An Integrated Assessment of Vulnerability to Glacial Hazards

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An Integrated Assessment of Vulnerability to Glacial Hazards

A Case Study in the Cordillera Blanca, Peru

The Rio Santa valley in the Cordillera Blanca, Peru, has been repeatedly affected by severe glacial flood disasters in the past decades. The continuing high rate of glacier retreat has led to the formation and rapid growth of a large number of glacial lakes. Due to the risk of lake outburst floods, downstream communities are confronted with serious hazards. The regional capital of Huaraz is one of the major sites exposed to these hazards. Mainly due to a lack of resources, no systematic evaluation of the existing hazards and related risks has been performed so far, nor have adequate warning systems been installed. Strict financial limitations make a prioritization of mitigation measures a necessity. Vulnerability assessments are an effective tool to this end. In this article, we present a method to measure the vulnerability of Huaraz to hazards from glacial lake outbursts integrating both physical (ie hazards-related) and socioeconomic factors. The difficulty of quantifying socioeconomic variables and its combination with physical factors, as well as a lack of corresponding concepts, is a challenge for measuring vulnerability. The resulting map shows a high vulnerability for several parts of Huaraz. The results of this study thus make an important contribution to effectively addressing the identified protection deficit and to efficiently assigning the limited resources in the context of a developing country. However, this article also shows the strong need for more vulnerability research integrating both physical and social science components and related theoretical frameworks to be readily applied in practice.

Keywords: *Glacial hazards; vulnerability; integrated assessment; Cordillera Blanca; Peru.*

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Introduction

Global warming has a major impact on glacial and periglacial dynamics, resulting in changes of hazards throughout the world's mountain regions. For instance, glacier shrinkage can lead to the formation or growth of glacial lakes. In particular moraine-dammed glacial lakes often bear some considerable risk of lake outbursts, eg triggered by mass movements affecting the lake and producing impact waves and subsequent dam failure.

In the Cordillera Blanca (CB, Peru 9°32′S 77°32′W), a large number of glacial lakes formed during the last century, that have repeatedly caused severe disasters. A careful assessment of the hazard is needed in order to take adequate measures of risk reduction and mitigation. Such measures mostly concentrate on the technical side of risk reduction, such as dam stabilization constructions, flood deflects on dams, etc (Reynolds et al 1998). However, the socioeconomic conditions of the people affected also exert a significant influence on the dimension of natural catastrophes.

This is where vulnerability studies can play an important role. Although a variety of vulnerability studies exists (Cutter 1996; Dikau and Weichselgartner 2005; Birkmann et al 2006), there is a lack of integrated concepts which combine physical and social vulnerability. This paper presents a method towards evaluation of integrated vulnerability for mountain regions in developing countries. To make vulnerability measurable, the concept must inevitably simplify the complex physical and social phenomena, and is further constrained by the availability of data. The method was applied to the CB using the example of Palcacocha glacial lake, and corresponding results are provided in the section on applying the approach in the Cordillera Blanca.

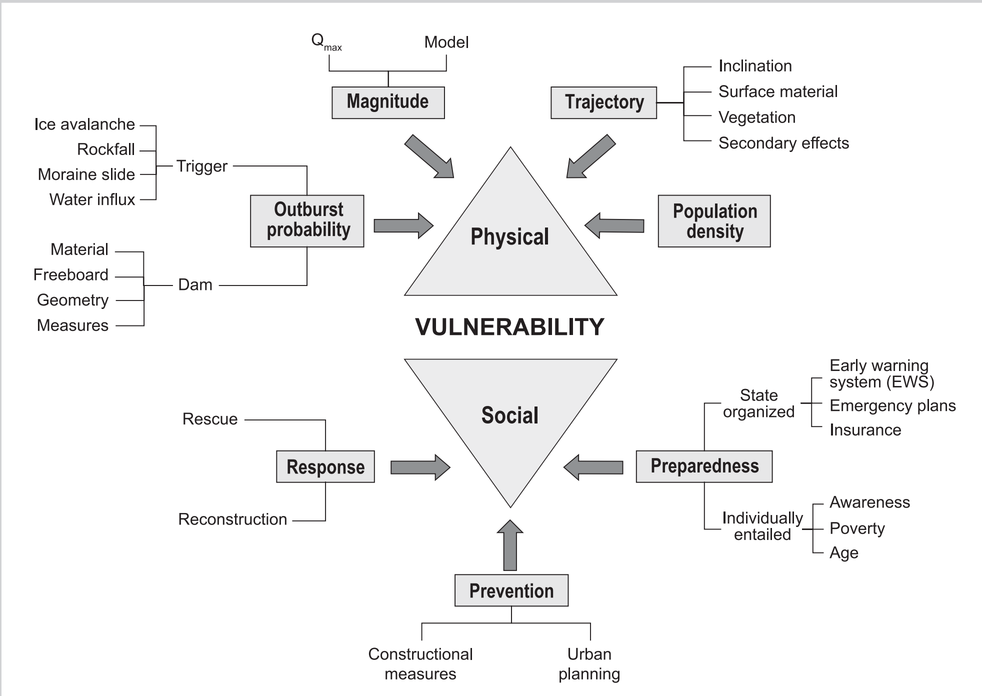
An integrated approach to assessing vulnerability

Vulnerability has become a widely used term, with many different definitions being offered. Here, we refer to Dow (1992), who defined vulnerability as the differential capacity of groups and individuals to deal with hazards, based on their positions within the physical and social worlds. Dow's definition implies that people are affected in varying degrees of severity, depending on their capability to cope with the disaster. This capability strongly correlates with some socioeconomic structures. In this context, Blaikie et al (2004) mention a lack of resources and information as well as limited political weight. Elderly people and children, for instance, are harder to evacuate, which increases their vulnerability significantly. The poor generally have limited access to resources, in addition to living mostly in badly constructed houses. Furthermore, the ability to recover from loss of housing is very limited for a poor person (Dasgupta 1995; Wilbanks et al 2007).

