LANDSLIDE AND GLACIAL LAKE OUTBURST FLOOD HAZARD IN THE CHUCCHÚN RIVER BASIN, CORDILLERA BLANCA, PERU

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ABSTRACT

The Chucchún River basin was hit by glacial lake outburst flood (GLOF) triggered by ice/rock avalanche which caused spill over from the Lake 513 (April 11, 2010). The whole region is also highly susceptible for landslide occurrences, therefore the GLOF and landslide multi-hazard map were prepared for the watershed. Definition of the GLOF hazard zones was done using 1D mathematical model HEC-RAS for modeling of flooded areas. Landslide hazard zonation was based on landslide inventory mapping and historical records of the landslide occurrences. Resulting multi-hazard map shows that 26% of the studied river basin is under some degree of hazard from landslides or GLOFs. It clearly shows the most endangered inhabited areas as well as places, where floods and landslides may adversely affect each other increasing intensity of the hazardous event.

Keywords: landslide hazard, GLOFs, flood hazard, Cordillera Blanca, Peru

1. Introduction

Landslides and glacial lake outburst floods (GLOFs) represent high danger especially in glaciated mountain regions recently experiencing adverse effects of climate change, to which Cordillera Blanca belongs (Rabatel et al. 2013). Both of these processes may be interrelated in complex process chain increasing possible damage to affected communities. Landslides may often initiate the process chain by falling/sliding into the glacial lake (Hubbart et al. 2005; Vilímek et al. 2005; Klimeš et al. 2014; Schneider et al. 2014; Emmer et al. 2014) and causing impact wave, which overtops the lake dam and transforms into GLOF or debris flow moving downstream and causing the main damage. Resulting GLOF may be also responsible for triggering landslides on the river banks, which in turn may at least partly block the river causing local and temporal water level increase, which along with subsequent breaches may be responsible for further damages.

Recent works suggest that climate warming causing permafrost degradation may be main factor governing occurrence of slope movements in permafrost regions above glacial lakes (Huggel 2009; Haeberli 2013). Nevertheless, there are some other works suggesting that deglaciation and permafrost degradation effects on slope stability is less straight forward with diverse slope responses depending on geological and hydrological properties (Holm et al. 2004) or may be over-ride by other landslide triggers, among which an extreme precipitation and earthquakes are the most common ones. The latter proved to be the main landslide trigger in the Cordillera Blanca as documented by landslide inventory done by Plafker et al. (1971) after May 1970 earthquake. During that event hundreds of landslides occurred including two catastrophic ice/rock avalanches (Evans et al. 2009) from the Huascárn Norte Mt. Along with the main ice- and rock avalanche which destroyed the city of Yungay (in the Santa River valley) a smaller event happened in the Llanganuco Valley destroying base camp of mountain climbers. Despite the frequent natural hazards and long lasting experience with their catastrophic effects also in the Cordillera Blanca (Carey et al. 2012), the Andean societies increase their exposure and vulnerability by rapid urban development and population growth (Hermanns et al. 2012). Historical catastrophic GLOFs, which claimed thousands of lives in the Santa River basin below Cordillera Blanca Mts. caused high sensitivity of the local as well as national population to these events (Carey et al. 2012). It was proved by strong media and political response to even small magnitude events during last decade. In April 2003 NASA's false warning about possible fall of ice avalanche into the Palcacocha Lake caused economical problems for the local capital of Huaraz with high economic looses from decreased tourism during Eastern Holidays (Vilímek et al. 2005). Minor flood on the Quilcay River running from the Palcacocha Lake through regional capital city of Huaraz occurred the following month (March 2003). It rise again large attention of the local population and urged rapid response of Peruvian scientists and authorities. Also the GLOF from April 2010 from the Lake 513, which damaged property in the city of Carhuaz – Acopampa (Carey et al. 2012; Klimeš et al. 2014), rise national wide attention and the affected river basin is now subject of international development project (Schneider et al. 2014).

