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A robust debris-flow and GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru

Abstract The town of Santa Teresa (Cusco Region, Peru) has been affected by several large debris-flow events in the recent past, which destroyed parts of the town and resulted in a resettlement of the municipality. Here, we present a risk analysis and a risk management strategy for debris-flows and glacier lake outbursts in the Sacsara catchment. Data scarcity and limited understanding of both physical and social processes impede a full quantitative risk assessment. Therefore, a bottom-up approach is chosen in order to establish an integrated risk management strategy that is robust against uncertainties in the risk analysis. With the Rapid Mass Movement Simulation (RAMMS) model, a reconstruction of a major event from 1998 in the Sacsara catchment is calculated, including a sensitivity analysis for various model parameters. Based on the simulation results, potential future debris-flows scenarios of different magnitudes, including outbursts of two glacier lakes, are modeled for assessing the hazard. For the local communities in the catchment, the hazard assessment is complemented by the analysis of high-resolution satellite imagery and fieldwork. Physical, social, economic, and institutional vulnerability are considered for the vulnerability assessment, and risk is eventually evaluated by crossing the local hazard maps with the vulnerability. Based on this risk analysis, a risk management strategy is developed, consisting of three complementing elements: (i) standardized risk sheets for the communities; (ii) activities with the local population and authorities to increase social and institutional preparedness; and (iii) a simple Early Warning System. By combining scientific, technical, and social aspects, this work is an example of a framework for an integrated risk management strategy in a data scarce, remote mountain catchment in a developing country.

Keywords Debris-flows · GLOF · RAMMS · Risk management · Early Warning System

Introduction and background

Management of risks related to mass movements and mass flows is critical to reduce loss of lives and damage to property and public infrastructure. Loss of lives due to landslide hazards is thereby higher in developing countries (Petley 2012) where resources for risk analysis and management are often limited. Somewhat simplified, two approaches of risk management can be distinguished: one that is based on technical risk analysis which typically requires a substantial amount of qualitative and quantitative data, extensive field work, often accompanied by numerical modeling (e.g., Guzzetti et al. 2003; Remondo et al. 2008; Reichenbach et al. 2013; Corominas et al. 2014). Risk management is then based on the results of the quantitative risk analysis, and practical management decisions and activities are often applied in a more top-down manner. Such approaches are more commonly found in the developed world and typically rely on an existing set of observations and data.

However, in many regions of the developing world that face landslide and mass flow risks, available data is scarce or non-existent, making it difficult to apply technical and quantitative risk analysis methods including the determination of spatial landslide intensity and frequency, and assessment of vulnerability and potential degree of damage of elements at risk, as recommended by Corominas et al. (2014). Standards of tolerable risk that would form a basis for risk management (Jakob et al. 2013) are often lacking as well in such regions. And importantly, government institutions are often weak and lack capacities, representing a major barrier to successful risk management. In view of such constraints, bottom-up, community-based approaches with some learning by doing are often applied in developing world contexts to reduce landslide risks (Holcombe et al. 2013; Anderson et al. 2014).

The discrepancy between technical, expert-based risk analysis and community-based risk perceptions and mapping can be considerable. Sudmeier-Rieux et al. (2012), for instance, compared community risk maps with geological landslide risk maps to better understand and communicate community risk perceptions, priorities, and coping strategies. The appropriate consideration of different risk perceptions and social, political, and institutional aspects is essential for successful risk management (Carey et al. 2015). Overall, though, there is limited experience how technical risk analysis can be applied in areas with scarce or absent data, and how it can be effectively combined with community-based risk management approaches.

Here, we present a study from the southern Andes in Peru, a region that includes several communities west of Machu Picchu and extends from warm tropical areas up to glacierized areas >6000 m a.s.l. Exceptionally large mass flows from deglaciated areas have heavily impacted the area over the past decades and caused many casualties. In this study, we concentrate on the Sacsara river catchment that encompasses the municipality of Santa Teresa and several communities scattered along the river. The catchment is a large remote area, and the mass flow source zones, including several glacier lakes, can only be reached in several days by foot. Environmental monitoring and related information is virtually non-existent, and event documentation is limited to anecdotal reports of local people.

It was therefore clear that a full quantitative risk analysis was unfeasible. Accordingly, the objectives of this study are to develop and apply a risk management strategy that would be able to cope with the prevailing data scarcity, and as a consequence, would be robust against uncertainties in the risk analysis that result from limited available data and resources as well as limited understanding of physical and social processes.

As a basis to develop a risk management strategy, a risk analysis was performed, divided into hazard assessment including analysis of past events, and modeling of future scenarios, and a vulnerability assessment involving local communities. The development of the risk management strategy was furthermore accompanied by an intensive interaction with the local authorities and local population. Three main components were eventually distinguished and implemented: (i) risk sheets that described the prevailing risks per community, made recommendations for risk reduction measures, and thus served as a basis for decision makers of the municipality and leaders of the local communities; (ii) preparedness and capacity building activities with the local government and population; and (iii) the design of an early warning system to reduce loss of lives due to large mass flows, including glacier lake outburst flows (GLOFs).

Study site and data

Santa Teresa (13°07′50″ S, 72°35′40″ W, 1550 m a.s.l.) is located in the Central Andes, about 6 km northwest of Machu Picchu, Southern Peru (Fig. 1). In the close vicinity of the municipal center of Santa Teresa, three sub-catchments, Sacsara (228 km^2), Salcantay (372 km^2), and Ahobamba (129 km^2), flow into the main river Río Urubamba, originating in the Cordillera Vilcanota, about 200 km in the southeast. Elevation differences of more than 4000 m, from glaciated peaks (Nevado Salcantay, 6254 m a.s.l.) to densely vegetated mountain forest, with steep slopes characterize the topography. Air masses coming from the Amazonian Basin in the north govern the climatic conditions, resulting in a dry season in the austral winter (April–September) wet season in the austral summer (October–March). Annual precipitation amounts to more than 2000 mm, of which about 75 % fall during the wet period from October to March. A number of studies on landslide and debris-flow hazards are available for the zone of the Machu Picchu UNESCO world heritage site (e.g., Vilimek et al. 2006; Best et al. 2009; Canuti et al. 2009): related monitoring and warning systems (Bulmer and Farquhar 2010) and risk assessments (Puglisi et al. 2013), including capacity building (Sassa et al. 2009) and social impacts (Sassa 2013).

For the nearby zone of Santa Theresa, the investigation site of the present study, very few studies are available. In the past, this region has been affected by several debris-flow events, and in 1998, three debris-flows of extreme magnitudes occurred in the zone of Santa Teresa. On 13 January, a debris-flow in the Sacsara catchment virtually destroyed most of the town of Santa Teresa and the settlement of Yanatile (cf. 2.1). Two weeks later, on 27 January 1998, another debris-flow in the same catchment occurred, flowing over the deposits of the pervious event and destroying the few remaining structures in Santa Teresa. Only 1 month later, on 27 February 1998, an extreme flow event occurred in the Ahobamba catchment, which was already affected by an outburst from a glacial lake at the foot of the north face of Nevado Salcantay in 1996 (Hermoza et al. 1998). Total flow volume of the 1998 event in the Ahobamba catchment is estimated to be extremely large, about 25–50 × 10^6 m^3 (Carlotto et al. 2000), reached the Urubamba main valley, depositing large amounts of sediments in the river bed down to Santa Teresa, and causing panic in the traumatized population, which in the mean time had been relocated to higher ground above the former location of Santa Teresa. These deposits dammed the Urubamba River, which caused a flooding and consequent destruction of the Machu Picchu hydropower station, located in the main valley, about 1 km upstream from the confluence of the Ahobamba and Urubamba rivers. The triggers of this event remain unclear, a GLOF was not observed, nor were ice or rock avalanches. After this main event, two minor debris-flows followed in 1998, on 12 March and 22 November, incorporating material from the main event, but without causing major damage in the nearly unpopulated Ahobamba catchment. In the following, we concentrate on the Sacsara catchment, which hosts several populated places.

13 January 1998 debris-flow

On 13 January 1998 at around 7.30 pm Peruvian Time (PET = UTC−5 h), first pulses of a large and long-lasting debris-flow event reached Santa Teresa. Before this, at around 4 pm, an explosion-like noise was heard, according to locals. Pulses of varying magnitude passed every 10–15 min, the main bridge across the Urubamba River collapsed at 10 pm, and 1 h later the train station was destroyed. The event went on until 5 am to 10 am on 14 January (depending on the source of information), when the last pulses were observed in Santa Teresa. About 80 % of Santa Teresa was destroyed, just as the nearly complete destruction of the local communities of Yanatile and Andihuela (cf. Fig. 2) and related infrastructure. Five casualties were reported, but 150 persons were listed missing; in total 340 buildings were destroyed, and 90 ha of agricultural land was lost. As a consequence, Santa Teresa was rebuilt at a higher location, about 60 m above its previous location.