Measures taken by governmental or non-governmental organizations to increase preparedness can reduce vulnerability. Emergency plans, awareness building campaigns, early warning and insurance systems are possible measures that can decrease vulnerability (Weichselgartner 2002).

To make vulnerability measurable, a concept of vulnerability was developed that integrates the two

FIGURE 1 The concept of integrated vulnerability with the determining factors and indicators.



aspects of vulnerability—the physical-technical one and the socioeconomic one. This concept of vulnerability, presented in this paper, is divided into two parts termed physical and social vulnerability, based on Chambers' original approach (1989) and distinguishing between exterior and interior vulnerability (Bohle 2001) (Figure 1). Factors that possibly lead to and determine the dimension of a glacial lake outburst (in our case in the CB) are evaluated for physical vulnerability (ie exposure), whereas social vulnerability (ie coping) is governed by factors that influence the community's capability to deal with such an event.

In the following sections, physical and social vulnerability are defined in more detail.

Physical vulnerability

Physical vulnerability describes the exposure of a place towards a possible event. This exposure depends on the hazard defined by the physical process (here a lake outburst), the magnitude, and the probability of such an event (Hunt 1984). Magnitude and outburst probability constitute the first two factors in the concept. Trajectory can have a de- or increasing effect on the event and represents a third factor (Reynolds Geo-Science Ltd 2003). Population density as a fourth factor locates the number of people possibly affected (as a demographic aspect, this factor may seem to fit rather into social vulnerability; however, it does not influence people's capability to cope with the event).

To evaluate the complex factors of physical vulnerability, several indicators are introduced below for each factor.

Lake outburst probability

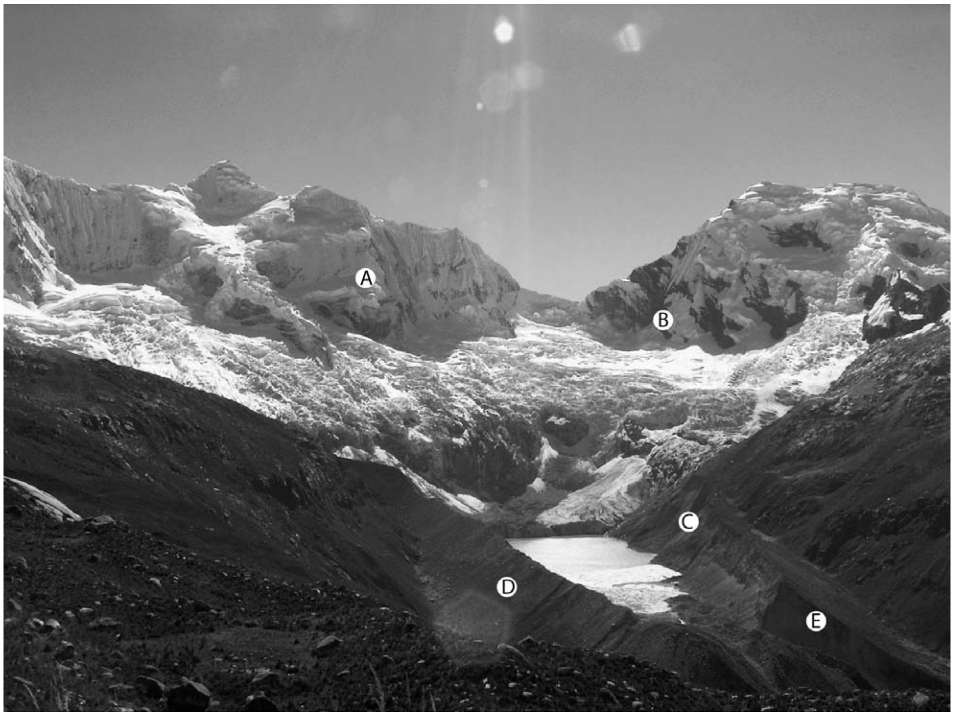
The probability of a flood event occurring is usually deduced from its frequency or return period (Van Steijn 1996; Zimmermann et al 1997). Since lake outbursts often are one-time events and because of the changing hazard due to continuing glacier shrinkage, other methods have to be applied to estimate the probability of lake outburst (Huggel et al 2004; McKillop 2007).

Two variables are crucial for the assessment of lake outburst probability: first, the probability of a trigger that may provoke a lake outburst; and second, the dam characteristics.

Lake outbursts are usually the consequence of a chain reaction. For instance, an impact wave produced by mass movement into the lake can erode the dam, leading to dam breakage and to partial or total emptying of the lake (Reynolds 1992; Clague and Evans 2000; Richardson and Reynolds 2000). Ice avalanches (Figure 2A), debris flows, rock fall (Figure 2B), or landslides (Figure 2C) may act as triggers, as well as sudden water influx due to extreme weather events (Huggel et al 2004) or outbursts of lakes located upstream. In this case study, ice avalanches, rock falls, moraine slides, and sudden water influxes were found to be potential triggers.

