed in sedimentary and volcanic rocks. Recently the mountain range is not glaciated, but there were identified 16 glacial lakes which formed during the Pleistocene glaciations (Concha 1974). Rich deposits of polymetallic ore are being exploited in this region.

1.3 Glacial lakes

Majority of the lakes in the Cordillera Blanca Mt. are of glacial origin. They formed either in deepened bowel like basins in the base rock carved by glaciers or behind moraines (terminal, recessional or lateral moraines). Moraines are formed by unsorted or poorly sorted sediments showing certain degree of compaction. The moraines have often asymmetric triangular cross sections with steeper inner slopes. Dip of the outer slopes ranges between 30° and 40° and total high sometimes exceeds 70 m. According to Concha (1974), there are 52% of glacial lakes dammed by moraines. The rest of the glacial lakes is dammed by base rock or combination of the base rock and moraines. Only small part of the lakes in the Cordillera Blanca (6.5%, Concha 1974) formed behind dams consisting of rockslides, rock avalanches and debris flows deposits.

Level of hazard of a lake to produce dangerous GLOF can be assessed based on the type of dam and its slope, distance of the lake from the glacier and probability of major ice or rock fall into the lake (Concha 1974). Complete overview of the characteristics important for the lake dam stability gives Emmer (2011). The most dangerous are considered those lakes with direct contact to the glaciers and dammed by moraines with steep slopes. On the other hand, the safest glacial lakes are those with base rock dams since their rapid erosion or breakage due to sudden increase of water level is almost impossible. Evolution of the glacial lakes and their safety conditions are very dynamic, thus repeating evaluation of the level of hazard for given lakes should be performed, to maintain reasonable safety level of the local inhabitants.

2. Methods

Field mapping and interpretation of the remotely sensed data (satellite images – SPOT, LANDSAT 1999 and WorldView 2010) were used to map basic geomorphological features of the studied areas. The mapping focused only on the valley parts within the Cordillera Blanca Mts., their foothill sections were omitted since the mapping focuses primarily on glacial valley forms. Detailed description and assessment of the terminal parts of the valleys around the glacial lakes was performed during field mapping in 2003 and 2011.

Genetic type of the material and morphology were used to define geomorphological classes. Among the landforms directly associated with glaciations are recessional and terminal moraines. In many cases these moraines have triangular cross-profile, forming asymmetric ridges. Presence of this morphology was one of the major attribute necessary to map moraines on satellite images. Glaciofluvial and glaciolacustrine deposits were identified during the field work. Among the other landforms covering valley bottom and lower parts of the slopes are talus deposits and dejection cones. Sediments on slopes, which were not attributed to any of the above mentioned class, were identified as colluvial deposits. It is possible that in some parts these are formed by moraine material, but this could not be determined based on field mapping constrained to the valley floor and information extracted from the satellite images.

3.Results

3.1 Geomorphology of the Rajucolta and Pumahuaganga Valleys

The Rajucolta Valley starts with glacial cirque bellow Huantsan Mt. (6395 m a.s.l.) and runs south-west entering the foothills of the Cordillera Blanca at the altitude of 4000 m a.s.l. (colour appendix Figure I). It has form of narrow (320–500 m), U-shaped valley modeled by repeating mountain glaciations (Rodbell and Seltzer 2000). Five hanging valleys are connected to the main valley which floor is 150 m to 300 m lower. The Rajucolta glacier is still connected with the lake, which formed behind its terminal moraine at elevation of 4272 m a.s.l. The lake is 1.5 km long, 0.5 km wide with volume of 17,546,151 m^3 as measured in 2004 (personal communication N. Santillán, National Water Authority, Lima). In total the mapped valley part is 8.8 km long and majority of its floor is covered by glaciofluvial material. In several regions it gradually transforms into lacustrine deposits showing areas of older lake basins. In two cases, they are found upstream from remnants of recessional moraines, which are probably responsible for damming the old lake basins and reached up to 2.2 km from the moraine dam. Surface of the deposits is flat or gently rolling with often well developed deep gullies carved by the streams in soft lacustrine deposits. Foots of the valley slopes on both sites are covered by almost continuous band of talus deposits with slope dip between 30°–45°. The talus is deposited bellow rock slopes and rock faces outcropping in the lower and steepest part of the valley sides where the slope exceeds 50°. In several places, dejection cones formed instead of the talus deposits. They resulted probably from repeating debris flows which transported colluvial and moraine material from the upper and also less steep parts of the ridges and hanging valleys located in general above 4750 m a.s.l. In this region, the slopes vary between 20°–35° and are mainly covered by moraine accumulations with typical, triangular morphology. Many glacial lakes are being formed behind those moraines often formed bellow horns of the mountain peaks. Length of the lakes does not exceed 350 m, but typically is around 60 m. According to the 1999 LANDSAT image, there were 11 such lakes. The rest of the slopes are either covered by colluvial deposits which could not be further specified or is formed by the outcropping base rocks.