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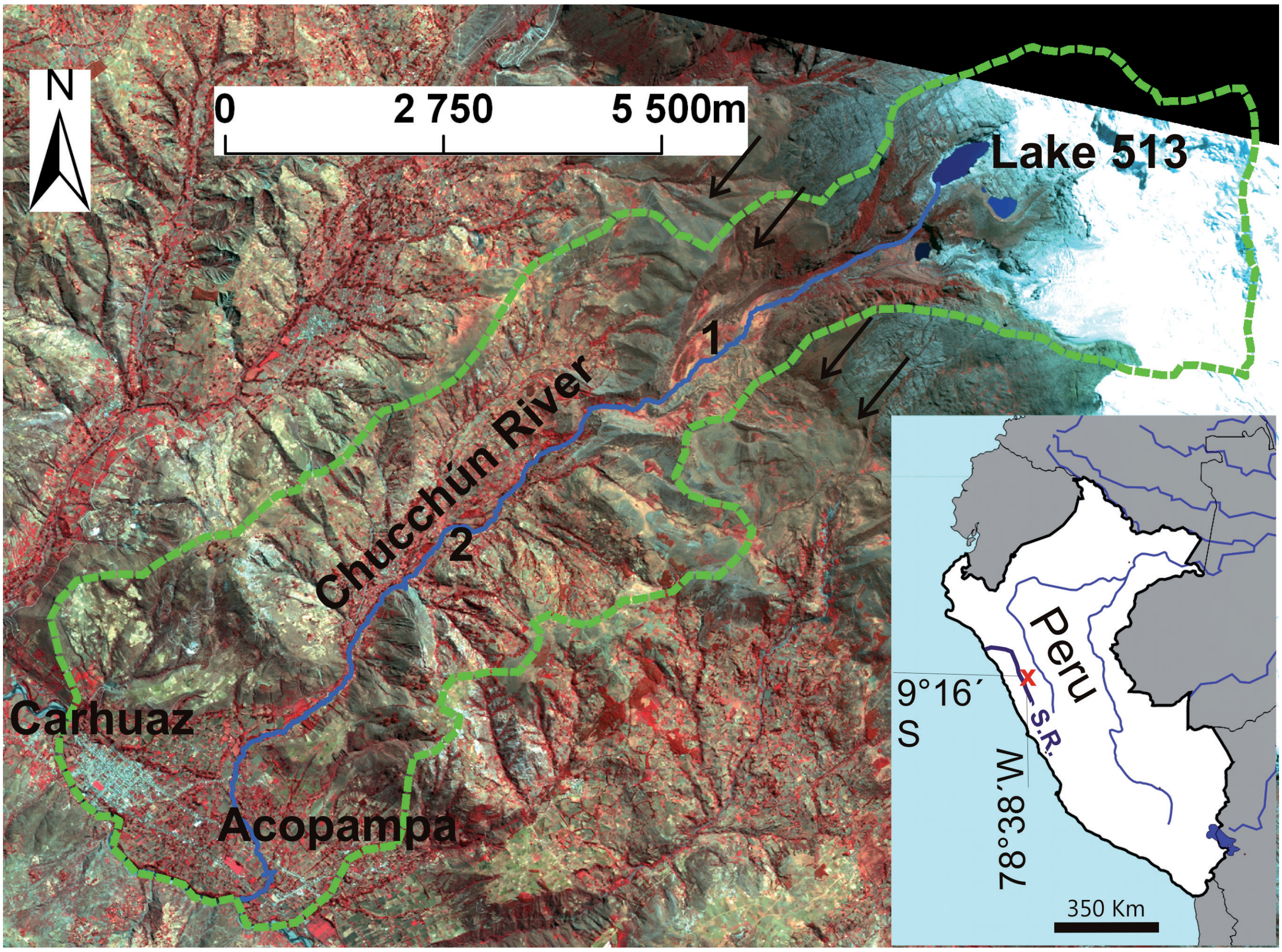

Fig. 1 Chucchún River basin is shown by dashed line, arrows point to the Cordillera Blanca normal fault scarp, 1 – Pampa Schonquil, 2 – Pariacaca Village, background image is 2010 SPOT View image.