The dam characteristics essentially influence outburst probability. Material, geometry, freeboard, and

FIGURE 2 Lake Palcacocha dammed by a large Little Ice Age moraine. In the background Mt Palcaraju (left, 6274 m asl) and Mt Pucaranra (6156 m asl). Letters refer to lake outburst variables (see text). (Photo by E. Hegglin)



type of drainage play a major role in dam stability (Huggel et al 2004). Moraine dams (Figure 2D) are more problematic than rock dams because dam breakage caused by regressive erosion and breach building (Figure 2E) is possible. Geometry and freeboard influence the hydraulic gradient of the moraine, affecting dam stability. Dam infiltration may cause piping and increase outburst probability considerably (Haeberli et al 1989). Structural measures, a good number of which are found in the study area, are a risk reducing factor. Dam stabilizing measures and drainage tunnels are prevalent methods to reduce the risk posed by glacial lakes (Reynolds et al 1998; Haeberli et al 2001).

Based on these considerations, we defined the following variables to evaluate dam stability: dam material (rock or moraine), freeboard, geometry, drainage (subsurface or subaerial), and existing technical measures on the dam.

Flow magnitude

Magnitude includes maximum water discharge (Q_{max}) and the reach of the outburst flood expressed by the average gradient of the flow trajectory (α_{av}). Q_{max} heavily depends on lake volume. As a worst-case scenario, dam breach and complete lake emptying has to be assumed.

α_{av} of outburst floods is in relation to sediment concentration. For coarse-grained debris flows originating in moraines and talus slopes, a minimum α_{av} of 11° has been observed in the European Alps (Haeberli 1983; Huggel et al 2002). However, flows with low sediment concentration can reach an α_{av} of far below 11°. The Lake Palcacocha outburst flood of 1941, for instance, reached an α_{av} of 4°. In the Alps damage reach between 2 and 3° has been determined (Haeberli 1983).

To determine the extent of potential flooding, we used the modified single flow direction (MSF) model (Huggel et al 2003b), a non-dynamic GIS model providing a relative likelihood of inundation per grid cell. α_{av} is a key variable of this model, depending on lake volume and maximum discharge.

Flow trajectory

The flow trajectory can have an aggravating or diminishing effect on the flood, depending on incorporation or deposition of material, respectively. Material incorporation depends, inter alia, on inclination of the trajectory (Reynolds Geo-Science Ltd 2003; Huggel et al 2004), surface material (Reynolds Geo-Science Ltd 2003), and vegetation (Gray and Sotir 1996; Menashe 1998). As a fourth indicator, there are possible secondary effects to be observed. Water reservoirs in the flow path may increase the flood volume (as with the Palcacocha incident in 1941), and blockage can lead to a second outburst (Huggel et al 2003a; Vilímek et al 2005). Secondary landslides can be provoked by under-cut slopes (Cenderelli and Wohl 2003).

Population density

Population density provides an indication for the number of people possibly affected and related human loss.

Damage to infrastructure as well as economic consequences of an event have deliberately been left out in this study, which emphasizes people's vulnerability.

Social vulnerability

With the objective of determining the capability of the community to respond to and recover from a hazard event, we divided social vulnerability into 3 factors: preparedness, prevention, and response. As with physical vulnerability, indicators have to be introduced for measurability. The selection of factors and indicators was based on pertinent literature study, the local conditions in Huaraz, and the availability of corresponding data.

Preparedness

Preparedness refers to the state of being prepared, as an individual or a community, for a disaster. Preparedness of the community depends on preparatory measures taken by the authorities on the one hand, and by individuals on the other. The latter measures are mainly formed by socioeconomic structures.

Regarding state-organized preparedness we distinguish between:

- Early warning systems (EWS);
- Emergency plans;
- Insurance systems.

The following questions must be asked in the evaluation of each indicator: is it 1) existent? 2) effective? 3) known to people? 4) equally accessible to everybody?

Indicators for individual preparedness are:

- Awareness
- Age
- Poverty

Awareness in itself does not increase preparedness but forms its basis for people accepting laws and projects in connection with risk reduction (Weichselgartner 2002; Carey 2005). Age affects the ability for evacuation, meaning that children and elderly people are harder to evacuate and more susceptible to diseases (Penning-Rowsell and Fordham 1994; Cutter et al 2000; Birkmann et al 2006; Wilbanks et al 2007). Poverty increases vulnerability in different ways: in case of house loss, there is no way of recovering; badly constructed houses are easily destroyed; marginalization leads to limited access to information and paradoxically often to lack of governmental assistance (Burton et al 1993; Dasgupta 1995; Cutter et al 2000). Although other indicators such as gender or ethnicity may also have an effect on preparedness, they were not considered here. This was due to a homogeneous population distribution among town quarters; moreover, it would have required a more in-depth investigation, which would have been beyond the scope of this study.

Prevention

Prevention refers to measures taken to avoid or minimize the adverse impacts of hazards and can be divided into structural and non-structural measures. Here, only structural measures of prevention are considered (prevention in connection with information and awareness is already included in the preparedness factor). Any existing prevention measures in and around the river channel have to be analyzed in terms of effectiveness. Urban planning is a very effective way of prevention in that the most exposed zones are barred from being populated (Weichselgartner 2002; Kienholz 2003).

Response

Response means the capability to recover from a natural disaster including immediate reaction after, and long-term coping with, such an event. Professionally organized and efficient rescue operations can drastically reduce the impact of a disaster. The time after the event until the rescuers arrive is crucial (Penning-Rowsell and Fordham 1994). Well-organized rescue as well as a sufficient number of appropriately trained rescuers are indispensable for fast and effective action.