In a steep valley in the upper part of the catchment, the starting zone of this event can be identified (Fig. 2). It is located in morainic material at elevations between 4200 and 4450 m a.s.l. with a length of about 400 m, 100 m wide and about 30 m deep. A flat valley bottom, covered with blocks and boulders of various sizes, follows the steep slope of this detachment zone. About 2 km downstream, at the bridge of Mukayoc, the first pulses of the event were registered at about 6.20 pm, i.e., about 70 min before they reached Santa Teresa, which is approximately 21 km farther downstream, resulting in an average flow velocity of about 5 m s^{-1}. After this flatter section, the debris-flow was channeled and laterally eroded the steep hill slopes, producing landslides and thereby adding more sediment to the flow. The height drop from the starting zone to the confluence with the Urubamba River at Santa Teresa at a distance of 29 km is nearly 3000 m, resulting in an overall slope of 0.10.

Several eyewitnesses reported drying of the riverbed before the event; some even said the river dried during the event between flow pulses, indicating a temporal blockage of the river upstream. Considering the strong lateral erosion during the event, smaller blockings of short durations are plausible. However, no indications or traces of a larger temporary dam and a related temporary lake can be found in the region downstream of the starting zone.

Data

Data from meteorological stations is sparse. In a range of 75 km around the starting zone of the January 1998 debris-flow, 13 stations are run by the National Meteorological and Hydrological Service (SENAMHI) (Fig. 1), but only five stations have data series dating back to 1998, and four of them are located on the Altiplano, which has a different, dry-cold climate. For investigating the pre-event precipitation history, data from the Tropical Rainfall Measurement Mission (TRMM, Smith et al. 2007) satellites were used (tiles 125, 126, 140, 141, cf. Fig. 1).

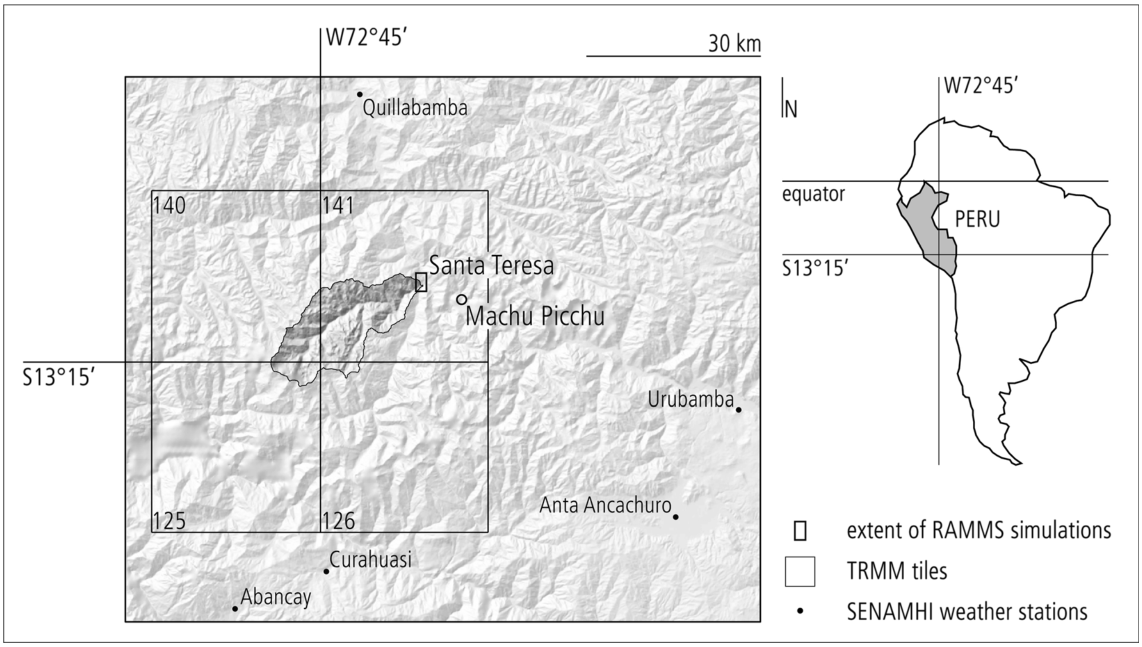

Fig. 1 Location and overview of the study region, location of weather stations and extents of TRMM tiles. The extent of the Sacsara catchment is enhanced in the hillshade view of the SRTM DEM (*left*)

For the sensitivity analysis of the debris-flow modeling (cf., 3.2.2), the ASTER Global Digital Elevation Model, version 2 (ASTER GDEM2) with a spatial resolution of 30 m was used. In order to have more detailed terrain information, a 6-m digital elevation model (DEM) was derived from two stereo images (nadir-looking and backward-looking) of the Panchromatic Remote-sensing Instruments for Stereo Mapping (PRISM) sensor on board the Advanced Land Observing Satellite (ALOS), the DEM corresponds to July 2009 with some areas filled as of June 2008, hereafter called ALOS DEM.

No direct measurements exist from the 1998 events. All available information comes from the reports of the events by Hermoza et al. (1998) and Carlotto et al. (2000), field investigations during

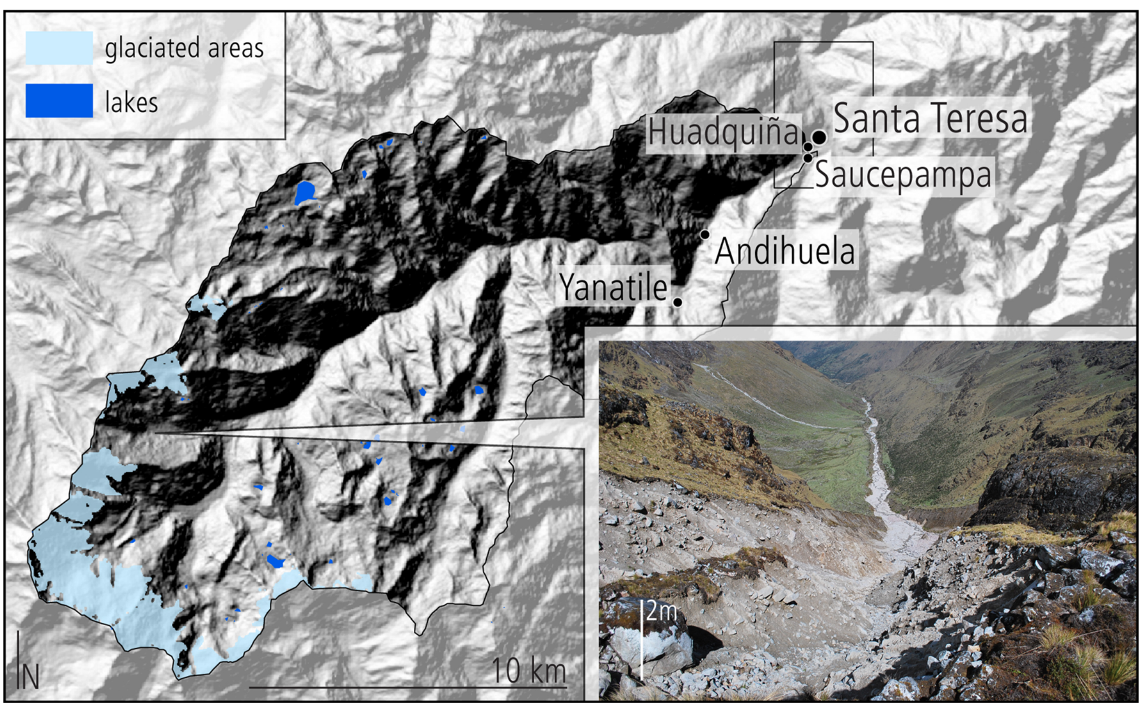

Fig. 2 Hillshade view of the Sacsara catchment, glaciers, and lakes, as well as smaller communities are indicated. The *rectangle around Santa Teresa* delimitates the extents of Fig. 5. *Lower right*, photo from the starting zone of the 1998 event, looking down valley, towards East (November 2012)

the years after the event and remote sensing analyses, as well as eyewitness reports.

Risk analysis

Trigger analysis

Pre-event precipitation and temperature, as well as earthquakes were analyzed as potential triggers for the 1998 debris-flow. Figure 3 shows the cumulative precipitation in the 30-day period prior to the event on 13 January 1998 recorded at five meteorological stations in the region around Santa Teresa, and daily precipitation values since 1 January 1998, estimated for the four TRMM tiles covering the Sacsara catchment (see Fig. 1 for locations of stations and TRIMM tiles).