The first GLOF model for the Chucchún basin (Figure 1) was done by Valderrama and Vilca (2010) before the 2010 GLOF event which unfortunately had no effects on flood hazard mitigation in the basin. It presents a scenario-based debris flow model in Flow2D. Their calculations showed that transitions between hyper-concentrated flood and debris flow will occur during the course of the GLOF. It was later confirmed by geomorphological research (Vilímek et al. 2014) and also reflected in debris flow simulations performed in RAMMS software as part of process chain modelling (Schneider et al. 2014). The RAMMS model was done using 8 m resolution digital elevation model (DEM) derived from 2012 WorldView satellite images (Schneider et al. 2014). It calculated peak discharge at the lake dam of 9,000 m^3 for the 2010 event. The debris flow models made using Flow2D were also prepared for other sites within the Peruvian Andes (Castillo et al. 2006; Valderrama et al. 2007).

Landslides have been causing serious damage in Peru for a long time (Kojan and Hutchinson 1978; Plafker et al. 1971; Vilímek et al. 2000), and recently, large attention has been broad to national wide landslide inventory and susceptibility assessment. The most general one covers south part of Peru (not including the study area) displaying landslide inventory and susceptibility maps at scale 1 : 750,000 (e.g. Fídel et al. 2006). The small map scale is determined by extend and remoteness of the mountainous terrain of the Peruvian territory. More detailed landslide and susceptibility mapping was performed for the Ancash Region covering the study area (Zavala et al. 2009). It contains series of 1 : 250,000 landslide susceptibility maps based on heuristic approach. Site specific landslide studies in the Ancash region focused mainly on sites affected by rock avalanche from the Huascarán Mt. (Evans et al. 2009; Klimeš et al. 2009) or catastrophic landslide at the Rampac Grande village, Cordillera Negra (Klimeš and Vilímek 2011). In most cases, the landslide susceptibility maps are very general with respect to used input thematic information (e.g. geological map, topographic data) to be applicable on local level. Due to the overview scale of the maps, they also can not contain all landslides which may be important for the local hazard assessment. Therefore we decided to perform the first detail landslide inventory mapping for the Chucchún basin producing susceptibility and hazard maps. This information is combined with results of flood models based on in field measured topographic profiles using 1D hydrological simulation in HEC-RAS software. Resulting flood characteristics (e.g. flooded areas and maximum flood depths) are combined with landslide hazard assessment identifying areas where floods and landslides may combine to possibly increase hazard during specified GLOF scenarios.

2. Study area

Head part of the Chucchún River basin is in the granitic rocks of the Cordillera Blanca batholit, which is limited by normal fault forming prominent scarp (indicated by arrows on Figure 1) of the graben type valley of the Santa River. It is filled with Mesozoic and Tertiary sedimentary and volcanic rocks which are partly covered by glaciofluvial sediments. Water level of the Lake 513 is fixed by tunnel carved in the bed rock at 4,431 m asl. The Chucchún stream starts here and runs for 14.4 km to its mouth with the Santa River at 2,650 m asl. Upper part of the stream runs across very steep slope formed mostly by bed rock below which it reaches wide area of paleo-lake in site called Pampa Schonquil (no. 1 on Figure 1). Middle reach of the valley is mostly narrow in some parts forming narrow canyons, whereas the lowest part flows across wide alluvial fan. Detailed description of the valley morphology is in Vilímek et al. (2014). The highest up-stream located village is Pariacaca (no. 2 on Fig. 1) whereas Carhuaz and Acopampa are located on the alluvial fan, where houses are often placed very close to the river. According to the 2007 national census data (INEI), there are 650 inhabitants living in Acopampa and 3,596 in Carhuaz districts located on the cone.