Long-term assistance after the disaster—such as psychological aid and support in reconstruction—facilitates the return to daily life (Parker and Handmer 1992; Penning-Rowsell and Fordham 1994). If reconstruction is left entirely to the people affected, it is once more the poor who suffer most.

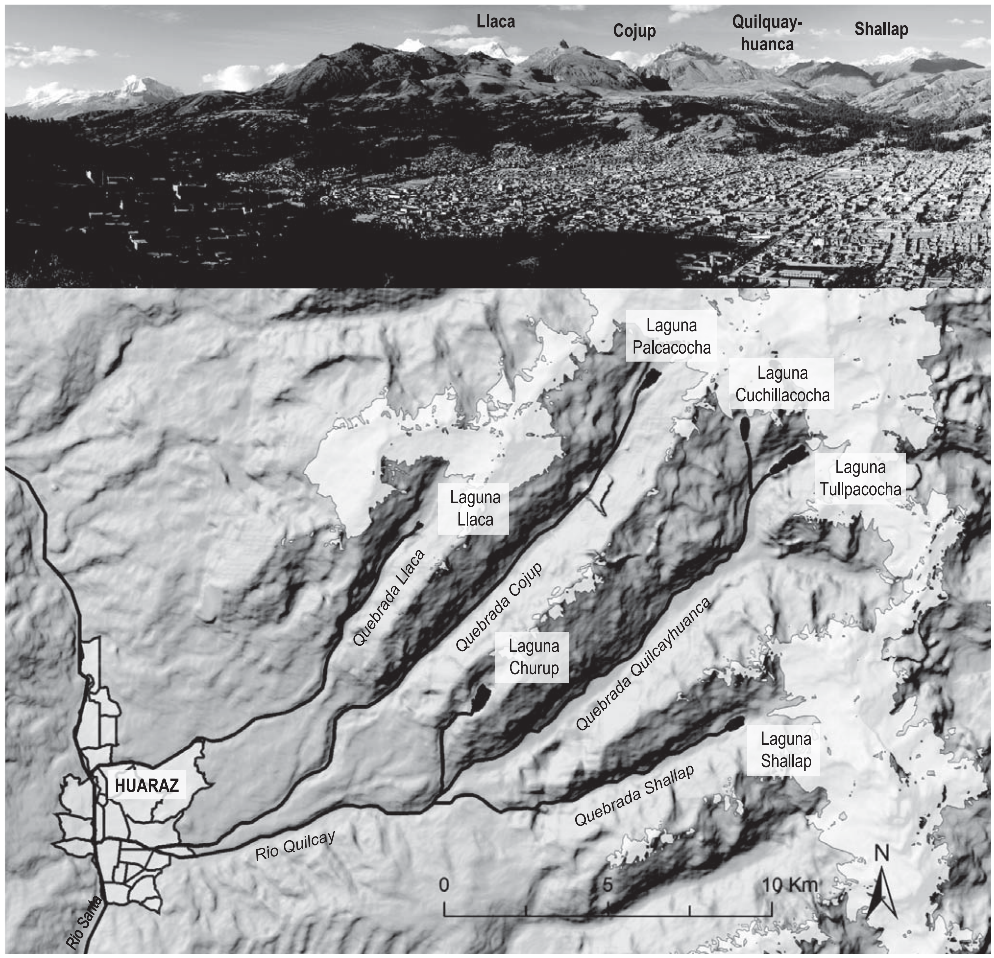
Applying the approach in the Cordillera Blanca

In the following sections, we describe the application of the integrated vulnerability concept to Huaraz and lake outburst flood hazards posed by Lake Palcacocha. Huaraz is the major town in the CB, with over 100,000 inhabitants (Figure 3). Five moraine-dammed glacial lakes drain through Huaraz. Lake Palcacocha, situated 20 km above the town, became famous when its 1941 outburst flood destroyed a third of Huaraz and killed around 5000 people (Carey 2005). The current situation of the lake continues to cause concern (Vilímek et al 2005).

Data

Lake measurement and digital elevation model (DEM, 30-m ground resolution) creation were achieved using a 2002 ASTER satellite image with a 15-m resolution. The DEM was used for modeling the outburst flood. The resolution is not completely satisfactory for our study, but alternatives are currently not available. The limitation of the topographic data has to be taken into account when interpreting the model outputs and the vulnerability maps.

FIGURE 3 A view of Huaraz with glacial valleys (top), and map of the proglacial lakes and the corresponding river systems. (Photo and map by E. Hegglin)



Fieldwork was necessary for the assessment of outburst probability as well as for the evaluation of trajectory. Lake volumes were determined by bathymetric surveys performed by the National Institute of Natural Resources (INRENA) and ASTER satellite images.

The population census of 1993 was consulted for sociodemographic data per town quarter (more recent censuses were not yet available at the time of this study). Ten semi-structured interviews with technical experts in the local administration were conducted; these were essential for the evaluation of social vulnerability (Hegglin 2006). The town map of the municipality provided the spatial basis for the vulnerability map.

