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The Share of Landslides in the Occurrence of Natural Hazards and the Signifance of El Niño in the Cordillera Blanca and Cordillera Negra Mountains, Peru

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Abstract

Various types of natural hazards are often compared, in terms of danger or frequency of recurrence. Such analyses are, among other things, influenced by the character and quality of the database used. The Peruvian DesInventar database is homogenous and, thus, serves as a useful tool for describing the significance of landslides and evaluating the role of the El Niño Effect among different causes of catastrophes. During the 1971–2009 period, the most frequent type of natural hazard in the Ancash Department was alluvion (a local term for debris flow), followed by floods and extreme rainfall. If we group various forms of mass movement together, they comprise a dominant portion among natural hazards. A major portion of natural hazards are generated by the direct impacts of extreme hydrometeorological events. Considering the influence of El Niño episodes, it is important to emphasize the fact that 41% of all catastrophes caused by extreme weather, during the observed period, were generated by this phenomenon. This research was conducted within the framework of IPL Project M 129 (Evaluation of natural hazards associated with rapid glacial retreat in Cordillera Blanca, Peru) and the World Centre of Excellence on Landslide Risk Reduction, registered in the Czech Republic (Landslide field research and capacity building through international collaboration). Financial support was provided by the Ministry of Education, Youth and Sports of the Czech Republic, project no. MSM0021620831 "Geographic Systems and Risk Processes in the Context of Global Change and European Integration".

Keywords

Natural hazards, Landslides, El Niño, Cordillera Blanca and Negra, Peru

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Figure 9.1 Huascaran Mt. has been the source of several rock and ice falls (e.g. 1962, 1970). A much larger prehistoric event was recently studied in this area. (Photo by V. Vilímek)

9.1 Introduction

This paper's primary objective is to evaluate the role of landslides in the context of other natural hazards in a specific area – the Ancash Department, with cooperation between the IPL project and the WCoE. The paper also explores the influence of El Niño on landslide activity and, finally, compares various types of landslides, in a search for the most typical landslide type.

Due to the fact that natural hazards play an increasingly important role in society, it seems necessary to not only study recent processes, but also to look into history – to evaluate databases of natural hazards. Vilímek and Spilková (2009) discuss connections between natural and social sciences, in general and Blahůt and Klimeš (2011) contributed to the terminology in landslide risk studies. The Ancash region has been influenced by natural hazards for a very long time. The most important reason behind this is the orogenic activity of the area; climate change and increasing population pressure play important roles as well. For these reasons, we decided to use the Peruvian DesInventar database to compare various types of natural hazards. Vilimek et al. (2010) provide a detailed description of the role of WCoE (World Centres of Excellence) in international collaboration in Cordillera Blanca.

9.1.1 Description of the area

The Cordillera Blanca and Cordillera Negra Mountains in northwest Peru are part of the Cordillera Occidental mountain system. In terms of the administrative division of the country, upon which natural hazard registers are based, this area is in the Ancash Department, with the capital of Huaraz. This town is situated in the Santa River Valley (Calleyon de Huaylas), which separates two mountain ranges – the higher Cordillera Blanca (Huascarán, 6,768 m a.s.l.) and the lower Cordillera Negra (Pico Rocarre, 5,187 m a.s.l.).

The two mountain ranges have differing geological structures and are thus predisposed to different types of mass movement. Cordillera Blanca's core is

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Editor's or typesetter's annotations (will be removed before the final TEX run) composed of medium to late Tertiary granites and granodiorites, which have penetrated into the Tertiary sedimentary "Calipuy" formation and into sediments from Upper Jurassic to Upper Cretaceous ages. The above-mentioned formations are discordantly covered by a series called "Lloclla", composed of fluvio-glacial and lacustrine sediments (e.g. Bonnot 1984). Rockfalls are characteristic of the high mountain areas; however, in the foothills, there is greater variety among mass movements (different forms of flows and slides). Cordillera Negra has a relatively diverse composition, in which volcanic sediments (rhyolites, andesites) predominate.