Besides considerable differences among the stations and TRIMM tiles, it is apparent that cumulative precipitation amounts for the 30-day pre-event period were extraordinary high at Anta Ancachuro station, above the long-term average for Abancay and Carahuasi, and average for Urubamaba and Quillabamaba, the latter having a wetter climate due to its proximity to the Amazonian basin. Spatial correlation between the stations is low, indicating that convective precipitation plays an important role, which is not surprising for the mountainous terrain of the study region. At the same time, this points to the fact that local precipitation values at the release zone of the debris-flow might differ considerably from the station measurements. TRMM measurements indicate heavy precipitation in the days before the event. In particular on 12 January, the day before the event, daily precipitation sums exceed the climatic average by more than three times in each of the four tiles. Three-day sums from 11 to 13 January as well are 2.5–3.1 times above the climatic average, and also the week sum exceeded average values substantially. It is noteworthy that TRMM data aggregated over short time periods (day to weeks) have lower correlations with ground truth data than measurements accumulated over 15 or more days (Scheel et al. 2011).

Monthly maximum temperatures of all stations are 0.5–3 °C above climatic averages at all stations in both December 1997 and January 1998, except the January 1998 maximum at Abancay station. Since temperature maxima can be used as a proxy for snow melt rate, this suggests that snowmelt contributed additionally to soil saturation, pore pressure, and thus soil stability.

On 9 January 1998 at 11.54 pm PET, a M6.1 earthquake was registered 150 km northeast of the Sacsara trigger zone (USGS Earthquake Archive, http://earthquake.usgs.gov/earthquakes/search/) that was also noted by the population in Santa Teresa. Another earthquake of M5.3 occurred on 13 January at 12.01 pm local time (i.e., about 4 h before the probable start of the debris-flow), some 130 km southwest of the release area. There are no reports that the population felt this earthquake; nevertheless, it could have contributed to the destabilization of the material, in combination with the observed intense precipitation.

Debris-flow modeling

Rapid mass movement simulation software RAMMS

The numerical simulation software RAMMS was originally developed to simulate the granular flow of extreme snow avalanches in three-dimensional terrain (Christen et al. 2010b; Bühler et al. 2011). As debris-flows can also be treated as granular flows, similar modeling approaches can be applied. Based on large-scale debris flow experiments at the Illgraben test site in Switzerland (Berger et al. 2011), a debris-flow module of RAMMS was calibrated and released in 2011. Key features of the debris-flow modules are an efficient second-order numerical solution of the depth-averaged equations of motion (shallow water equations) and the definition of the disposition using a hydrograph.

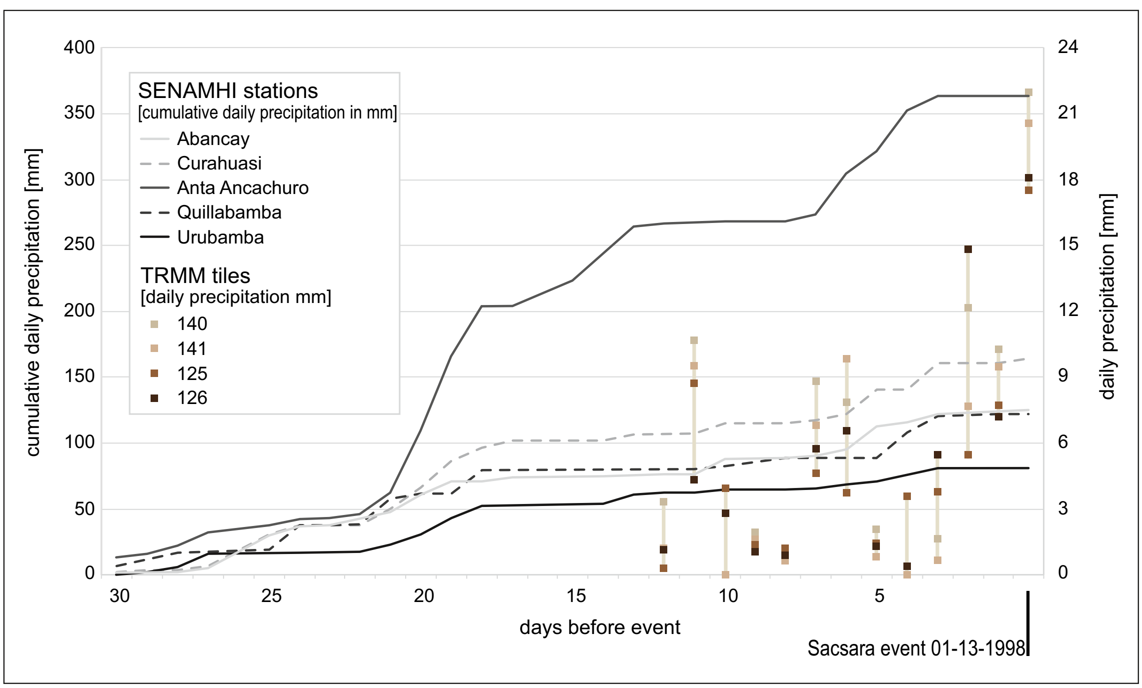

Fig. 3 Pre-event precipitation for meteorological stations (cumulative precipitation for the 30-day pre-event period, *left y-axis*) and from TRMM measurements (daily precipitation sums since 1 January 1998, *right y-axis*). See Fig. 1 for locations of stations and TRMM tiles

The numerical model uses the two-parameter Voellmy-Salm relation (Salm et al. 1990; Salm 1993) to describe the frictional behavior of the flowing debris on a rectangular x, y grid (Christen et al. 2010b). Momentum balances in x and y directions are given by

$$\partial_t (HU_x) + \partial_x \left(HU_x^2 + \frac{g_z H^2}{2} \right) + \partial_y (HU_x U_y) = S_{gx} - S_{fx}$$

and

$$\partial_t (HU_y) + \partial_y \left(HU_y^2 + \frac{g_z H^2}{2} \right) + \partial_x (HU_x U_y) = S_{gy} - S_{fy}$$

where H is the flow depth, g is the gravitational acceleration and g_z its component perpendicular to the slope, U is the depth-averaged flow velocity, and S_g and S_f the slope-parallel accelerations and decelerations, respectively. S_g in x and y directions are given by

$$S_{gx} = g_x H$$

and

$$S_{gy} = g_y H$$

Slope parallel deceleration components S_{fx} and S_{fy} in x and y directions are determined by the Voellmy model (Voellmy 1955), which combines a dry Coulomb friction μ with a velocity-squared dependent turbulent friction ξ (given in m s^{-2}):

$$S_{fx} = \frac{U_x}{\sqrt{U_x^2 + U_y^2}} \left[g_z H \mu + \frac{g \left(U_x^2 + U_y^2 \right)}{\xi} \right]$$

and

$$S_{fy} = \frac{U_y}{\sqrt{U_x^2 + U_y^2}} \left[g_z H \mu + \frac{g \left(U_x^2 + U_y^2 \right)}{\xi} \right]$$

More physics of the RAMMS model beyond these governing equations can be found in Christen et al. (2010b).

Based on the digital elevation model (Bühler et al. 2011) and an assessment of the disposition, RAMMS is able to calculate flow path, run out distances, flow heights, flow velocities, and impact pressures of extreme debris-flows. To successfully apply the simulation software in specific torrents, field observations are essential to assess the disposition and, if possible, to get information about run out distances of past events. This model has already been successfully applied to model large debris-flows in the Alps (Hussin et al. 2012; Scheidl et al. 2013; Hergarten and Robl 2015; Schraml et al. 2015) and GLOFs in Peru (Schneider et al. 2014).

Sensitivity analysis and parameter determination

Deposits from the 1998 event were mapped from high-resolution imagery available in GoogleEarth and refined in the field. This polygon serves as a reference for both the sensitivity analysis and the calibration of the RAMMS calculations. Furthermore, this polygon allows for a rough estimation of the involved volumes: its area of 900,000 m^2 (3000 m × 250 m) multiplied by an average depth of the depositions of 10 m (corresponding to deposition heights from 5 to 20 m as reported by the population and according to the fact that the buildings of former Santa Teresa were buried completely) indicates a total volume of the deposits to be about 7.5×10^6 m^3. Large uncertainties are not only related to the estimation of the deposit height, but also to the downstream limitation of this polygon, which is somewhat arbitrary because in the main river deposits form the 1998 Sacsara event cannot be discriminated from other deposits.

Also knowledge and experience about the rheological parameters of debris-flows of the magnitude given here is limited. Model parameters were therefore elaborated in an approach similar to Pirulli and Sorbino (2008). Rheological parameters are taken from literature and combined with depositions as observed in high-resolution satellite imagery from GoogleEarth. Sensitivity was analyzed for the two friction parameters of the model, the starting volume, starting velocity, and starting discharge, and the time lag between the initiation of the flow and the peak discharge ($t1$).

Runout distance is most directly influenced by the dry-Coulomb friction parameter μ, whereas in the steep parts of the flow profile, where the flow mass accelerates, the turbulent friction ξ is dominating. Sensitivity to μ was assessed by plotting the resulting flow heights on a profile corresponding to the line with the highest flow-height values on the deposition zone at Santa Teresa. According to the overall slope of the catchment, μ was set to 0.1 as a first approximation. In literature, μ values from 0.01 to 0.2 can be found (e.g., Armento et al. 2008), whereas large events have a tendency to lower values. Therefore, the initial value of 0.1 was successively lowered to 0.05, by steps of −0.01.