The Pumahuaganga Valley begins with the Uruashraju glacier named after 5722 m a.s.l. high mountain on which southwest slopes it evolved. The lake is situated at 4600 m a.s.l. and is 210 m long and 108 m wide. It is dammed by bedrock dam with some moraine sediments on top of it. Total length of the mapped valley is 4.2 km. It vents into the over deepened valley which floor is about 200 m bellow the Pumahuaganga hanging valley floor. Distribution of the main geomorphological units varies significantly from the Rajucolta Valley (colour appendix Figure III). Sediments are dominated with almost 2 km long side moraine which is well developed mainly on the southeast side of the valley below the glacier. The opposite site of the valley is covered by slightly stratified colluvial sediments without moraine form. These consolidated sediments form very steep, erosional slope where stones are rolling down almost at all times. Denudated remnants of moraine accumulations were identified at the east side of the valley mouth. Moraine accumulations are almost entirely missing on the higher elevations bellow the horns of the mountain peaks. There are also no glacial lakes on the mountain ridges. Large part of the valley floor is filled with lacustrine deposits of old lake now forming marsh. Talus deposits rim only part of the valley slopes. Dejection cones are entirely missing in the valley, suggesting that there was not enough material on the upper parts of the slopes to be transported down the valley floor in form of debris flows.

3.2 Natural hazards of the Rajucolta and Pumahuaganga glacial valleys

The rock slopes of the glacial valleys underwent repeating compression and unloading during the advances and retreats of the mountain glaciers. It is reflected by many opened cracks visible on the rock cliffs and several rockfall/rock slides which occurrence could be related to stress relaxation after the glacial retreat. These rather large rockfalls/rock slides are in both valleys located near their lower end (letters A on Figures I and III – colour appendix). The accumulations are formed by large angular rock blocks often exceeding 2 m in size and in some cases reaching up to 4.5 m. Dense forest of the Polylepis sp. trees covers all of the identified accumulations (compare to Cáceres 2007). Other identified landslides (rock slides) within the Rajucolta Valley originated from the highest parts of the ridges and have narrow elongated shape. In the Pumahuaganga Valley, debris flows are concentrated to the northwest slope near the lake, where the moraine sediments are exposed in very steep slope.

Other possible source of natural hazardous events represents gullies connecting side hanging valleys or upper parts of the valley slopes with the main glacial valleys. Recently, these channels are mainly eroding the talus or dejection cone sediments. Nevertheless, it is clear that they were responsible for deposition of some of the dejection cones in the past. Thus potentially dangerous debris flows accumulating moraine material from the upper parts of the ridges on the valley floor may occur in the future.

3.3 Natural hazards around Rajucolta and Uruashraju glacial lakes

The moraine dam of the Rajucolta Lake is covered by dense vegetation (herbs and shrubs) preventing the water erosion of its surface. Its outflow was dammed by 13.6 m high earth filled dam in 2003. At the same time, water conduct was constructed to lower the lake level by some 7 m. It resulted in lowering total water volume (by 5,000,000 m^3 personal communication N. Santillán, National Water Authority, Lima) and added additional protection from outburst floods. The potential displacement wave now needs to overcome the constructed dam. Despite of this safety improvement, there were identified several potentially hazardous sites on the inner slopes of the lake dam.