In both mountain ranges, natural hazards have primarily been studied with regard to the occurrence of extreme events, the most famous and most catastrophic of these being ice and rockfall (Fig. 1) from the northern summit of Huascarán (e.g. Ericksen and Plafker, 1970; Plafker et al., 1971; Klimeš et al., 2009). Zapata (2002) published a survey of natural hazards that occurred between 1702 and 1997. Atkins (2005 ed.) provides more recent data, up to 2003. With the ongoing retreat of glaciers, recent attention, e.g. Zapata et al. (2003) and Vilímek et al. (2005), has focused on glacial lake outburst floods. Considering the area's recent history, a huge catastrophic event of this type occurred in 1941, when the natural dam of Palcacocha Lake burst and about 5000 inhabitants of the town of Huaraz died.

The Ancash Department, to which the DesInventar database used is related, is one of 25 such departments in Peru. It is a coastal region transected by the two above-mentioned mountain ranges of the Cordillera Occidental. Ancash Department is politically divided into 20 provinces and 166 districts, for which the DesInventar database collects data. Over one million inhabitants live in the department's area of nearly 36,000 km^2. They live on the coast (at the mouth of rivers flowing into the Pacific Ocean) and in mountain valleys, which are prone to many problems with mass movement.

9.1.2 ENSO

ENSO has become a standard abbreviation for El Niño – Southern Oscillation, a complex system of atmospheric and ocean current processes in the tropical Pacific region, with insufficiently understood links to the behaviour of the atmosphere and hydrosphere in other parts of the world. Atmospheric and oceanic phenomena interact with one another and are mutually influenced. They have a quasi-periodic character. Scientific knowledge concerning ENSO has seen considerable progress recently, with many significant findings coming to light during the last two decades (e.g. Philander, 1990; Brázdil and Bíl 1998; Barry and Chorley, 2003).

El Niño "proper" has been observed and monitored for the longest time. It describes the occasional weakening or absence of the cold Peruvian current (also known as the Humboldt Current) which normally flows along the coasts of Chile, Peru and Ecuador towards the equator. The current's low temperature is maintained by upwelling, i.e. the rising of deeper colder water towards the surface. This is due to the fact that trade winds, airflows from the South American continent, drive the surface water away from the coast and cold water from the depths compensates for this decrease in volume.

A decrease in the energy of these trade winds causes a decrease in the intensity of upwelling and an increase in the temperature of surface water along the South American coast. In some cases, even very warm water from the equator can make its way to the Ecuadorian and Peruvian coast. The warming of water along the coast results in intensive atmospheric convection and the generation of convection clouds, which lead to heavy and intensive atmospheric precipitation in the coastal belt of Ecuador and Peru. This is an area that is normally very dry and the torrential El Niño rains result in flooding, erosion, landslides and other harmful manifestations.

The name El Niño (child of God, small Jesus) is likely a reflection of the fact that the phenomenon often begins at Christmastime. El Niño occurs with a varying periodicity. The time interval between two occurrences of this phenomenon generally oscillates between two and seven years, but exceptional intervals, i.e. eleven years have been recorded (Table 9.1). The duration of El Niño is also subject to great variability from several months to approximately two years. The most frequent duration of El Niño is about one year. Considering a long-term perspective, El Niño occurs in approximately 25% of all years and is absent in 75% of the same years. Consequently, some authors consider El Niño to be an anomaly; however, we find this inappropriate. An anomaly is a variation from a normal state and El Niño is a quite normal phenomenon in the area of

Table 9.1 The most important manifestations of El Niño since the middle of the 19th century (after Kuroiwa, 2004)

Intensity	Year/period
Feeble	1885, 1889, 1923, 1930–32, 1960, 1963
Mean	1911, 1918, 1921, 1939, 1964–65, 1986–87, 1991–92, 1994, 2002–03, 2009–10
Strong	1856, 1940–41, 1953, 1957–58, 1972–73
Very strong	1891, 1925–26
Extreme	1982–83, 1997–98

its occurrence. It is a characteristic part of the local climate and of the regime of local oceanic conditions.

If El Niño is caused by decreased energy of the trade winds, we are led to ask: what is the cause of this change in the trade winds, the strongest part of planetary atmospheric circulation? Meteorologists and climatologists would love to better understand this. Some have attempted to explain it hypothetically, but, as of now, no definite answer to this question has been given.