A Simulation Performance Index (SPI) was applied for the zone of the mapped depositions: the SPI corresponds to the ratio of cells correctly modeled to be affected by the flow and the total number of cells in this deposition zone. It therefore takes into account that false negatives (cell modeled to be not affected but actually was affected) are more critical, as this results in a false sense of security. False positives (cell modeled to be affected although it was not the case), on the other hand, are not considered. SPI for the variations of the dry-Coulomb friction μ is shown in Fig. 4: best agreement was found for results from model runs with $\mu = 0.85$ and 0.9, therefore $\mu = 0.9$ was used for all further model runs.

The turbulent friction ξ has a strong influence in the acceleration zone of the debris-flow, when the mass is moving at high velocities. Pirulli and Sorbino (2008) recommend ξ values of 100–1000 m s^{-2}; Christen et al. (2010a) found extreme values for ξ of 3000 m s^{-2} for snow avalanches. For large events, high turbulent friction is realistic, as geometry is less important than for smaller events. Here, sensitivity was tested with ξ values from 500 to 3000 m s^{-2}, with steps of +250 m s^{-2} between 500 and 1500 m s^{-2}, and steps of +500 m s^{-2} between 1500 and 3000 m s^{-2}. It was found that runout distance, flow height, and flow velocities in the deposition zone are nearly independent of variations of ξ. $\xi = 1500$ m s^{-2} was chosen for all further simulations.

A series of empirical relations of flow volume and maximum discharge exist for debris-flows (e.g., Rickenmann 1999) and related to dam failures (Evans 1986; Costa and Schuster 1988; Rickenmann 1999); however, the unknown volume of individual debris-flow surges is strongly limiting their use in the present case.

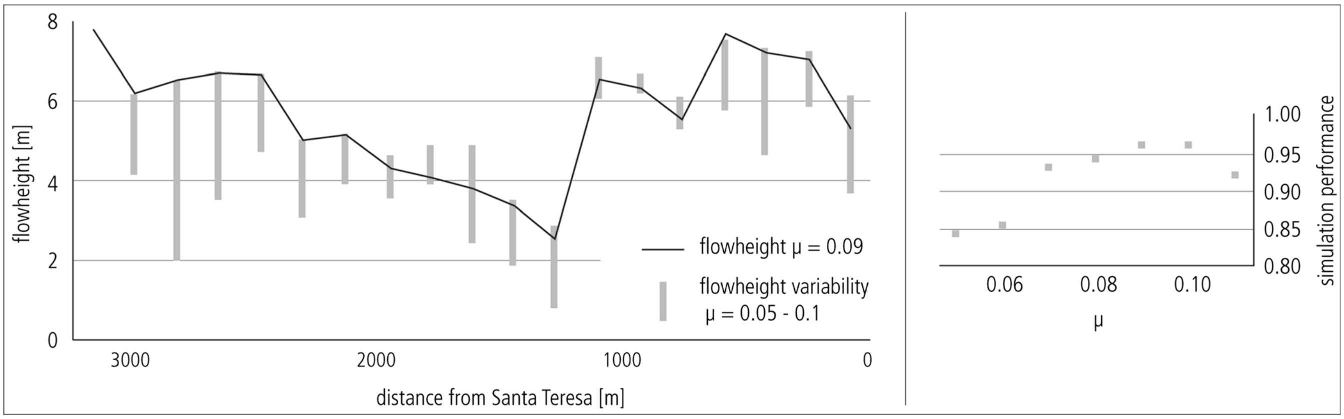

Fig. 4 *Left*, flowheights resulting from model runs with μ values varying between 0.05 and 0.1, along a profile at Santa Teresa. The continuous line connects the values from the $\mu = 0.09$ simulation. *Right*, corresponding simulation performance index (SPI)

Model runs showed a good agreement with observed depositions when peak discharges of 7500 $m^3\ s^{-1}$ were chosen, corresponding to the maximum discharge as calculated with the relation proposed by Costa and Schuster (1988) for a volume of $5 \times 10^6\ m^3$ and a dam height of 25 m. Variations of this value by ±25 and ±50 % resulted in larger flow heights in Santa Teresa for the −25 % and the −50 % variation, and smaller flow heights and strongly decreasing sensitivity for the ±0 % and the +25 and +50 % scenarios, with corresponding extended runout distances.

Modifications of t1, the time between flow initiation and the maximum discharge in the release area, as well only has a very low influence on resulting flow height, velocity, and runoff distance. Default values were used for other model-specific parameters.

Calibration

The magnitude of an event, i.e., the involved volume, has a strong influence on both flow velocity and flow height. Larger volumes lead to increasing average and maximum flow velocities, increasing flow height, and a further runout. But the splitting of the total involved mass into various flow surges complicates the volume determination for the modeling. Reconstructions from the detachment zone and estimates on the amount of material eroded along the flow route based on field and remote sensing data, as well as the mapped deposition zones, allow estimating the total volume. For debris-flow modeling and also for the hazard assessment, however, the mass involved in individual flow surges, in particular the largest surge, is essential, since this determines the extent and intensity with which a zone is affected.

The largest volume of an individual surge was calibrated with deposits from the 1998 event as recognized in the high-resolution satellite imagery from GoogleEarth. In order to estimate the volume of the largest individual debris-flow surge, the estimated total volume of $7.5 \times 10^6\ m^3$ was iteratively reduced until the extent of mapped deposits close to Santa Teresa was well simulated. The mentioned uncertain downstream boundary of the mapped deposition area was not considered for this, as it was reported that the flow continued for several kilometers downstream after the confluence with the Urubamba River. As shown in Fig. 5, a volume of $2 \times 10^6\ m^3$ yields to flow heights that agree well with the mapped deposits (maximum flow height values of less than 0.2 m are neglected). Considered as an estimate for the potential volume of the largest surge is $2 \times 10^6\ m^3$.

1998 event reconstruction

Based on the trigger analysis and the modeling, we suggest the following process for the January 1998 Sacsara event: the loose glacial sediments in the starting zone had been saturated by the intense precipitation during the 30-day pre-event period, in particular during the 3 days before the event. In addition, the relatively high temperatures in December and January caused snowmelt, which contributed to soil saturation as well. It is unclear but possible that the earthquakes from 9 and 13 January contributed to the slope destabilization. After the debris-flow initiation, flow speed was very fast in the first section (~15 $m\ s^{-1}$), but slowed down to 1–2 m in Mukayoc, the first deposition zone. After this flat section, the debris-flow accelerated again to 4–10 $m\ s^{-1}$ (7–8 $m\ s^{-1}$ on average) in the relatively steep valley down to before the settlement of Yanatile, about 8 km upstream of Santa Teresa. There the terrain is flatter and the valley bottom wider, additionally there is a sharp turn, which further reduced the flow speed to about 5 $m\ s^{-1}$, and finally, 2 km before Santa Teresa, to 2–3 $m\ s^{-1}$, due to another flattening and widening of the valley. Modeled average flow velocity from Mukayoc to Santa Teresa of about 6 $m\ s^{-1}$ correspond well to reported values and result in a travel time of 1 h 15 min to 1 h 25 min for the 27–30-km distance (depending on the exact flow path).

According to field observations in the starting zone, the volume detached from the release area is estimated to be about $1.2 \times 10^6\ m^3$ (cf. 2.1). Estimates of the total volume based on observed deposits at the confluence with the main valley are in the order of $7.5 \times 10^6\ m^3$ (cf. 3.2.2), indicating that about six times the initial volume has been eroded along the steeper part of the debris-flow trajectory. Iterative RAMMS runs suggest a maximum volume of a single surge of $2 \times 10^6\ m^3$ (3.2.3). Eyewitnesses reported five major surges in Santa Teresa with several pulses of considerable smaller volumes between. Based on this information, the total volume was likely split into five major surges of over $1 \times 10^6\ m^3$ and several smaller ones, of possibly around $100 \times 10^3\ m^3$. However, large uncertainties that are hard to quantify are associated with these numbers.