Operationalization

The crux of the concept implementation presented in this article is the operationalization of the factors and indicators, ie how to make vulnerability measurable. In order to map vulnerability, two delicate aspects need to be overcome: the first one concerns valuation of each indicator by giving scores in order to make them measurable in a quantitative way. The second difficulty is the combination of these scores. Three classes of scores were assigned by experts to each indicator, 0–2 for low, medium, and high. More classes would enable more accurate valuation of the indicators, but would also make the following combination of indicators and factors highly intricate and intransparent, both mathematically and conceptually. The factors are calculated by combining the indicators, while both physical and social vulnerability is obtained by combining the factors. Finally, the two vulnerabilities are merged in an integrated vulnerability map. Comprehensibility and reproducibility have to be taken into account when creating a vulnerability map. After all, not only the location and the degree of vulnerability is of interest, but also the reason why a place is vulnerable.

Physical vulnerability

Outburst probability

Outburst probability is calculated by adding up the triggers and dam characteristics. Various methods of combination

TABLE 1 Lake volume classes and the assigned minimum α_{av} for outburst floods based on empirical data from the European Alps, Himalayas, and Andes. (Source: Personal communication A. Ames; Huggel et al 2002; Hegglin 2006)

Lake volume	Minimum α_{av} for outburst floods
> 1 million m^3	3°
0.5 – 1 million m^3	5°
0.1 – 0.5 million m^3	6°
0.02 – 0.1 million m^3	8°
< 0.02 million m^3	not considered

were empirically tested, and addition turned out to be most transparent (Hegglin 2006). Lake Palcacocha's current outburst probability score reached 2 (= high probability).

Magnitude
Based on glacial lake outburst flood events from the Alps, Himalayas, and Andes (personal communication A. Ames; Huggel et al 2003b; Hegglin 2006), a relation between lake volume and corresponding α_{av} was established. Table 1 summarizes the empirical findings supporting the relation.

Palcacocha figures in the highest range with its current 3 million m^3, which means that an outburst would reach Huaraz with the given minimal α_{av} of 3° (Table 1). The output of the MSF model (ie the potentially flood-affected areas with related probability) was divided into 3 classes (0–2). The points of outburst probability were then added (Figure 4).

Trajectory
According to its characteristics, the trajectory was evaluated as decreasing (–1), neutral (0), or increasing (1) the effect of the flood. The trajectory of Palcacocha—Cojup valley—was rated neutral and therefore 0 points were added to the outburst model (Figure 4).

Population density
Population density was analyzed for the 28 quarters of Huaraz by calculating the area per person, and assigning it to 3 density classes (0–2). The population density map and the modeled outburst flood including outburst probability and the trajectory's characteristics were overlaid to obtain the map of physical vulnerability (Figure 4).

Social vulnerability

Preparedness
Due to limitations of available data, the mapping unit of social vulnerability was at the level of Huaraz town quarters. Poverty was mapped according to the NBI method (Basic Unsatisfied Needs, see FONCODES 2003). Persons below 15 years and above 64 years were considered as a vulnerable-age group, and its percentage of the population was assessed per quarter. Both poverty and age maps show 3 classes, with 0 for low and 2 for high vulnerability.

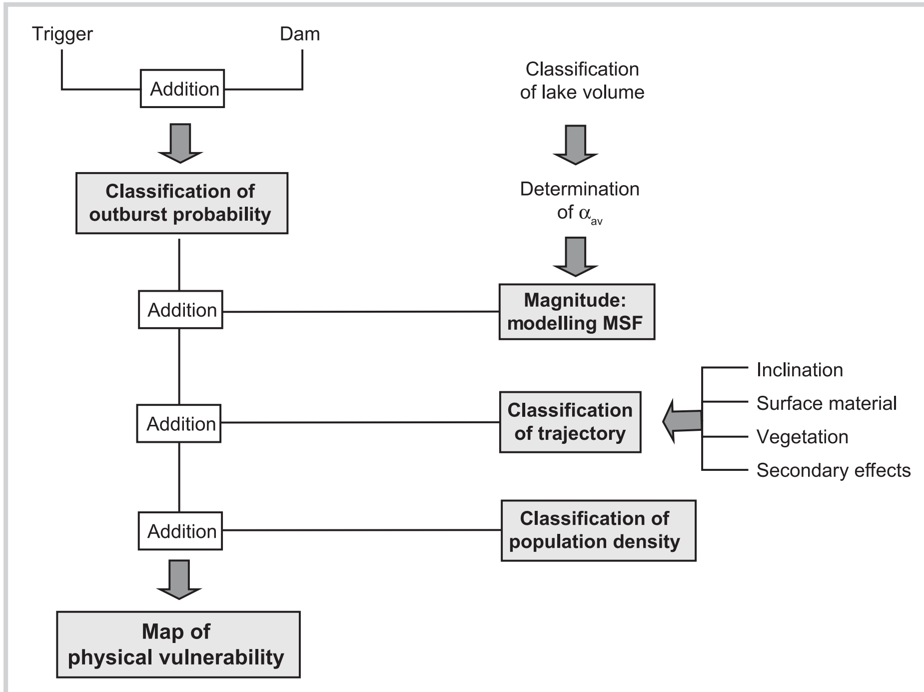
Poverty and age increase vulnerability whereas awareness as well as state-organized preparedness measures such as EWS, emergency plans, and insurance systems may reduce vulnerability (Figure 5). Accordingly, a score from 0 to –1 was chosen for these aspects where 0 means no reduction of vulnerability and –1 means effective measures and high awareness and correspondingly a reduction of vulnerability. People's awareness in Huaraz is rather contradictory. On the one hand, various severe disasters in connection with glaciers in the last century have raised people's awareness, on the other hand, there is a serious lack of faith in the information from government and scientists due to unfortunate experiences in the past (Carey 2005; Huggel et al 2008). Based on that and also on results from interviews, a medium score of –0.5 was attributed for awareness. EWS and social insurance do not exist (score: 0) while emergency plans exist but are scarcely known to people (score: –0.5). The indicators were summed up and reclassified to create the preparedness map with 3 classes.