In the 1920s, G.T. Walker (in Philander, 1990) discovered that a decrease in air pressure in the anticyclone of the southeast Pacific (one of the so-called action centres of the atmosphere) is regularly accompanied by increased air pressure in a large area to the west of this anticyclone. This oscillation of air pressure with an opposite phase in two parts of the southern Pacific Ocean is called the Southern Oscillation. The difference between the air pressure in Tahiti, i.e. in the central Pacific Ocean, and in Darwin in northern Australia, is a commonly used index monitoring the southern oscillation. Air pressure is generally, with the exception of El Niño periods, higher in Tahiti; during an El Niño period, however, it is higher in Darwin. Air pressure oscillation above the South Pacific is closely related to variations in water surface temperatures in different parts of the tropical Pacific.

We now know that El Niño, along the South American coast, is only one part of broader atmospheric and oceanic processes involving the entire tropical Pacific. These include periodic changes in air pressure which shift in phase above different parts of the ocean, so that the size and direction of the horizontal pressure gradient in the atmosphere also changes periodically. Periodic changes in water temperature at the surface can also be observed, as well as changes in ocean level and changes in the depth of the thermocline, a thin layer within a body of water wherein temperature changes rapidly with depth.

During periods without El Niño, the water level in the western reaches of the tropical Pacific is several decimetres higher than at the South American coast, as a consequence of the strong trade winds. The South American coast is dry, while Indonesia receives abundant rain.

In contrast, during El Niño periods, the islands of Indonesia are subject to drought and large-scale forest fires, while the South American coast is affected by catastrophes resulting from torrential rains. The mean ocean level at the South American coast is higher, during an El Niño period, while mean ocean level is below average to the north of Australia.

Only recently (since the 1990s), the term La Niña, proposed by the American Philander, has been used to describe a state of the atmosphere and the ocean that is directly opposite to El Niño, i.e. the period between two El Niños.

9.2 Methods

In the analysis that follows we consider natural hazards to be any and all events caused by endogenous or exogenous processes that result in damage to the population (according to DesInventar – deaths, injuries, missing persons, evacuations, migrations) or physical damage to private or public property (destroyed and damaged human dwellings, industrial and agricultural buildings and equipment, or technical, transport and public infrastructure). Our analysis focuses on the period from 1971 to 2009.

The DesInventar statistics do not consider earthquakes to be a separate cause of natural hazards and group them together with “other” causes. This makes it relatively difficult to determine which catastrophic events were caused by earthquakes. The share of earthquakes in the total occurrence of certain types of hazards, including mass movements, cannot, therefore, be determined with precision. If we want to know the precise share of hazards caused by the ENSO phenomenon out of the total number of climatically conditioned hazards, we must know the specific causes of each of the catastrophic events that occurred (Hanzlík 2007). Some hazards in the database are accompanied with a brief description of the cause of their occurrence. These are primarily catastrophic events, the causality of which can be to a certain degree measured, documented or simply recognized by the general public which, incidently, informs relevant bodies and institutions participating in the compilation of this database about such catastrophies. These causes include atmospheric precipitation, which is the primary factor behind inundations, flash floods, alluvions (debris flows), landslides and avalanches (i.e. the majority of natural hazards occurring in the area). In light of the large variety of hazards accompanying El Niño, a significant portion of catastrophic events are undoubtedly caused by El Niño.

9.3 Results

9.3.1 Occurrence of natural hazards in the Ancash Department

During the nearly forty-year period between January 1971 and December 2009, 914 natural hazards occurred in the Ancash Department, which translates to an average of two events per month. From a total number of 12,548 recorded catastrophies that occurred during the same period throughout all of Peru, 7.28% were in Ancash. Figure 9.2, which compares the frequency of natural hazard occurrence in all of Peru's 25 departments, clearly shows that Ancash ranks, in terms of the occurrence of natural hazards, among the six most risky Peruvian departments. Combined, the departments of Junín, Lima, Cusco, Arequipa, Piura and Ancash account for more than half of all the recorded events in Peru. The high amount of hazards in the Lima Department is connected with the region's high population density and with its high concentration of economic activities, both of which lead to increased hazard vulnerability. The majority of Peru's natural hazards are concentrated in coastal areas and in the Cordillera Occidental mountain system (also in the Cordillera Central in southern Peru). Moving inland, the quantity of natural hazard events decreases significantly (and/or such events are less frequently registered). This decrease in the frequency of natural hazard occurrence from the Pacific coast to the country's interior (west-east direction) is caused by many factors. These include, for instance, the decreasing intensity of the ocean's extreme climatic effects – especially ENSO – and the decreasing impact of subduction earthquakes. The depths of the hypocentres of subduction earthquakes in Peru increase from west to east and, consequently, their intensity (I_o) generally decreases as well. In coastal departments, a similar decrease in hazards can be observed in a north-south direction. This is caused exclusively by the decreasing intensity of El Niño (Hanzlík, 2007).