On the N part of the Rajucolta Lake banks, several gullies with small dejection cones developed. The slope is covered by colluvial sediments, which are underlay by base rock in shallow depth. The sediments come from moraine deposits in the hanging valley above where a small lake is also located. This geomorphological setting may impose high danger if larger amount of moraine material would be mobilized either due to extreme precipitations or outburst of the glacial lake. Further west on the moraine slope, a prominent terrain step is forming head part of temporarily inactive landslide, which accumulation area is situated bellow the water level. Remobilization of this landslide may cause displacement wave and subsequent flood. Southeast and south parts of the slopes above lake are again characterized by small glacial lakes in the cirques of the hanging valley. They are connected with the lake by small stream. The lakes are possible sources of GLOF which may increase its volume by mobilizing water of the Rajucolta Lake. Southwest of this stream, the slopes are very steep and long, covered by loosened colluvial deposits without vegetation. So far only small gullies and soil slips were identified on this section of the banks. Nevertheless, high inclination (35°–44°) and the length of the slope make this area susceptible to landslide or debris flows formation, which may have potential of triggering significant displacement wave and GLOF from the Rajucolta Lake.

The southwest slopes of the Uruashraju Lake possess high hazard due to very steep inclination, which is far from angle of repose of the forming material. Source areas of several debris flows were mapped there (colour appendix Figure II). The falls (rolling) of boulders were witnesses many times during several days of the field work. Nevertheless, the field evidences suggest that usually only relatively small amount of material is involved in each event. More intense precipitations or seismic shaking may mobilize much larger amount of material. Northeast and north slopes are formed by moraine sediments, which keep steep inclinations in their upper part, whereas the lower portion of the slope is rather shallow with strong limonite cementation of the sediments (personal communication Jan Novotný, Arcadis Geotechnika, a.s., Prague). There have been identified no lakes on the slopes above the Uruashraju Lake. This fact decreases probability of GLOF being triggered from the lake. Also its small dimensions make it much less dangerous than the Rajucolta Lake.

4. Discussion

The mapped glacial lakes show common geomorphological features, but differ significantly in the presence of moraine sediments on the upper part of the valley slopes, which are missing in the Pumahuaganga Valley. Such moraine sediments are abundant in the Rajucolta Valley where also considerable number of so far small glacial lakes is being formed. Similar moraine sediment distribution was identified in the Cojup Valley (Vilímek at al. 2005). Debris flow originated from moraine located bellow the Huandoy Mt. transported considerable volume of material to dejection cone in the Llanganuco Valley (Zapata 1995; Vilímek et al. 2000). The moraine sediments were mobilized due to intense precipitation and also probably due to melting of buried ice blocks located bellow the moraine surface. Similar events may occur also in the Rajucolta Valley imposing certain degree of hazard to the mapped dejection cones. Also any gullies connecting the upper valley slopes with the valley floor should be considered as potential conducts of dangerous debris flows. Even in the cases when erosion processes prevail during recent times.

The outflow of the Rajucolta Lake is reinforced by regulation dam with the purpose of improving the Santa River flow during the dry seasons to supply sufficient water for electricity generation in the Cannon del Pato power plant. The dam added additional space to retain possible displacement waves caused by potential ice or rockfalls to the lake. At the same time, if significant and quick changes of the water level due to the dam operation may occur, stability of the inner slopes could be lower possibly resulting into the landslide generation. Such event could also cause GLOF with unknown magnitude. Flood caused by landslide occurred in the Palcacocha Lake causing only minor damages down the Cojup River stream (Vilímek et al. 2005).

Recent GLOF events show (Bouška et al. 2011), that glacial lake characteristics previously thought to define safe lakes (Concha 1974) should be carefully revised. For example, considerable distance of glacier tongue from the lake and base rock dam type seems not to be sufficient to consider the lake safe with respect to the GLOF origin. As proved by the 2010 Lake 513 GLOF. Its glacier terminates 190 m above the lake, which is dammed by base rock and its water level was lowered by drainage tunnels. Despite of that, ice and rock fall to the lake caused GLOF damaging several houses and causing unrest within the local population. It seems to be necessary to carefully reconsider levels of GLOF hazard for all lakes within the inhabited watersheds. Hazard and risk assessment for the potentially flooded areas would be of great importance. Its results may be beneficial for development planning and civil defense. Implementation of the hazard assessment requires strong and long term interest of the local politicians with respect to the natural hazards. Unfortunately, local experiences show that the local authorities are not motivated to do so (Klimeš and Vilímek 2011).