Prevention
Huaraz lacks measures of structural prevention and urban planning, which leads to a score of 2 for prevention (no prevention, high vulnerability). Urban planning exists on paper but is not implemented.

Response
The evaluation of this factor was mainly based on expert interviews. Indicators such as the existence and implementation of emergency procedures for rescuers, rescue capacities, distance to the nearest hospital and its capacity, as well as the organization of reconstruction had to be analyzed carefully. Moreover, response to the small outburst flood from Palcacocha in 2003 gave an impression of rescue organization (personal communication E. Ramírez; Carey 2005). The overall assessment of response resulted in a medium score of 1 due to complicated and intransparent rescue organization, nearby but limited hospital facilities, and missing organization of reconstruction.

To obtain the social vulnerability map, the factors were averaged (Figure 5). The integrated vulnerability map (Figure 6) eventually resulted from overlaying the physical and social vulnerability maps. Based on empirical tests, we found that a reclassification of the maps in 3 classes before combining them provided the most comprehensible outcome, in particular for non-expert people, governmental authorities, etc. The combination was then calculated by averaging, resulting in 4 integrated vulnerability classes (low, medium, high, very high).

FIGURE 4 Flowchart outlining the steps from indicators and factors towards the map of physical vulnerability, with α_{av} = average gradient of the flow trajectory and MSF = modified single flow direction. For factors and indicators, also compare Figure 1.



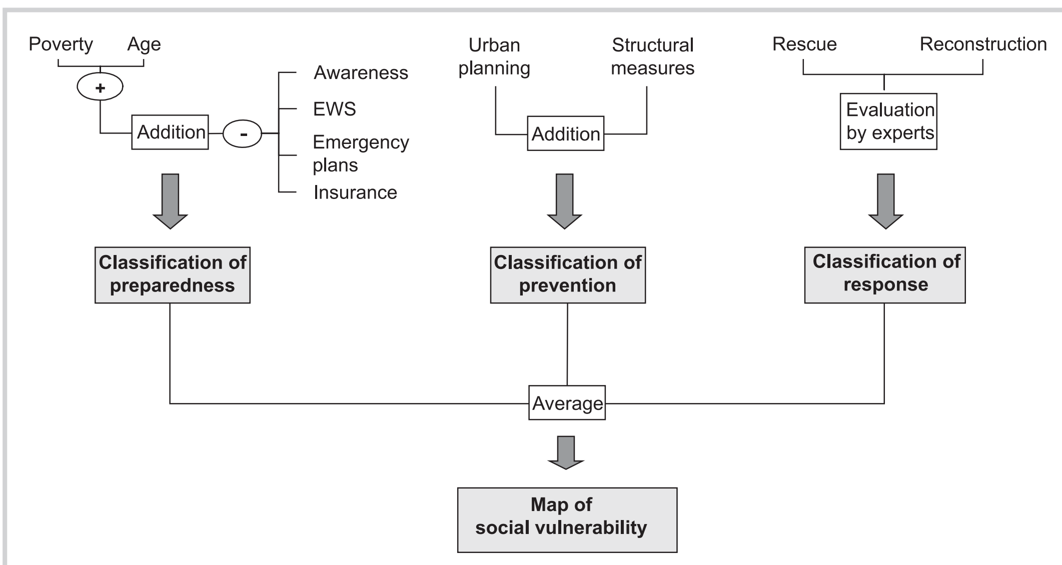


FIGURE 5 Flowchart outlining the steps from indicators and factors towards the map of social vulnerability, with EWS = early warning system. For factors and indicators, also compare Figure 1.