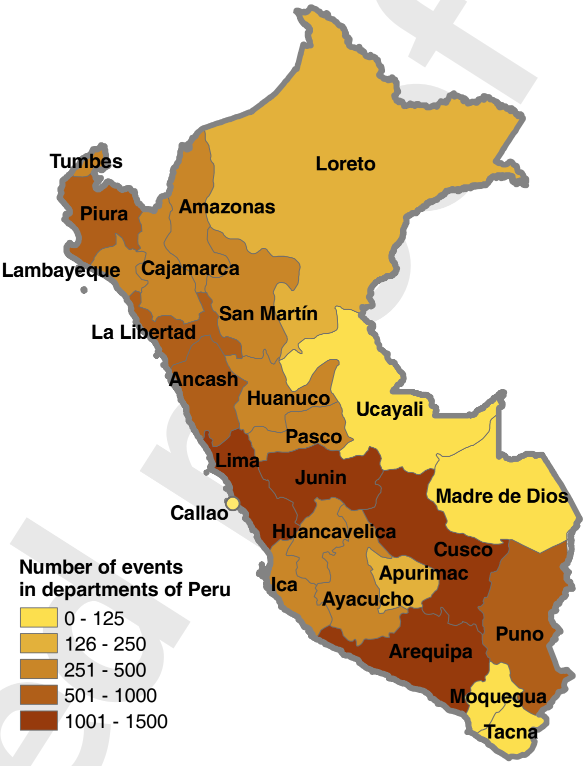

Figure 9.2 The spatial distribution of natural hazard occurrence in Peru's departments during the 1971–2000 period (data from DesInventar): Amazonas (261), Ancash (914), Apurimac (210), Arequipa (1151), Ayacucho (394), Cajamarca (329), Prov. Constitucional del Callao (106), Cusco (1091), Huancavelica (324), Huanuco (371), Ica (453), Junin (1446), La Libertad (561), Lambayeque (353), Lima (1406), Loreto (216), Madre de Dios (96), Moquegua (124), Pasco (304), Piura (963), Puno (584), San Martín (253), Tacna (123), Tumbes (392), Ucayali (113)

Alluvions (a local term for debris flow) are most prevalent among the natural hazards which affected the Ancash Department in this period, representing more than one fourth of all occurrences, i.e. 262 events. Figure 9.3 shows that, in addition to alluvions, the Ancash Department is frequently affected by floods (226), landslides (107), avalanches (30) and earth-

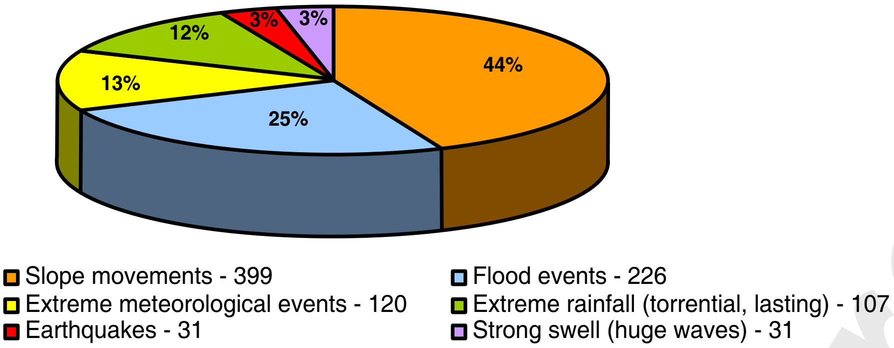

Figure 9.3 Occurrence and relative frequency of natural hazards by type in the Ancash Department during the 1971–2009 period (Data by DesInventar)

Figure 9.4 Intensive erosion and landsliding at the slopes of Callejon de Huaylas (close to Huaraz). These are typical processes after intensive rains (Photo by V. Vilímek)

quakes (31). Similarly, another database, i.e. a survey of civil-defence emergencies indirectly confirms the dominant share of slope movements among natural hazards recorded between 1995 and 2005 (authors of Defensa Civil, 2005). This source reported a total of 95 mass movements (floods were the second most frequent natural hazard reported).