5. Conclusions

Geomorphological mapping with the aid of satellite images enabled to characterize basic land forms and associated forming processes along their degree of hazard in selected glacial valleys. Field investigation was necessary to obtained detailed information about slope stability conditions important for reliable hazard assessment of respective glacial lakes. Areas which need further field investigation to ascertain possible degree of hazard were identified around the small glacial lakes located high above the Rajucolta Lake and also along the sides of its valley above altitude of 4750 m a.s.l. These small lakes and moraine accumulations located mainly in the hanging valleys may be source of dangerous debris flows or GLOFs in the future. Also their affect on much larger glacial lakes in the main valleys needs to be carefully evaluated and consider during the future research of the natural hazards. Recently documented GLOFs considerably hampered validity of the used glacial lake safety criteria formulated some 40 years ago. Thus new approaches evaluated the glacial lake hazards are necessary.

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RÉSUMÉ

Geomorfologie a přírodní nebezpečí vybraných ledovcových údolí v pohoří Cordillera Blanca, Peru

Pohoří Cordillera Blanca leží ve středním Peru a tvoří kontinentální rozvodí mezi Atlantským a Tichým oceánem. Nejvyšší hora Huascarán (6768 m n. m.) je zároveň nejvyšší horou Peru. Pohoří je budováno převážně granodiority a tonality třetihorního stáří, které jsou v nejvyšších partiích překryty erozními zbytky druhohorních sedimentárních a vulkanických hornin. Ze západní strany je pohoří omezeno výrazným zlomem, který je odděluje od údolí řeky Santy. To je vyplněno čtvrtohorními glaciálními a fluvioglaciálními sedimenty překrývajícími druhohorní sedimentární horniny.

Geomorfologické mapování bylo provedeno na základě interpretace satelitních snímků a ověřeno v terénu. Tomu byla také přizpůsobena legenda přehledné geomorfologické mapy. Byla zpracována dvě ledovcová údolí v jihovýchodní části pohoří, jejichž zdrojové oblasti jsou vzdáleny pouhých 5 km. Údolí Rajucolta je 8,8 km dlouhé a v jeho závěru je stejnojmenné jezero s rozměry 1,5 km a 0,5 km a s objemem 23 260 000 m^3. Jezero je hrazené ústupovou morénou. Druhé údolí – Pumahuaganga – je dlouhé 4,2 km a pod horou Uruashraju je (5722 m n. m.) je situováno jezero s rozměry pouhých 210 m a 108 m. Jeho hráz je z větší části tvořena podložní horninou.

Geomorfologické mapování ukázalo, že pro povodí Rajucolty jsou typické morény a malá morénová jezera v horní části svahů v nadmořské výšce nad 4750 m n. m. Jezera vznikají většinou ve visutých údolích se směrem S–J. V celém povodí bylo zjištěno 11 takovýchto morénových jezer. Jejich maximální rozměr nepřesahuje 350 m, ale většinou se pohybuje kolem 60 m. Na tato vysutá údolí navazují na dně hlavního údolí četné výplavové kužele. V povodí Pumahuaganga jsou morény v horních částech hřebenů výjimečné a jezera tam nebyla zjištěna žádná. Nejvýraznějším morfologickým tvarem v údolí je velmi rozsáhlá morénová akumulace v jeho závěru, která je situována výhradně na jeho jižním svahu. Na rozdíl od údolí Rajucolty zde nebyly identifikovány žádné dejekční kužely. V obou údolích byly zjištěny rozsáhlé skalní sesuvy situované v blízkosti jejich ústí. Na jihovýchodním svahu nad jezerem Uruashraju byla identifikována celá řada zdrojových oblastí drobných přívalových proudů. Ty vznikají na velmi prudkém erozním svahu v nevytříděných svahových sedimentech. Díky malému množství vody v jezeře tyto procesy nepředstavují výraznější nebezpečí. Jiná situace je u jezera Rajucolta, na jehož březích byly také zjištěny dočasně uklidněné, drobné přívalové proudy. Navíc je ve vysutých údolích nad jezerem situováno několik ledovcových jezer, u kterých není možné vyloučit vznik ledovcových povodní, které by ovlivnily jezero Rajucolta. Velký objem vody v tomto jezeře představuje potenciální nebezpečí pro níže položené osady včetně krajského města Huarazu.