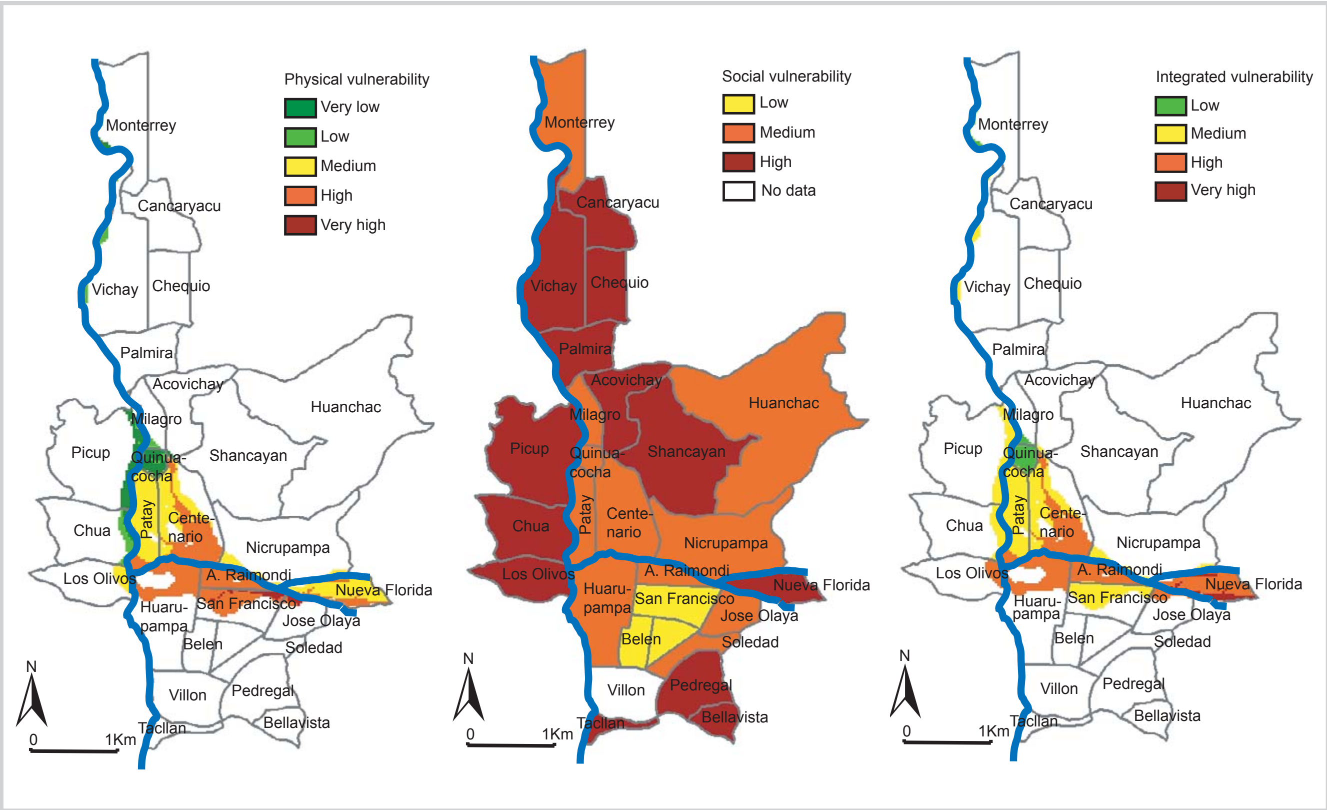
Discussion

Method: operationalizing vulnerability

Operationalizing vulnerability requires simplification of the complex theory and analysis of vulnerability. This is particularly true for social vulnerability, which is related to priorities and possibilities, and thus to people's perceptions. The concept presented here can account for these circumstances only in a limited way because it is constrained to a number of indicators. Although beyond the scope of the present study, the subject could benefit from a more in-depth examination of the relations among the indicators and the respective social institutions. This would require extensive research into local perceptions based on a sample large enough to be representative.

A main challenge with regard to operationalizing vulnerability is the transformation of qualitative to quantitative variables, which inevitably leads to a loss of information, but this is necessary to bring the socioeconomic data into congruence with the physical data. The strength of the method lies in the evolution of an integrated concept for vulnerability evaluation. While there are various studies on the evaluation of the physical hazards (ie lake outburst hazards), there is a lack of practical suggestions as to how to quantitatively meas-

FIGURE 6 Vulnerability maps of Huaraz: the combination of the map of physical vulnerability (left) and the map of social vulnerability (middle) results in a map of integrated vulnerability to Lake Palcacocha outburst floods (right). (Maps by E. Hegglin)



ure social vulnerability. Quantification is required for the sake of reproduction, objectivity, and comprehensibility. Our method is a first step towards measuring integrated vulnerability and could be extended both conceptually and thematically.

The method presented here is designed according to scales and conditions in the CB. Application in other areas (geographically and thematically) requires the classification to be adapted to specific local characteristics and data availability.

Results: strategies for vulnerability reduction

In Huaraz, high vulnerability is found around the river Quilcay (Figure 6). To take effective measures for vulnerability reduction, the underlying causes in highly vulnerable zones have to be analyzed: the town center is likely to be affected by a potential Palcacocha lake outburst and at the same time it shows very high population density, which results in high physical vulnerability. In addition to population density, the alleyways of the Antonio Raimondi quarter around the town center are daily crowded due to a street market (not included in map).