According to data for lower administrative units, floods are concentrated in the coastal provinces (Santa, Casma, Huarmey) and in the river valleys of the Santa (Huaraz, Recuay) and the Pativilca Rivers (Bolognesi). The highest occurrence of mass movements was registered in provinces in part of the Santa River basin (Callejón de Huaylash) between the Cordillera Blanca and Cordillera Negra mountain ranges (particularly in Huaraz, Huaylas, Carhuaz and Yungay). This is due to the relatively steep slopes and the fact that the majority of the inhabitants of high mountain provinces live in these areas. The highest number of earthquakes affected areas in the regional fault belt, in the provinces of Callejón de Huaylash and in the coastal area immediately affected by the subduction zone of the Peru-Chile Trench, i.e. the provinces of Casma and Santa. The Ancash Department is also largely affected by various extreme hydrometeorologic events, the most frequent being extreme rainfall (107) in the form of lasting or torrential rains. Precipitation accumulated in the rainy period, lasting roughly from November to April, is connected primarily with the provinces in the Cordillera Blanca and Negra Mountains (Fig. 9.4). Precipitation accompanying El Niño also extends into coastal provinces. The area is affected by a large number of extreme meteorological events (120) with a relative frequency between 0.33–3.39% (see Table 9.2). The low frequency of each of these phenomena makes any correct statistical interpretion of their geographical distribution within the department difficult if not impossible.

9.3.2 Natural hazards caused by exceptional weather conditions, including ENSO

The values of cumulative relative frequencies, presented in Table 9.2, show that the five most frequent hazards, i.e. alluvions, floods, extreme meteorological events, landslides and extreme rainfall, make up more than 88% of all events from the 1971–2009 period.

With the exception of earthquakes (relative frequency 3.39%) and the negligible number of mass movements caused directly by seismic activities or by anthropogenic factors, the vast majority of these events are caused by the direct impacts of weather. Among the other natural hazards included in the database that exhibit a lower relative frequency, flash floods and avalanches are also directly related with the weather. As with mass movements, a negligible quantity of such events can be caused by factors other than the weather.

To begin to comprehend the number of hazards caused by the ENSO phenomenon and their share within the total number of hazards conditioned by extraordinary meteorological conditions, we must correlate the temporal distribution of the occurrence of such hazards (Fig. 9.5) and the temporal distribution of ENSO occurrence. Figure 9.6 best documents the occurrence in time and the intensity of ENSO in the Ancash Department, by displaying Sea Surface Temperature oscillation in the Niño $1 + 2$ region, i.e. in the region situated nearest to the Peruvian coast.

Comparing the values of both graphs confirms an increased frequency of hazards caused by extreme weather during ENSO, particularly during strong El Niño episodes. Extreme rainfall is responsible for an absolute majority of the most frequent natural hazards caused by exceptional climatic conditions, i.e. floods, flash floods, alluvions and landslides (e.g. recently Klimeš and Vilímek 2011 or from adjacent Cordillera Huayhuash, Engel et al. 2011) As shown by measurements at pluviometric stations in the Ancash Department, the highest rainfalls are registered exclusively during El Niño periods. Extreme atmospheric precipitation is, therefore, the main cause of the increased frequency of hazards during El Niño periods.

In contrast, extraordinary climatic events caused by La Niña are connected with a decrease in rainfall amounts and an associated increase in the risk of catastrophic droughts or fires. La Niña is also accompanied by certain extreme meteorological events, including extreme temperatures, severe frosts, snowstorms, etc. The relative frequencies of occurrence of these various La Niña-related hazards are so low that even their cumulative frequency, during certain episodes of this phenomenon, barely exceeds the average number of catastrophes occurring in the Ancash Department, during normal periods. Consequently, the resulting graph, presenting the temporal distribution of hazards initiated by hydrometeorologic extreme events during the 1971–2009 period, shows a proportional distribution of risks with three pronounced maxima during periods of strong El Niňo occurrence, in 1972/73, 1982/83 and 1997/98.