Hazard assessment

For assessing the hazard situation, a strategy using two approaches has been chosen: (1) scenarios of potential future events have been

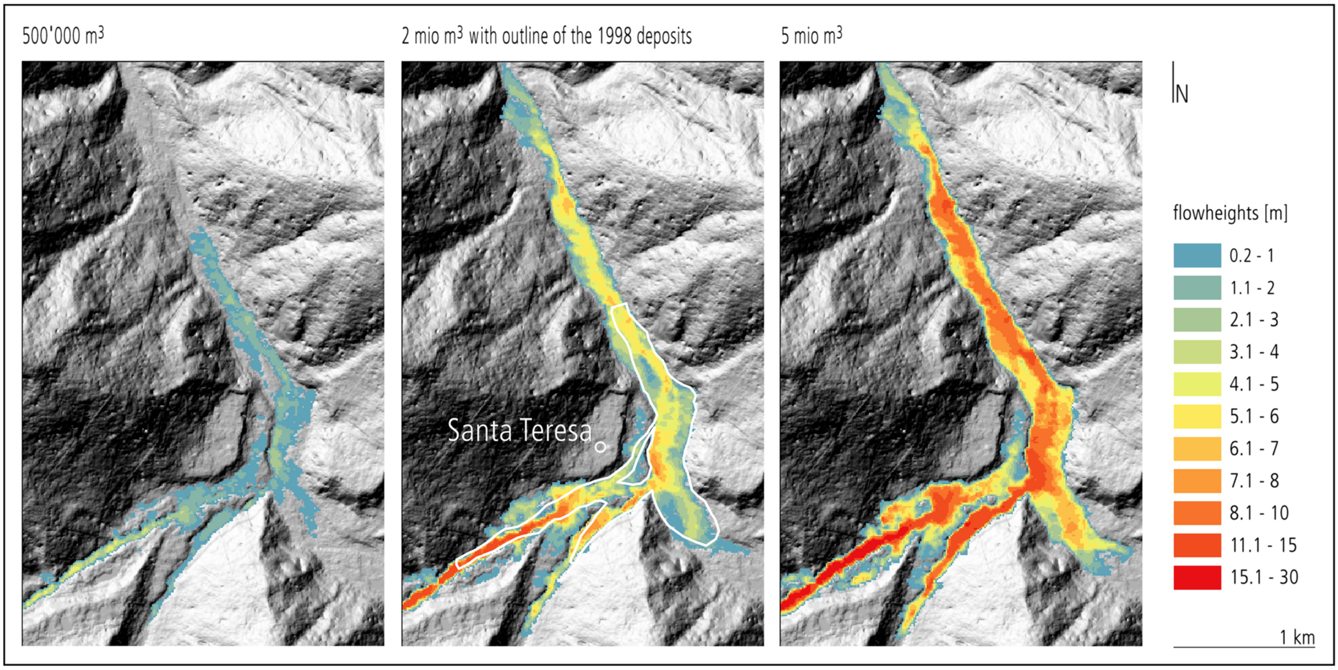

Fig. 5 Maximum flow height values for total flow volumes of 0.5×10^6 m^3 (*left*), 2×10^6 m^3 (*center*), and 5×10^6 m^3 (*right*). Mapped deposits from the 1998 event are indicated by the *white outlines in the central panel*. Hillshade view from the ALOS DEM in the background

modeled, in order to evaluate the consequences of large-scale mass movements affecting the entire catchment. (2) Qualitative hazard maps on smaller scales have been compiled for each of the populated places, based on the model results from (1), but including additional information from site visits and fieldwork and the analysis of high-resolution imagery form GoogleEarth. For the scenario model runs, a small, medium, and large event was modeled, corresponding to the three event dimensions as used in the guidelines for mass movement hazard assessments in Switzerland and other countries (Raetzo et al. 2002). However, these dimensions cannot be directly translated into probabilities or return periods as postulated in these guidelines, as there is no record on historical events that would allow for establishing frequency-magnitude relations (e.g., Hungr 2005). To assess the full range of possible processes, the large-magnitude scenario was outlined to represent a worst-case scenario.

Future scenarios

Guided by the findings of the reconstruction of the 1998 debris-flow, possible mass movement events for potential future scenarios have been modeled. We assume that the 1998 event corresponds to the upper bound of potential debris-flows triggered from unstable and saturated sediments regarding event magnitude; the location of the trigger zone might differ though.

In addition to potentially large debris-flows, two glacier lakes have been identified in the upper reaches of the catchment, posing a threat for potential GLOFs. One of the lakes is forming by the coalescence of supraglacial ponds on a debris-covered glacier tongue, which consists of dead ice since the separation from the main glacier tongue. Currently, the zone is a mix of water and (floating) debris-covered ice, but high-resolution imagery from GoogleEarth indicates that the potential future size of the lake might reach an area of 100×10^3 m^2 (about 700 m long and 150 m wide). Hanpi K'ocha, the other lake, lies in a bedrock depression formed by glacial erosion, below a small glacier. It has an area of 100×10^3 m^2 as well (500 m long and 200 m wide), no significant area changes are expected.

For both lakes, three outburst scenarios have been modeled, a partial and a full outburst without significant sediment incorporation, and—in order to have a worst-case scenario for assessing the full range of potential hazards—a full outburst scenario with a large sediment incorporation of 1 and 1.5 times the water volume for rock and moraine dams, respectively. Average depth of a fully evolved glacier lake on the debris-covered former glacier tongue is estimated to be 10 m; 20 m average depth are assumed for Hanpi K'ocha, since there is probably not much sediment on the lake ground and the shape less elongated. Modeled total flow volumes therefore are 0.3×10^6, 1×10^6, and 2.5×10^6 m^3 for outburst scenarios of the potential future lake on the dead-ice tongue, and 1×10^6, 5×10^6, and 10×10^6 m^3 for outburst scenarios of Hanpi K'ocha. Parameters of the three GLOF scenarios for the two lakes are shown in Table 1.

For the outburst of the future lake on the dead ice body, μ was set to 0.08, according to the overall slope of 0.1 that was lowered by 20 % to account for the higher amount of water compared to the 1998 debris-flow. For the Hanpi K'ocha outburst scenarios, μ was set accordingly to 0.09 (overall slope of 0.11). Based on the sensitivity analysis, ξ was set to 1000 m s^{-2} and input velocity to 15 m s^{-1} for all scenarios. Peak discharges were calculated based on the assumed outburst volumes for the three scenarios, according to Costa and Schuster (1988). It is assumed that the entire volume will burst out in a single surge, although in the case of impact-triggered lake outbursts often a

Table 1 Parameters used for modeling the GLOF scenarios. Values for the currently forming dead-ice lake are based on the assumption of a fully developed lake. For Lake Hanpi K'ocha, no changes are expected for the future

	Dead-ice lake			Lake Hanpi K'ocha		
Scenario	Small	Medium	Large	Small	Medium	Large
Outburst volume (mio m^3)	0.3	1	2.5	1	5	10
Peak discharge (m^3 s^{-1})	500	1500	3500	1500	2600	5500
μ	0.8	0.8	0.8	0.9	0.9	0.9
ξ (m s^{-2})	1000	1000	1000	1000	1000	1000

seiche, i.e., a wave sloshing back and forth in the lake basin, is observed (e.g., Westoby et al. 2014), causing repeated overtopping and, hence, pulsed outburst floods. But this aspect is neglected here, due to the objective to cover the worst-case scenarios.

Modeling results for the future GLOF scenarios (Fig. 6) show that all scenarios reach Santa Teresa, except the smallest scenario from the future lake on the dead-ice body. The settlement of Yanatile, which had been rebuilt on higher ground after its complete destruction in 1998, can be considered safe from debris-flows and GLOFs in the main valley, the same applies for Santa Teresa itself. In contrast, Andihuela, Saucepampa, and Huadquiña, the latter two located close to Santa Teresa, are still threatened by such large-scale flow events. In particular, the settlement of Andihuela may be affected by all scenarios reaching this zone because the buildings are located at a short distance to the main river (both vertical and horizontal).

Here, areas inundated by more than 0.1 m according to the flowheights modeled by RAMMS are considered as the hazard zones. A classification into different degrees of hazard as a function of intensity and probability, such as suggested by Raetzo et al. (2002) and Hürlimann et al. (2006), is not made here. Reasons are the large uncertainties related to the magnitude of the events and, in particular, the ambiguities of assigning return periods to the different scenarios. In the case of the Sacsara catchment, it is not even evident that larger events have smaller probabilities of occurrence.