3. Methods

3.1 Landslide hazard assessment

Landslides were mapped using recent GoogleEarth images (2012 and 2013) and classified as debris flows and landslides which were further subdivided into shallow and deep-seated landslides. The later contains features with estimated shear plane depth exceeding 15 m. The landslide bodies were first identified and mapped and then, more generalized polygons were drawn reflecting their possible extend during potential future reactivations. The polygons were defined based on landslide morphology, estimated depth and expert knowledge of landslide run-out distances in the study area. In cases when several smaller landslides occurred on one slope or within local drainage basin, they were grouped and entire slope was mapped as single landslide prone area. This approach defines landslide prone areas based on previous occurrences but it is clear that the landslide susceptibility outside the mapped landslides and debris flows is not zero and needs to be assessed. Therefore we used the slope dip as simple criterion to distinguish more landslide prone regions on slopes where no evidences about previous landslide occurrence where found. This approach proved to be relevant for different types of landslides including shallow landslides and debris flows (Klimeš 2008). We analyzed the mapped landslides against the digital elevation model and assigned the slope interval of 15°–35° as more landslide prone than slopes below 15° or above 35°. Resulting map represents spatial prognostic landslide susceptibility map.

To evaluate landslide temporal occurrence probabilities we used long-term annual occurrence frequencies based on historical records for large part of the Santa River valley (Vilímek et al. 2012). The historical landslide occurrence data cover period 1971–2009 and thus do not reflect the effect of major earthquake in 1970. During the evaluated period (39 years) seven debris flows, three landslides and one major snow avalanche or rock-fall occurred on average every year. Thus we assigned the high occurrence probability to debris flows and medium probability to landslides and deep-seated landslides.

Then we combined the spatial and temporal information into the hazard classes. The "very high" class was assigned to the debris flows, "high" to landslides and "medium" hazard class to the deep-seated landslides which are unlikely to reactivate as a whole, but represent highly favorable conditions for development of secondary landslides (Klimeš and Blahůt 2012). "Low" landslide hazard class was assigned to slopes with dip 15°–35°. This class represents parts of the study area where no evidences of past sliding were found, but due to the favorable morphological conditions its future occurrence cannot be excluded. The rest of the study area (e.g. 0°–15° and > 35°) was assigned as "very low" landslide hazard class where only landslide accumulation may occur.

3.2 GLOF hazard assessment

We assume that the majority of floods which have occurred in the Chucchún basin have originated from the glacial lakes. Among different causes of GLOFs, ice or ice/rock avalanches triggering overtopping wave in the Lake 513 is the most probable one. The flood mapping was based on modeling in one-dimensional mathematical model HEC-RAS v. 4.1.0. The stream and floodplain geometry was characterized by topographic cross-sections measured in a field for particular intervals (reach lengths) selected based on character of valley morphology. Therefore the flow conditions, e.g. cross-section shape, surface roughness, and slope vary from one section to the next. A mix flow regime was used for the steady flow analysis with a supercritical flow regime modelled mostly in the steep upper part of the river and a subcritical regime modelled in its shallower lower part. For more details regarding the input data and calculations please refer to Klimeš et al. (2014), which also includes online supplement with the necessary input data for flood model calculation.

Magnitude frequency relationship of the ice/rock avalanches is unknown for the study site as well as the Cordillera Blanca Mts., therefore we defined the flood hazard classes based on documented historical event and geomorphological evidences. Only two hazard classes were defined. The "very high" hazard class was based on the results of the April 11, 2010 GLOF model (Klimeš et al. 2014). To reflect uncertainty in the flood model results and magnitude estimation of possible future GLOFs, we set the down-stream boundary condition in the model as water level 1 m above the maximum flood height calculated for the 2010 event. We assume that this flood scenario has the highest occurrence probability. Low hazard class was defined by mapping the lowest fluvial terraces of the Chucchún River which are not regularly flooded during recent times, but were formed by repeating floods of different magnitudes during the evolution of the valley. Therefore we cannot exclude that these regions could be flooded in a future as well. Such a flood would require significantly larger flow than the 2010 event and therefore we assume its relatively low occurrence probability.