There was only a feeble El Niño in 1994, but many natural hazards occurred (see Fig. 9.5). This can be explained by an analysis of the frequencies, temporal and spatial distributions of hazards conditioned by uncommon weather during that year. According to DesInventar statistics, 71 natural hazards occurred in 1994; 90% of these were alluvions (31), floods (17) and landslides (16). All occurred in winter, i.e. in the rainy season, but a pronounced maximum is clear in March. The majority of hazards occurred in high mountain provinces. Earthquake statistics (IGP, 2001; NGDC, 2005) for these months do not register any more intense earthquakes. Similarly, there is no statistical information on any more significant anthropogenic factors. The above facts clearly indicate that the only possible cause for this increased frequency of hazards in 1994 was the abnormally intense rainy season (in addition to falling during the period of

Table 9.2 Frequency of natural hazard occurrence in the Ancash Department during the 1971–2009 period (prepared on the basis of DesInventar data, own calculations)

Type of natural hazard in Ancash	Frequency	Relative frequency (%)
Slope movements	*399*	*43.65*
Alluvions	262	28.67
Landslides	107	11.71
Avalanches (snow avalanches and rockfalls)	30	3.28
Flood events	*226*	*24.73*
Floods	212	23.19
Flash floods	14	1.53
Earthquakes	*31*	*3.39*
Extreme meteorological events	*120*	*13.13*
Drought	31	3.39
Storms with dangerous associated phenomena	29	3.17
Extremely low temperatures	21	2.30
Strong wind (storm)	19	2.08
Hailstorms	12	1.31
Snowstorms	5	0.55
Extremely high temperatures	3	0.33
Extreme rainfall (torrential, long-lasting)	*107*	*11.71*
Strong swell (huge waves)	*31*	*3.39*
In total	*914*	*100.00*

a feeble El Niño), which is connected with regular climatic oscillations. This is also verified by precipitation amounts at the Huaraz station, which, in 1994, were above long-term normal precipitation amounts, but did not reach the amounts registered during the strongest El Niño episodes.

The previous text documents a significant increase in the amount of hazards during El Niño, whereas the amount of hazards during La Niña periods remains within average frequency limits of hazards for normal years. The majority of catastrophic events occurring in normal years (i.e. in years without ENSO) are connected with extreme hydrometeorologic events, which occur in this area with the same frequency as in other areas of Peru. In the mountainous regions of Cordillera Blanca and Cordillera Negra, earthquakes (resulting from active tectonic uplift), flash floods (resulting from a sudden collapse of moraine dams caused by the overfilling of glacier lakes, due to the progressive melting of glaciers, see Fig. 9.7), ice falls and snow avalanches (resulting from permanent glaciation, etc.) are more frequent than in other territories (Hanzlík, 2007).

With a minimal statistical discrepancy, we can, therefore, claim that five strong El Niño episodes in 1972/73, 1982/83, 1986/87, 1991/92 and 1997/98 generated nearly half (41%) of all hazards, caused by extraordinary weather conditions and occurring in the Ancash Department from 1971 to 2009 (Table 9.3). Precisely determining the frequency and share of hazards caused by extreme weather conditions, during La Niña episodes, on the basis of the DesInventar database is not possible. And any alternative methods that might lead to such a determination would be subject to significant statistical discrepancy.

9.3.3 Mass movements caused by El Niño

The previous section clearly documents what types of catastrophes are most closely connected with El