In addition to large-scale events affecting the entire catchment, such as described above, the potential of smaller events

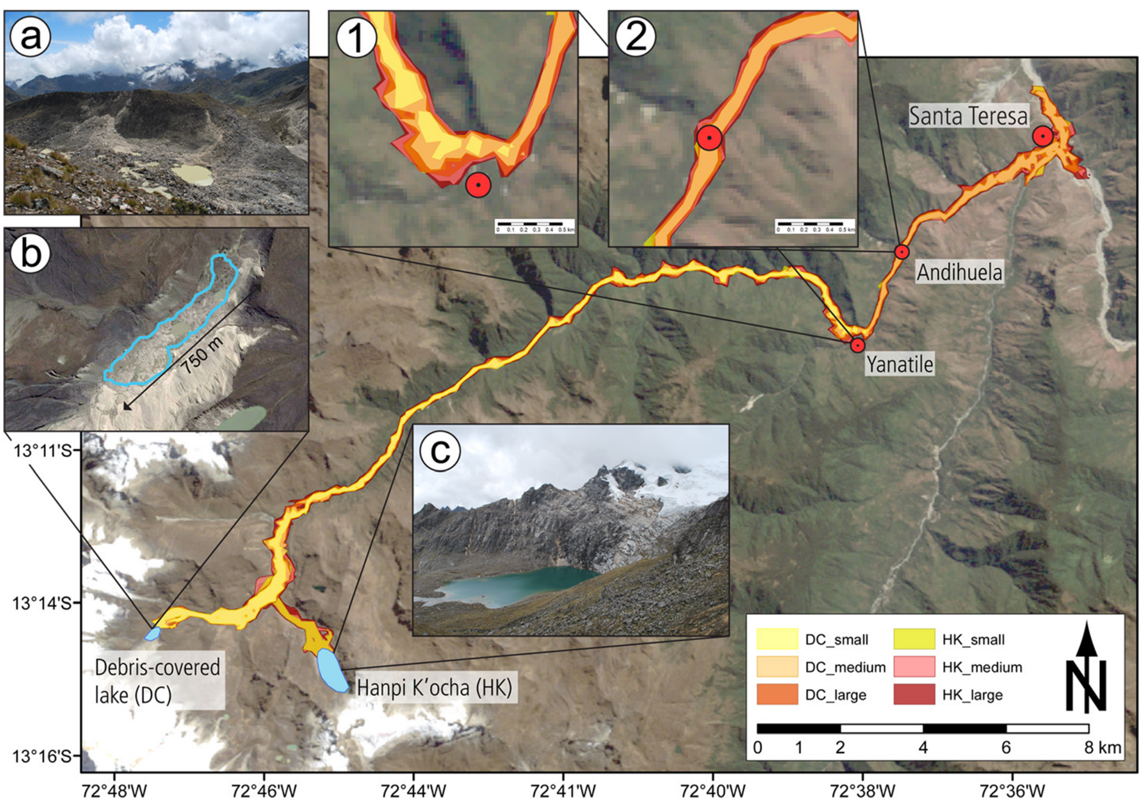

Fig. 6 Modeling results of GLOF scenarios from the potential future lake on the debris-covered dead ice body (DC) and Lake Hanpi K'ocha (HK). Inundation heights of <0.1 m are neglected. (*1*) and (*2*) show zooms to the zones of Yanatile and Andihuela, respectively. (*a*) DC Lake in November 2012, (*b*) GoogleEarth image from June 2014, possible extent of the fully developed potential future lake indicated in *blue*. (*c*) Lank Hanpi K'ocha (November 2012). Photos *a* and *c* from November 2012 (by C. Giráldez)

has been considered for the punctual hazard assessments for the populated places. However, due to the lack of any records of historical events, knowledge of potential starting zones, and thus information on potential event magnitudes, it is not possible to define event scenarios of different dimensions. Model runs with RAMMS were therefore discarded. High and medium hazard zones have been defined based on high-resolution imagery form GoogleEarth and field mapping. Flashfloods and debris-flow hazards were considered for both the main valley and, typically steep, tributary valleys; additionally, locations with potential lateral erosion have been identified in the riverbed of the Sacsara main river. Taking into account all the points above, these maps rather correspond to "hazard indication maps" than to real hazard maps.

Hazard assessment for populated places

The identification and characterization of potential hazards for the populated places was done based on the scenario modeling results, but additionally taking into account historical data, satellite-imagery analysis, and in situ studies (both fieldwork and interviews with locals). For this local hazard assessment, two types of hazard are discriminated in terms of space and origin: remote and close. The involved processes are debris-flows and floods for the former, which to a large extent are based on the RAMMS results, and landslides, marginal erosion of riverbeds, and debris-flow from smaller tributary torrents for the latter. Uncertainties related to the qualitative hazard assessment without information from the model runs are high as well. Magnitude and intensity, and probability of occurrence and return periods cannot be quantified and the affected areas are estimated according to geomorphological criteria, rather than dynamical aspects of the mass movements into account.

Vulnerability assessment

The vulnerability was evaluated through several sources: in situ interviews with local inhabitants and authorities, the official "plan for land-use and disaster-mitigation measures" from the municipality of Santa Teresa, the population and housing census statistics from the National Statistical Institute (INEI), and participative workshops following the "Climate Vulnerability and Capacity Analysis" (CVCA) method, whose main aim is to understand climate-related challenges, identify adaptation solutions and take steps towards them, through a participatory analysis which engages all stakeholders (CARE 2009). Four types of vulnerability were taken into account: physical (materials for building), social (level of organization and participation), economic (access to economic activities), and institutional (institutional strength and capability). They reflect the sensitivity of the population (i.e., the magnitude of the impact that can be produced by a hazard on the exposed elements) and its resilience (i.e., the capacity of an exposed system to resist, respond, adapt, and recover from an impact). The four types of vulnerability were divided into further variables to which a level of vulnerability was given as a percentage following a previously established criterion, where 0 % means no vulnerability and 100 % extremely vulnerable. This procedure is illustrated at the example of physical vulnerability (Table 2): The physical vulnerability is related to the quality and type of material used for building every aspect of the communal life (housing, industry, services, infrastructure, etc.). The variables identified are (i) construction materials for housing, (ii) geological characteristics of the ground, and (iii) land-use laws. For each variable, four levels of vulnerability (low–medium–high–very high) were defined in detail and quantified in terms of percentages: low vulnerability corresponds to <25 %; medium vulnerability to 26–50 %; high vulnerability to 51–75 %; and very high to 76–100 %. Thus, for example, the first variable (materials for housing) could range from low vulnerability, <25 %, i.e., concrete or steel seismic-resistant structure, to very high vulnerability, 76–100 %, i.e., adobe, reed, and other low resistance structures in precarious state.

Corresponding tables were used for the economic, social, and institutional vulnerabilities. The observed variables are economic activity, access to the labor market, level of income, and poverty situation for the economic vulnerability; level of organization, participation in communal works, relation between and integration of local institutions and organizations for the social vulnerability; and autonomy, political leadership, civic participation, and degree of coordination of actions between authorities for the institutional vulnerability. The mean percentage is taken as the overall percentage for the given vulnerability type, and the average of the four vulnerability types equals the overall vulnerability for a given community. Results from this analysis for the five communities located in the Sacsara catchment are shown in Table 3. Vulnerability has been assessed for all 17 communities in the Santa Teresa region, resulting in 13 communities having a high vulnerability, and 4 having a medium vulnerability, among them the Yanatile and the main populated center of Santa Teresa

Risk assessment

Finally, risk is assessed by intersecting the hazard and vulnerability levels according to a standard matrix, shown at the bottom of Fig. 7 and in the risk sheet in the supplementary material. Figure 7 shows the hazard, vulnerability, and risk maps for Huadquiña and Saucepampa, the two towns located adjacent to the main center of Santa Teresa. Such sets of four maps have been produced for all the 17 communities and form part of the risk sheets elaborated for each community (cf. 4.1). From the communities of the Sacsara catchment, Andihuela, Huadquiña, and Saucepampa have zones of very high risk; for Yanatile and Santa Teresa zones, medium risk are present. The main reason for this is the relocation to higher ground for the latter towns, after their destruction during the 1998 event, which avoided any coincidence of the highly vulnerable assets in zones of high hazards.

Risk management

Based on the findings from the hazard and vulnerability assessment, an integrative risk management strategy consisting of three different components has been developed. The strategy aims at considering socio-cultural and economic, as well as political and environmental aspects, corresponding to the framework for disaster risk reduction from the UN Framework Convention on Climate Change (UNFCCC 2012, Fig. 7 therein). It includes (1) technical risk sheets that have been elaborated for the populated places, serving as tools for spatial and structural

Table 2 Assignment of vulnerability levels for assessing the physical vulnerability

Variables	Vulnerability level			
	Low <25 %	Medium 25–50 %	High 51–75 %	Very high 76–100 %
Building materials	Earthquake-resistant structure, concrete/steel	Concrete, steel, wood structures, not earthquake-resistant	Adobe, stone or wood structures, without structural reinforcement	Adobe, reed structures in precarious state
Geology and type of soil	No faults or cracks, soil with solid geotechnical characteristics	Presence of some cracks, soil with average load capacity	Presence of cracks, soil with low load capacity	Presence of many cracks and faults, collapsible soil
Land-use laws	Laws established and executed	Laws established and partially executed	Laws established but not executed	No established laws

planning; (2) collaboration and interaction with the local people and authorities with the objective to increase preparedness and reduce vulnerabilities and risks; and (3) an Early Warning System (EWS) with a modular implementation plan.

Risk sheets for populated places

Based on the risk assessment, risk sheets have been produced for each of the 17 communities in the zone of Santa Teresa. These sheets should help to inform the population about hazardous zones and processes, and serve as a planning instrument for local authorities to have a guideline and to prioritize most important actions. The complete risk sheet for Huadquiña and Saucepampa (see also Fig. 7) is available in the supplementary material.