The resulting multi-hazard map was prepared by overlaying the GLOF hazard map with "very high and low" classes over landslide hazard map containing "very high, high, medium, low and very low" classes. The glaciated part of the Chucchún watershed was excluded from the analysis and its hazard is not shown on the resulting map. It is because the landslide initiation conditions in this part of the study area are largely unknown and differ significantly from the non-glaciated terrain.

4. Results

4.1 Landslide hazard assessment

The landslide inventory map of the Chucchún basin contains 61 landslides with area of 5.4 km^2 (54% of the total landslide area), 39 debris flows covering 1.2 km^2 (13% of the total landslide area) and only 5 deep-seated landslides, which though cover in total 3.2 km^2 (33% of the total landslide area). In the case of the debris flows, potential transport areas from each source zone are also included on the map, despite there were no recent signs of debris flows travelling through majority of the gullies.

The landslide hazard map (Figure 2) shows that the majority of landslides and debris flows occur in the middle and lower part of the watershed, whereas the head of the valley is almost free of them. The only exceptions are deep-seated landslides which develop in the area near the Cordillera Blanca fault, suggesting that they may be predisposed by tectonic activity of the fault. Debris flows occur either on steep slopes (over 35°) or in the head parts of the right tributaries of the Chucchún River. Their activity in some of the tributary valleys is evidenced by freshly looking debris accumulations on the valley floors. Landslides are represented either by rather small features which developed on the river banks or occur within several large areas along the lower reach of the Chucchún River.

4.2 Flood modeling and hazard map

The GLOF scenario defining the "very high" hazard class resulted into the peak flow of 965 m^3 s^{-1}. The maximum flood depths increased significantly in many of the river reaches (Figure 3) compared with the 2010 event flood model. The most significant flood depth increase occurred in the middle, most narrow part of the valley (Figure 4), where the flooded area remained almost identical compare to the 2010 event. "Low" hazard class covers majority of the Carhuaz-Acopampa alluvial fan and flat part of the Pampa Schonquil. Two minor low hazard areas were also mapped on the middle reach of the river (A, B on Figure 3).

Combining the two described hazard maps into a single map gives the multi-hazard landslide/flood map (Figure 5).

5. Discussion and conclusions

Key issue when producing hazard maps is assessment of their reliability and possible uncertainties involved in their preparation which may limit their use (Klimeš 2013). In the study area, absence or short period of historical records on the past dangerous events is the main limiting factor in hazard assessment. It is especially true in the case of the GLOFs which return period is impossible to define using scarce historical records. Moreover, climate change may adversely change environmental conditions contributing toward higher occurrence of ice/rock avalanches, which are among the most dangerous GLOF triggering mechanisms. Also estimation of the basic characteristics of the possible future ice/rock avalanches (e.g. volumes, velocities) are very subjective, although are critical in assessment of the resulting GLOF volumes (Schneider et al. 2014). To avoid these uncertainties, we adopted conservative approach to define future flood scenario which defines the "very high" GLOF hazard class. Its definition is based on the only well-known historical GLOF event from April 2010 in the Chucchún River basin. The resulting zonation is probably rather optimistic, e.g. assigning relatively small portion of the study area into the "very high" hazard class. On the other hand, the "low" flood hazard class defined by field mapping of alluvial terraces and alluvial fan represents conservative scenario – it assigns relatively large part of the study area to this hazard zone. It is mainly true for the alluvial fan where only part of it may be affected during a single GLOF event. Its magnitude depends mainly on water volume stored in the Lake 513 which remains the same due to the already existing drainage system.