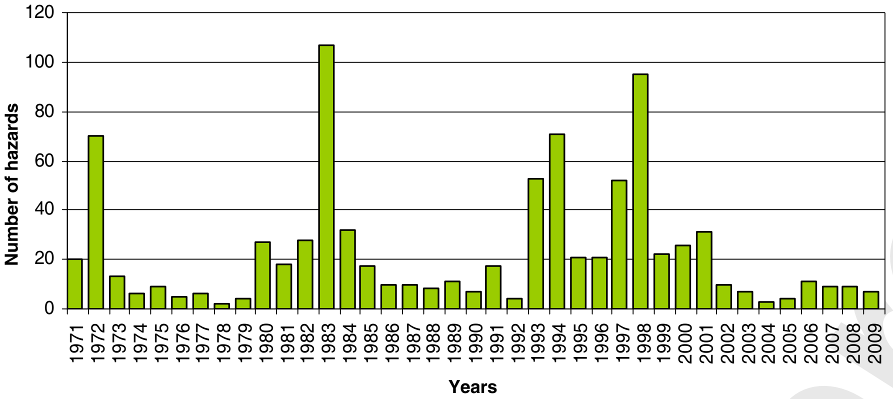

Figure 9.5 Temporal distribution of the occurrence of hazards caused by extreme hydrometeorologic events in the Ancash Department during the 1971–2009 period (source of data: DesInventar)

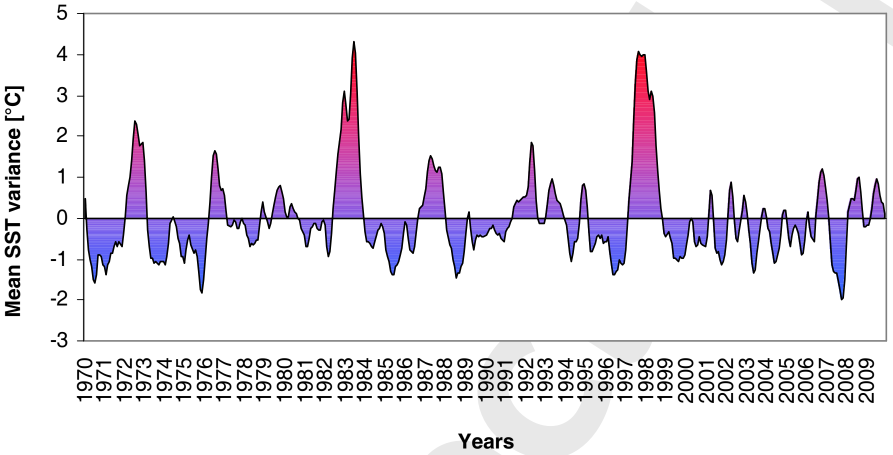

Figure 9.6 Variance of sea surface temperature (SST) in the Niño $1 + 2$ region, during the 1971–2009 period (source of data: CPC – NOAA, 2011)

Niño impacts in the Ancash Department. At the same time, it indicates the main factors behind these catastrophes, i.e. the abnormally abundant precipitation that inevitably accompanies each episode of El Niño. This section focuses on mass movements caused by precipitation, which is the main factor influencing the temporal and spatial frequency of their occurrence.

In the Ancash Department, a total of 399 mass movements occurred during the period from 1971 to 2009. DesInventar statistics divide these into three groups (Table 9.3). Alluvians were the most numerous (262 catastrophes). They include all movements during which material flows down the slope. The second group, landslides (107), includes a large group of movements on the sliding surface. The third group consists of rapid movements of rocks, ice or snow, during which the material moves, at least part of the time, by free-fall or is only in minimal contact with the earth's surface. The vast majority of mass movements are connected with long-lasting or torrential rainfall, which occurs every year during the rainy period in the Cordillera Blanca and Cordillera Negra Mountains. Mass movements occurring during the drought period (i.e. May through December) are a less common phenomenon. In the majority of cases, such movements are connected with extraordinary atmospheric phenomena; in the other cases, with non-meteorological causes – primarily earthquakes. The maximum intensity of earthquakes (I_o) and the frequency of their occurrence in the Ancash Department (according to

Figure 9.7 Palcacocha Lake in Cordillera Blanca after the outburst (1941). The water level is at a much lower position now, but due to glacial retreat the volume of the lake is growing rapidly. Inner slopes of the moraines are often subject to landslides. (Photo by Z. Patzelt)

DesInventar; NGDC, 2005; IGP, 2001) do not fall into the same periods as mass movements. For this reason, we can confirm the hypothesis that the majority of mass movements initiated during El Niño were caused by abnormal amounts of precipitation. Figure 9.8 shows the correlation between average monthly precipitation at the Huaraz Station and the frequency of mass movement occurrence.