Each risk sheet has three pages and consists of the same elements: First, a map of the community can be seen with the risk area colored following a color-coded risk matrix which combines the hazards and the vulnerability, corresponding to the example shown in Fig. 7. Then, a general and socio-economical characterization is included (general remarks, total surface area, inhabitants, construction materials, climate, and relief and ground type). After the general remarks, the core diagnosis is provided. It is divided into the hazard diagnosis (process and description), the vulnerability diagnosis (percentage and description of the four types of vulnerabilities), and the final risk level result. Finally, some intervention measures are proposed for specific places. Currently, the risk sheets are in the process of being included in the communal development plans of each community, and in a few communities some of the proposed intervention measures have already been realized, and a new emergency plan and a concept for emergency simulation has been developed for the Santa Teresa district.

Social and institutional preparedness

Preparedness programs as part of risk management efforts are very widespread worldwide and also in Peru. Experience shows the importance of embedding such efforts within the local context and local perceptions of risks which may differ substantially from an "outside" technical assessment of risks (Jurt 2009; Huggel et al. 2015).

In the framework of the disaster risk management strategy, several activities together with the local inhabitants are implemented. First, a radio communication system has been established, and in the meantime became the main way of communication for messages on activities and information related to the disaster risk management, especially because it has a good spatial coverage and because its content is in Quechua language, the main language of the local population. Furthermore, meteorological stations, equipped with automatic pluviometers and temperature sensors, have been installed to collect temperature and precipitation data in this data-sparse region. In addition to that, totalizators for manual measurements of cumulative rainfall data have been installed to back up the automated measurements, but also to involve the local population in the measurement campaign. Risk perception maps have been elaborated with the population and crossed with the risk sheets described above (4.1), in order to establish a shared knowledge regarding the risks, risk perception, and safe areas in case of a hazardous event. Knowledge about the local perception of risks helps to direct daily life decision

Table 3 Vulnerabilities of the populated places in the Sacsara catchment

	Vulnerability				Mean	Level of vulnerability
	Physical	Economical	Social	Institutional		
Yanatile	29	46	48	49	43	Medium
Andihuela	65	50	59	53	54	High
Saucepampa	74	59	73	76	71	High
Huadquiña	68	65	54	59	62	High
Santa Teresa	51	51	53	40	49	Medium

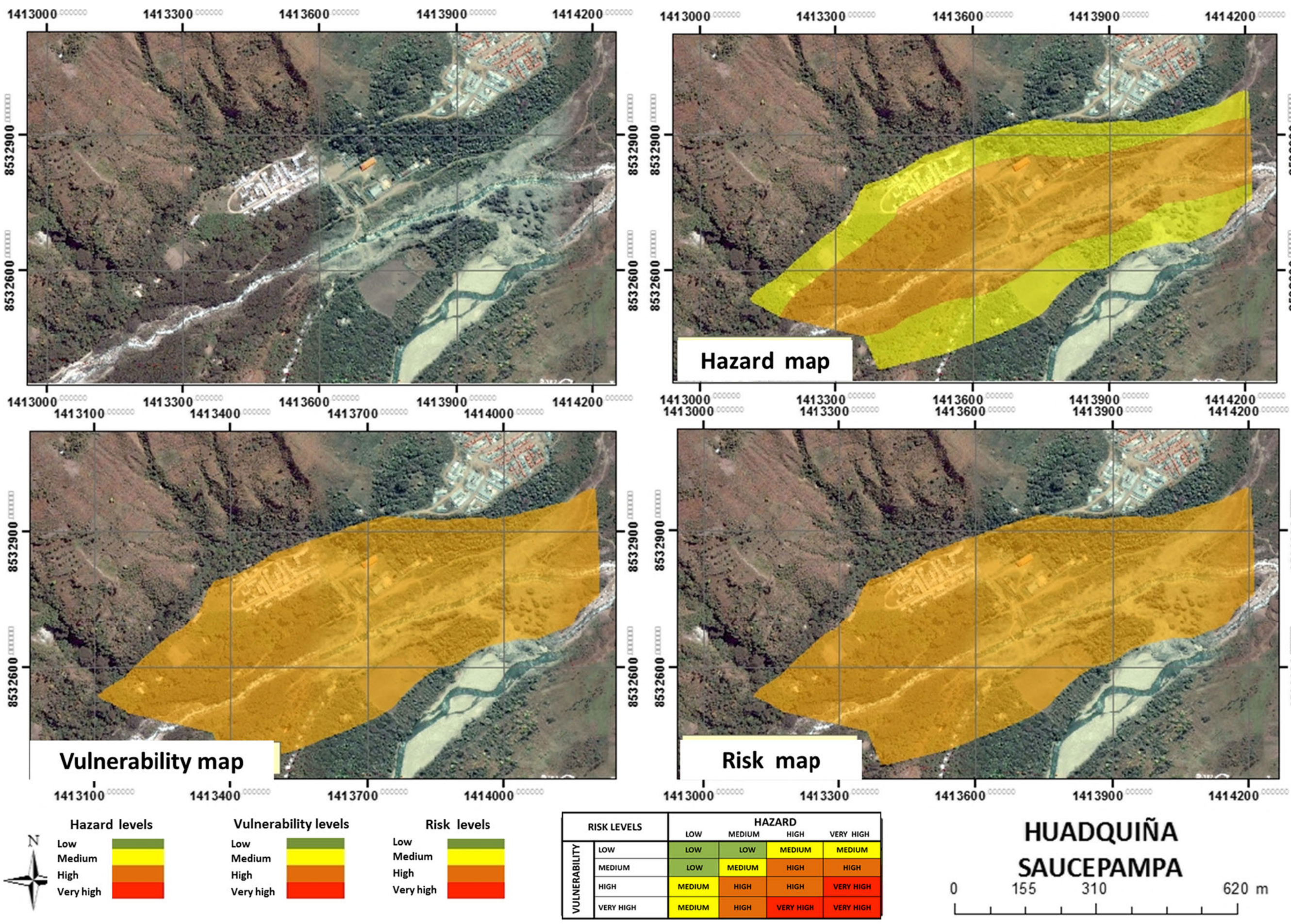

Fig. 7 Overview, hazard, vulnerability, and risk maps for Huadquiña and Saucepampa. Due to the vicinity of the two communities, only one map has been produced. The risk map corresponds to the intersection of the hazard (medium and high) and vulnerability levels (high). According to the matrix shown at the bottom, this indicates a high risk

regarding climate change adaptation in the direction of improving preparedness and response against hazardous mass movement processes. To achieve this, it is important to consider scientific, institutional, and local knowledge to work on preparedness.

In this context, it is important to consider migration dynamics during the past years. In the Santa Teresa district, as is the case in many other rural parts of Peru, many of the locals who experienced the 1998 debris-flow moved away; on the contrary, migrants from other parts of the district and the province migrated in, in order to find opportunities on tourism, mainly related to the Machu Picchu Sanctuary and the Inca Trail trekking route. Because of this, risk perception is less in this area, along with less cohesive communal organizations. To address this, so-called Leadership Schools have been held, working on capacity building of local leaders on topics such as glacier retreat, climate change, risk management, and adaptation measures, including the functionality of an EWS (cf. 4.3). In each community, a risk management committee has been established and approved by the local government in Santa Teresa, consisting of a governor, a health promoter, and a representative for the civil defense. Finally, topics on climate change, related risks, and climate-change adaptation have been integrated in the curricula of all local schools.

Early warning system

Modeling results of the reconstruction of the 1998 event and the potential GLOFs in the Sacsara catchment, as well as the findings from the risk evaluation for the populated places, highlight the urgent need for risk reduction measures for many of the populated places located close to the valley bottom. Structural measures such as deflection dams commonly require sufficient details on design floods and debris-flows. In the case of Santa Teresa and the Sacsara catchment, however, substantial uncertainties prevail and are difficult to eliminate based on the current level of available information and understanding, and considering the physical characteristics of the catchment with a very high number of potential trigger zones. Non-structural measures that increase the preparedness of people at risk are more robust against such uncertainties. Therefore, it has been decided to focus on early warning efforts, with the aim of significantly reducing the vulnerability and exposure by timely alarming the population in case of an event in the catchment, so that they can take appropriate measures and move to safe places (e.g., Huggel et al. 2012).

The main components of the planned EWS include two measurement stations located at two bridges crossing the Sacsara Valley, about 19 km (11 km) and 22 km (14 km) upstream of the confluence with the Urubamaba River at Santa Teresa (the settlement of Yanatile) (Fig. 8). These locations offer good accessibility required for the installation and maintenance of the stations, which at most other locations is hampered by the rough topography and dense vegetation. At each bridge, a set of wires will be stretched at different levels across the channel. In case of a debris-flow, these wires will be ruptured, triggering transmission of a signal (Arattano and Marchi 2008). This allows not only registering the height of the flow but also provides a certain confidence, as ruptures caused by other reasons, such as animals for instance, likely will not affect all wires up to a certain level. Another possibility is the installation of an infrared or acoustic water level sensor, this would allow for permanent water level measurement, and thus could as well detect strong reductions in the runoff, indicating a blockage of the river upstream. However, the turbulent flow is limiting such measurements, in particular for high water levels. Therefore, and to increase the redundancy of the system, a combination of the two systems, tripwires and water level measurements, is being pursued.