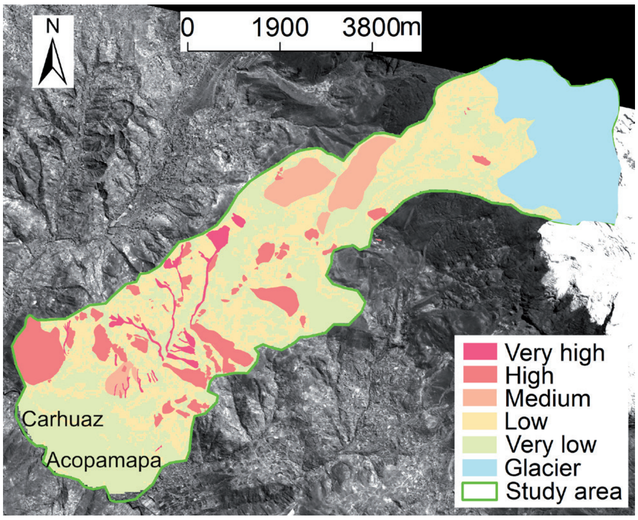

Fig. 2 Landslide hazard map with mask covering the glaciated part of the watershed as shown on 2010 SPOT View image.

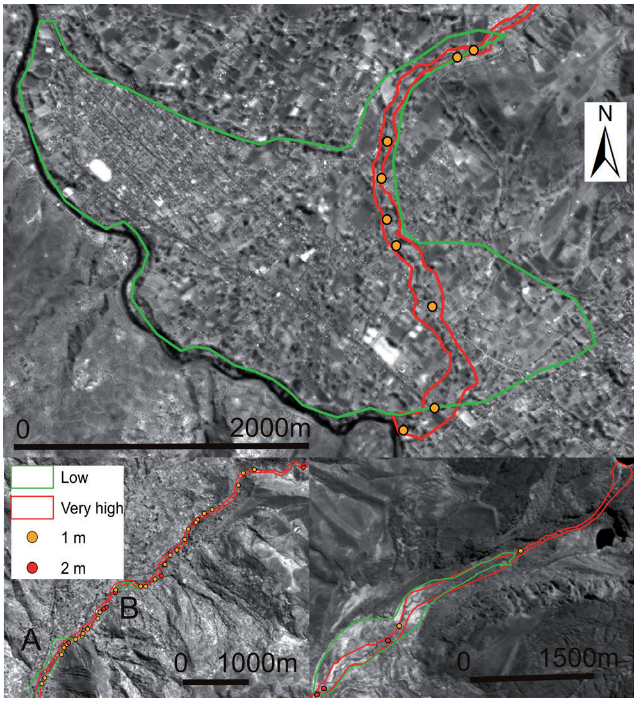

Fig. 3 GLOF hazard map, red line – "very high" hazard and green line – "low" hazard classes, background image is 2010 SPOT View image. Dots show increase of the maximum flow depths (orange – 1 m, red – 2 m) comparing the 2010 GLOF event model and the flood model used to define the "very high" hazard class.

Fig. 4 Deeply incised and narrow riverbed in the middle part of the Chucchún River valley, view to the north-east.

Possible source of uncertainties in the landslide hazard mapping is identification of previous, already denudated landslide forms, which in the study area may be in addition masked by intensive agricultural use of the region. It is well recognized that landslides tend to occur on places affected by slope movements in the past. Thus failing to identify such recently non-active and masked landslide forms may lead to underestimation of the hazard. Expert based aggregation of smaller individual landslides into larger landslide hazard zones probably leads to the more pessimistic landslide hazard zoning, e.g. larger areas were included into higher hazard class. This may compensate the possible underestimation of the landslide occurrence as described above. We also think that the more pessimistic hazard zoning is appropriate considering the possible seismic events, which may trigger much more abundant landslides compare to "regular" climatically governed triggering conditions which were probably responsible for occurrence of the majority of the studied landslides.

The expert based landslide hazard zonation approach was selected due to the lack of detailed and reliable preparatory factor maps covering the entire study region. The available geological information is based on the relatively large scale (1 : 100,000) maps. Lithological or structural information gained during the field works is available in great detail only for limited portion of the study area situated along the stream and thus is not suitable for regional landslide hazard zonation. On the other hand, the basic input information for the GLOF modeling was obtained from detailed field topographic surveys providing high resolution and reliable input information. Therefore combining results of GLOF model based on detailed field data with landslide hazard zonation prepared using large scale input maps would result in high spatial uncertainties. To avoid these additional drawbacks of the hazard assessment, we decided to perform subjective hazard zonation based on landslide inventory mapping done over equally distributed and high resolution satellite images available on GoogleEarth.