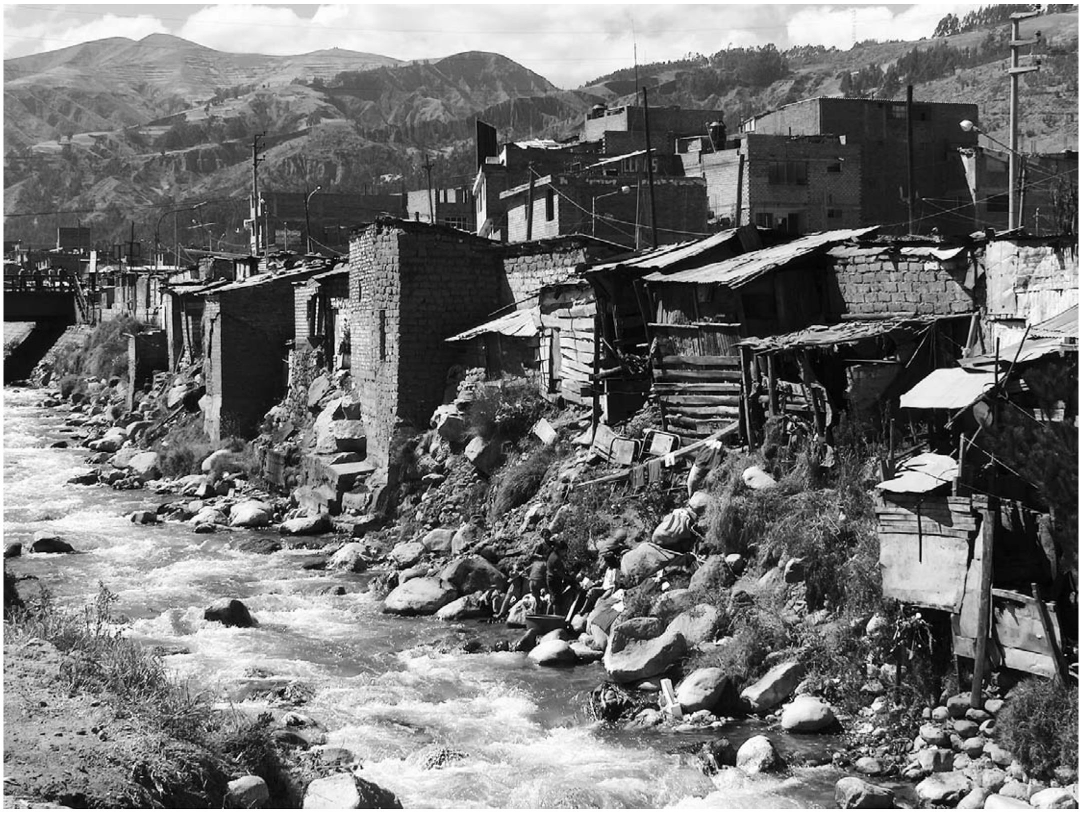
Social vulnerability in Huaraz ranges from middle to high, with persistently missing prevention, deficient response, and lack of state-organized preparedness, while individual preparedness varies depending on poverty, age, and awareness. Concerning integrated vulnerability, the most vulnerable areas are found where exposure, high population density, poverty, and vulnerable age coincide.

Vulnerability reduction, hence, should focus on strengthening these weak aspects. Improved urban planning could avoid the coincidence of exposure and high population density. However, given the current situation in Huaraz, people would have to be relocated, which is hardly practicable in reality (Carey 2008). By implementing urban planning in the future, construction of further dwellings in the most hazard-prone zones could be prohibited. However, implementing risk zones requires understanding, acceptance, and involvement of the people affected and, thus, appropriate awareness, education, and training measures (Figure 7). Deployment of an EWS—another possible measure to reduce vulnerability in Huaraz—would equally need to be accompanied by information dissemination and thus involvement of the local people.

Difficulties: limitations of implementation

Taking actions based on the findings of this study is constrained by a number of institutional, political, and economic limitations. The interest of the regional government in this topic is limited. Investments in prevention of, and preparedness for, such events do not entail obvious benefits for politicians. The risk of a glacial lake outburst disaster is difficult to assess quantitatively, and exact predictions are impossible, which makes

FIGURE 7 Huaraz town center with poorly constructed houses and people laundering exposed to possible hazards from the river Quilcay draining Lake Palcacocha in Huaraz. (Photo by E. Hegglin)



measures seem less urgent in view of a series of other problems faced by a developing country such as Peru. However, this is not a phenomenon observed only in developing countries. There are various examples in the Alps and other developed countries where the imminent risk was ignored (Zimmermann 2004). Furthermore, the local government in Huaraz is not interested in informing the inhabitants of potentially affected areas since this would lead to the inevitable question of why the government had not informed the inhabitants earlier or actively taken measures to protect them.

People's lack of faith in government and scientists represents another obstacle for the implementation of vulnerability reduction measures (Carey 2005). In a first step people's trust—lost after unfortunate experiences in the past—has to be regained to successfully undertake measures and disseminate information. The latter is a delicate matter and has to be done carefully. People's prevailing low level of awareness together with inadequate information results in a critical combination. However, this should not be an excuse to abandon activities. Scientists and government authorities have to work in a coordinated way and seek the dialogue with citizens.

Conclusions

The CB is a region repeatedly hit and continuously threatened by glacial lake outburst disasters, due to the existing hazards on the one hand and the growing population living close to the high mountains on the other hand.

The term vulnerability is widely discussed today and defined in different ways. In this study we refer to vulnerability as a function of people's exposure and coping capacity. The objective was to develop a concept of integrated vulnerability, capturing and combining the different factors in a transparent and comprehensible way, and therefore making it applicable to other regions. For implementation to other regions the concept has to be adapted to the local characteristics and data availability, especially regarding social vulnerability as the operationalization of the factors and their combination was developed according to the conditions found in the CB.

The method developed allowed us to assess the integrated vulnerability and to provide a basis for vulnerability reduction. The vulnerability map identifies the most vulnerable parts of Huaraz. Given the limited resources, reduction of vulnerability is best prioritized based on the analysis of causes underlying high vulnerability. For Huaraz it was observed that high exposure coincides with high population density. Social vulnerability ranges from middle to high for the whole city of Huaraz. Our study shows that social and total vulnerability could be reduced a great deal by instituting measures such as urban planning and EWS, and by educating people about risks of glacial hazards. In the context of the CB, however, strengthening the dialogue between authorities, scientists, and the local community is a necessary first step towards building people's trust.

In further studies the transferability of the concept to other areas (geographically and thematically) should be tested. Comparative studies would contribute to improving the method and therefore facilitate future vulnerability assessments.

Integrated vulnerability assessments offer developing countries a chance to effectively invest the limited available resources earmarked for natural disasters. This study, for instance, has demonstrated qualitatively, quantitatively, and objectively that vulnerability reduction measures such as urban planning or information dissemination can be an effective low-cost alternative to expensive technical mitigation structures.

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