A data center is planned in the main building of the municipality in Santa Teresa. All data collected by the sensors will be transferred to the main server in the data center and backed up on an external server or a cloud. Remote access via internet will be available as well. From the stations, data will be transmitted to the data center via radio, using the same repeater stations as the radio communication system (cf. 4.2) for the different local settlements. In case of the detection of a potential event, indicated by ruptured cables or absent runoff, an SMS will be sent to the persons in charge of the civil defense, who then has to decide on alarm release based on the information stored in the data center. Sirens in as well as the radio communication to the population centers will be used to alarm the population.

In addition to the technical components described above, further social and institutional aspects need to be considered for a successful implementation of the EWS (UNEP 2012). First of all, an appropriate communication with the local inhabitants, as outlined in the previous section, is fundamental for achieving confidence and acceptance, and thus eventually the necessary level of preparedness of the population according to defined stages of alert and alarm.

Discussion and conclusions

In view of the very limited data availability, and social and economic conditions in the Santa Teresa region, a technical, quantitative, top-down risk management strategy was considered unfeasible. Instead, a strategy was developed that combined elements both from bottom-up, community-based approaches, and technical hazard and risk analysis that should be able to reasonably cope with uncertainties concerning timing and magnitude of events, and account for the high vulnerability and degree of exposure of the local population and infrastructure. Such challenging conditions are common for rural mountain regions of developing countries. Although concrete circumstances and conditions might differ from region to region, the risk analysis and management framework presented here might be applied to other remote mountain catchments as well.

The lack of precise information and data on past events complicates the application of a physically based debris-flow model and increases the uncertainties associated to modeling results. Starting volumes can be estimated based on field evidence, for instance, but total flow volumes, friction parameters

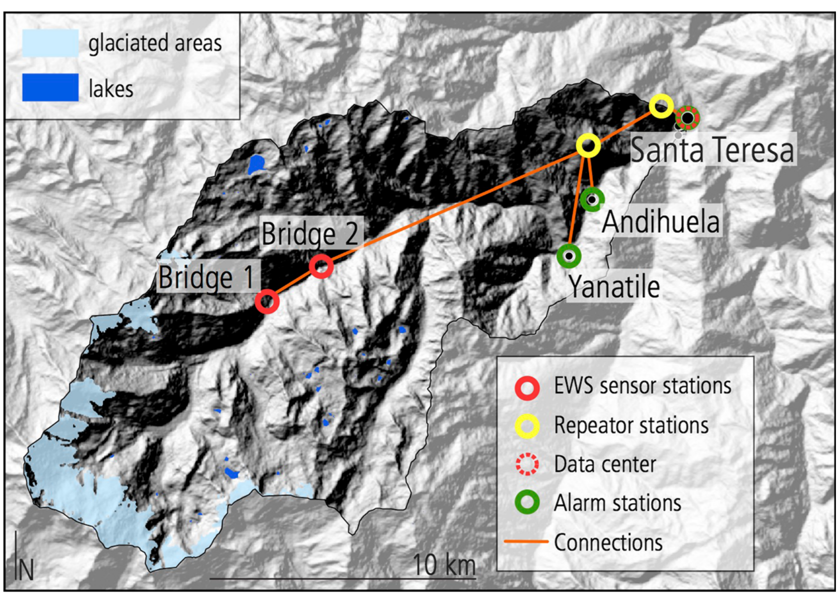

Fig. 8 Locations of sensor, alarm, and repeater stations of the first step of the EWS

characterizing the flow type, and peak discharge have to rely on a sensitivity analysis and a calibration based on depositions zones mapped several years after the event, which in the meantime have been superimposed by other processes. A further, yet common challenge arises from the use of DEMs for flow modeling that represent post-event topographies. Taking into account the estimated depositions heights of up to several tens of meters indicates that the pre-event topography must have differed considerably. The deviating information from eye-witness reports on the number and magnitude of flow pulses is a further aspect adding to the uncertainty of the RAMMS modeling. In particular, results for the potential future scenarios have to be interpreted rather as upper bound estimates for worst-case scenarios. The uncertainties and subjectivity related to these results are too large for using them for planning structural mitigation constructions. Nevertheless, they are valuable for non-structural mitigation and adaptation measures, such as the EWS and spatial planning. Due to the limited input parameters, RAMMS proved to provide useful results, also in cases with limited data availability, but the related large uncertainties must be considered any further use of this information.

A full hazard assessment, including the model-based mapping of low, medium, and high hazard zones, such as proposed by Raetzo et al. (2002) and done for instance by Schneider et al. (2014) for GLOF hazards for a glacier lake in Peru, is neither possible with the available data basis and process understanding. The hazard analysis performed here was guided by the objective to include potential worst-case scenarios, but estimates of probabilities of occurrence related to the estimated scenarios were not possible. This is a common problem for processes that occur only once, or very rarely, such as glacier lake outburst floods, and where a statistical basis is lacking (Huggel et al. 2004). It is furthermore doubtful that the higher magnitude scenarios are less probable than lower magnitude events, as it is generally the case (Raetzo et al. 2002; Künzler et al. 2012).

Regarding the implementation of risk reduction measures, it is important to consider that even if there is a consensus between the technical risk assessment and the local risk perceptions, this does not necessarily imply an adaptation of the everyday behavior of the affected population. For instance, knowledge about risks related to housing close to the river existed of course already before the large event in 1998; nevertheless, even among families who experienced loss of property from this debris-flow, some continued living in the same areas, despite some awareness of the risk. This is a result of a family decision process in order to stay close to their farms, to raise their animals and have access to a wider space in comparison with the area where they would have been relocated after the event. Thus, the mentioned aspects of everyday life are prioritized, in contrast to the possibility of experiencing a similar debris-flow event.

The collaborative efforts with the population and the local authorities (4.2) are key for a successful implementation of the different elements of the risk management strategy. Capacity building efforts in Santa Teresa tried to transmit the risk context to the inhabitants, and to cross with local knowledge and perception in order to identify ways for successful development and application of adaptation measures that are understood, accepted, and regarded as beneficial, thus enhancing their sustainability. Other actions, such as the installation of the radio communication network and the establishment of local leaders, aimed at improving the social cohesion within the local communities and eventually reduce the social vulnerability. This in turn can help to implement local adaptation measures and reduce the dependency from the weak and unstable governmental institutions.

The presented EWS (4.3) represents a non-structural measure with the aim of timely alerting and alarming the population in case of a hazardous event, and therefore reduce their exposure and vulnerability to such processes. As a result of many unknown factors and the wide range of possible processes, including the impossibility of identifying potential trigger zones, the system is relatively simple, and only allows for alarming in case of an already ongoing event. Due to the lack of cameras, it will not be possible to exactly identify the type of processes, but on the other hand, the proposed system requires much less energy than a more sophisticated system. It is relatively simple but redundancy is assured which overall makes the system more robust against technical failures. The modular design and the combination with existing communication infrastructure have the potential for extension of the system in the future. Before such an extension of the system in the Sacsara catchment is considered, however, installations of similar EWS in the other catchments (Salcantay and Ahobamba) must be evaluated.

In order to guarantee the support of the local authorities and to ensure the sustainability of the EWS, close collaboration with the mayor of Santa Teresa and his administrative body has been sought from the beginning of the risk management process, including the implementation process for the EWS. In this context, also a financial commitment from the municipality is expected, not only for the installation of the system but as well for its maintenance. This results in a dependency of the entire risk management strategy from these authorities and therefore also on political processes, such as elections. Although these aspects cannot be controlled and sometimes can have unforeseen and adverse effects on ongoing efforts and planning, we consider it as the best way to achieve sustainability and to ensure an independent continuation of actions and efforts.

The main components of the presented risk management strategy—the risk sheets for populated places, including recommendations for intervention measures, the community-based activities with the local population, and the EWS—are largely independent from uncertainties of the risk assessment, introduced by the limited availability of data and information, or they implicitly are designed to cope with such uncertainties. Many of the mentioned non-structural risk reduction and adaptation measures aim at improving the social and institutional, as well as the infrastructural situation within the local communities. This should on the one hand reduce the vulnerabilities of the local population, and on the other hand ease the implementation of the proposed risk reduction measures and help to make them more sustainable. As soon as new or better information becomes available, the proposed risk management strategy should be revised. Constant revisions and frequent updates of the different risk management aspects are also required in order to account for the continuous changes in the environmental, social, and institutional conditions.

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