Note the similarities between the presented GLOF hazard assessment and results of Schneider et al. (2014) based on RAMMS and IBER models of the complex chain of processes leading to the GLOFs. The "very high" hazard zones defined in both studies are almost identical.

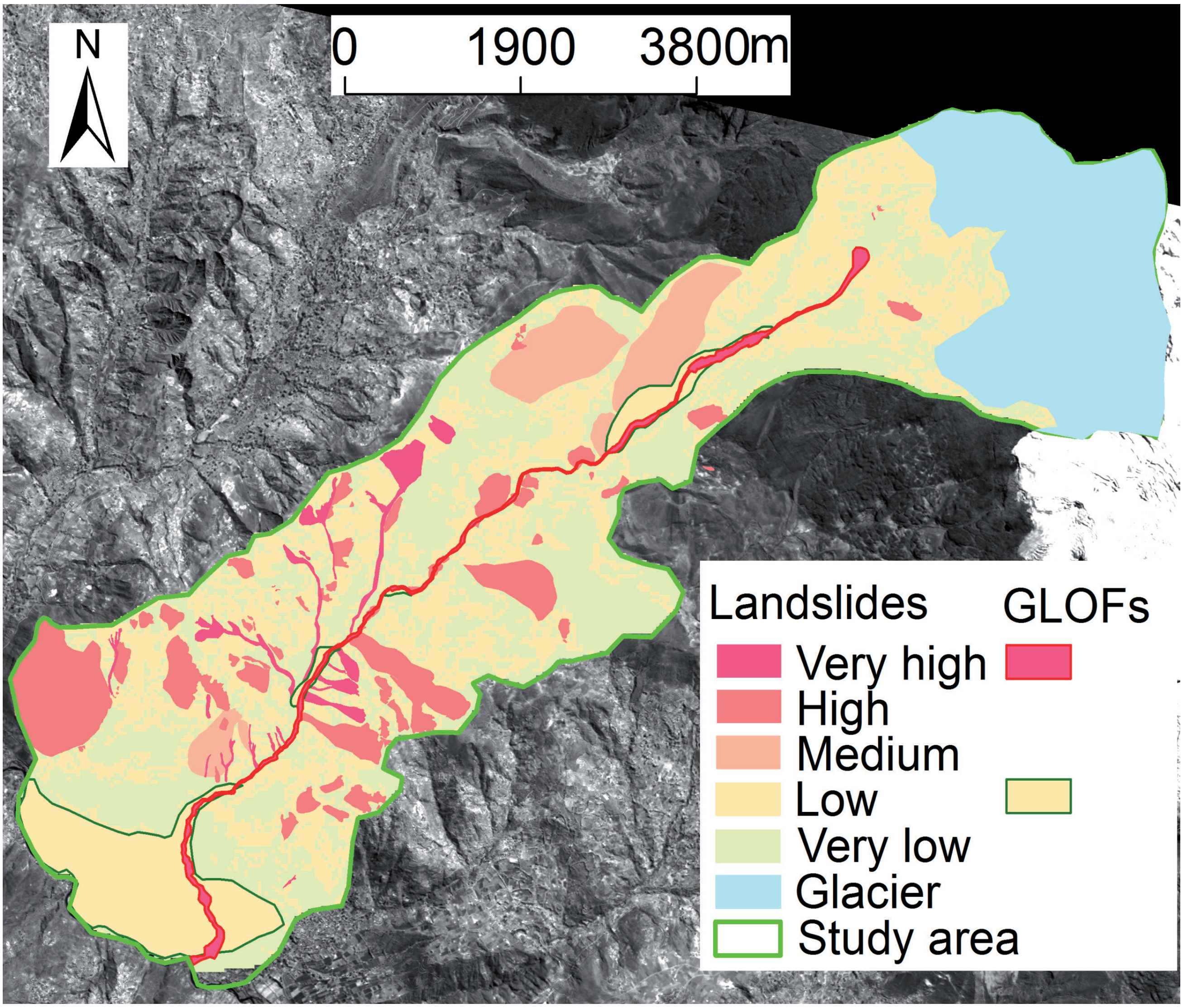

Fig. 5 Multi-hazard map for the Chucchún basin, background image is 2010 SPOT View image.

Also the "low" GLOF hazard class on Fig. 4 is almost identical with "residual" and "low" hazard class in Schneider et al. (2014) with the only significant difference on the steep rock slope just below the Lake 513. The similarities between GLOF hazard zonation could be consider as validation of the results encouraging their practical applications in GLOF risk management at the local level. This is very difficult and sensitive process, but in the case of the Chucchún basin the ongoing development project "Proyecto Glaciares" funded by Swiss Agency for Development and Cooperation provides all necessary conditions for successful application of the scientific results into the practical use.

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RESUMÉ

Nebezpečí vzniku povodní z ledovcových jezer a sesuvů v povodí řeky Chucchún, Cordillera Blanca, Peru

Pohoří Cordillera Blanca leží ve středním Peru a je součástí kontinentálního rozvodí mezi Atlantským a Tichým oceánem. Pohoří je budováno převážně granodiority a tonality třetihorního stáří, které na jeho úpatí v údolí řeky Santy přecházejí do druhohorních sedimentárních a vulkanických hornin. Ty bývají často překryty čtvrtohorními glaciálními a fluvioglaciálními sedimenty. Pohoří je na západě vymezeno výrazným normálovým zlomem. Studované povodí řeky Chucchún je pravým přítokem řeky Santy. V jeho

horní části se nacházejí ledovce a tři ledovcová jezera. V roce 2010 se pod vrcholem Hualcán (6125 m n. m.) uvolnila lavina ledu a sněhu, která zasáhla jezero 513. Došlo k přelití vody přes skalní práh tvořící hráz a vznikla povodeň, která zničila několik domů a mostů v údolí. Tato relativně malá povodeň vyvolala velké obavy místních obyvatel, a proto byly zahájeny práce k vytvoření mapy nebezpečí pro možné budoucí povodně. Vzhledem k tomu, že pohoří Cordillera Blanca i údolí řeky Santy jsou silně náchylné ke vzniku různých forem svahových pohybů, byla vytvořena také mapa nebezpečí pro tyto jevy.

Mapa nebezpečí pro povodně je vytvořena na základě modelování rozlivů povodní s různým maximálním průtokem. Výpočty byly provedeny v programu HEC-RAS na základě topografických profilů zaměřených přímo v terénu. Vzhledem k velmi omezeným historickým informacím o vzniku povodní z ledovcových jezer, byly velikosti povodní stanoveny na základě události z roku 2010. Během této povodně byl modelovaný maximální průtok 580 $m^3 s^{-1}$. Předpokládáme, že povodně podobné velikosti jsou v daném území nejčastější. Proto rozliv této povodně definuje vysoký hazard. Povodeň dosahující maximální úrovně hladiny o 1 m vyšší než povodeň z roku 2010 a s průtokem 965 $m^3 s^{-1}$ definuje oblast středního nebezpečí z povodní.

Mapa nebezpečí vzniku sesuvů byla vytvořena na základě inventarizace sesuvů s pomocí dostupných snímků GoogleEarth s vysokým rozlišením. K vymapovaným svahovým deformacím byly na základě zkušeností ze studované oblasti a morfologických poměrů, dokresleny oblasti předpokládaného nejzazšího dosahu jednotlivých svahových deformací. Nejvyšší stupeň nebezpečí byl přiřazen k přívalovým proudům, které v širší studované oblasti vznikají nejčastěji. Střední nebezpečí bylo přiděleno k sesuvům a nejmenší nebezpečí představují hluboké svahové deformace. Mapy nebezpečí vzniku sesuvů a povodní byly zkombinovány, aby daly lepší přehled o přírodních nebezpečích ve studovaném povodí.

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