During the El Niño period the quantity of precipitation in the mountains is further amplified, and it even rains in areas along the normally arid coast, where precitipation amounts can be several times greater than long-term normal values. Due to the reasons mentioned above, increased activity of slope processes can be observed precisely during periods of strong ENSO occurrence. Figures 9.9–9.11 present the temporal relationship between the precipitation amounts registered at climatic stations in the mountains (Huaraz Station) and along the coast (Chimbote Station) and the occurrence of mass movements in the Ancash Department.

Comparing these graphs reveals a correlation between the frequency and the intensity of extreme hydrometeorologic events and the catastrophic processes that they cause. The highest frequency in the years affected by an event is, logically, manifested by alluvions (156 catastrophes). As their origin and occurrence on steep mountain slopes of the Cordillera Blanca and Cordillera Negra Mountains suggest, such movements accompany each and every incident of torrential rainfall, which exceeds in intensity the amount that the underlayer is able to absorb. These slopes are composed of Tertiary sediments or of Quaternary fluvio-glacial and river sediments. Weathered material is also mobilized during extreme rainfall.

Because of the petrologic composition and sparse vegetation cover, alluvions also occur on arid western slopes of the Cordillera Negra Mountains and in less steep foothill areas passing progressively into the coastal lowlands region. From a climatic-morphogenetic viewpoint, this is an area of very intense physical weathering. The area's location at 10 to 12° south latitude means that solar radiation is very intense when the sky is not cloudy. Due to the altitude and intense radiation, nighttime temperatures are relatively low and daily temperature oscillations are quite high. Physical weathering results in a great quantity of weathered material being deposited on slopes and,

Table 9.3 Portion of hazards caused by El Niño from the total amount of hazards caused by extreme weather in the Ancash Department from 1971 to 2009 (source: DesInventar, own calculations)

Type of natural hazard in Ancash	Number of hazards	Number of hazards caused by a strong El Niño	Percentage of hazards caused by a strong El Niño (%)
Slope movements	*399*	*201*	*50.38*
Alluvions	262	156	59.54
Landslides	107	44	41.12
Avalanches (snow avalanches and rockfalls)	30	1	3.33
Flood events	*226*	*120*	*53.10*
Floods	212	112	52.83
Flash floods	14	8	57.14
Extreme meteorological events	*120*	*14*	*11.67*
Drought	31	0	0.00
Storms with dangerous associated phenomena	29	10	34.48
Extremely low temperatures	21	2	9.52
Strong wind (storm)	19	0	0.00
Hailstorms	12	2	16.67
Snowstorms	5	0	0.00
Extremely high temperatures	3	0	0.00
Extreme rainfall (torrential, long lasting)	*107*	*28*	*26.17*
Strong swell (huge waves)	*31*	*2*	*6.45*
In total	*883*	*365*	*41.34*

during incidents of rainfall, transported by the valley network. The nature of asphalt roadways further attests to the catastrophic events that accompany the passage of alluvions – at river and stream crossings within the trajectories of alluvions, there are no bridges, but only concrete fords which, during the greater part of the year (and during periods of drought), enable both the passage of transport and, during rare, intensive rainfall, the unencumbered passage of an alluvion through the valley. No bridges are destroyed; however, transport is temporarily impossible.

The second most important process, landslides (44), is caused by long-term precipitation conditions in the area. Landslides are triggered by long-lasting rainfall, the cumulative amount of which, over several consecutive days, weeks, or months causes the oversaturation of soils, weathered material or sedimentary rocks, after which the material starts to move along the impermeable underlayer. In addition to increased precipitation, El Niño is also accompanied by a significant increase in temperature, causing more rapid melting of snow and ice in the highest mountain localities. In the glaciated Cordillera Blanca Mountains, landslides and rockfalls are, consequently, more frequent. Rockfalls are common in the Ancash Department with its glacier-formed mountain valleys, the steep rock walls of which are very vulnerable to this process. The long-term neotectonic uplift, which enhances the differences in altitude, is also substantial. Along with avalanches, the various factors described in this section caused more than 55% (201 catastrophes) of all events that occurred from 1971 to 2009.

The majority of slope processes initiated by extreme rainfall during El Niño occur on steep slopes of the Cordillera Blanca and Cordillera Negra Mountains and, therefore, the largest catastrophic events from the 1971–2000 period are registered in the provinces of the densely populated Callejón de Huaylash Valley

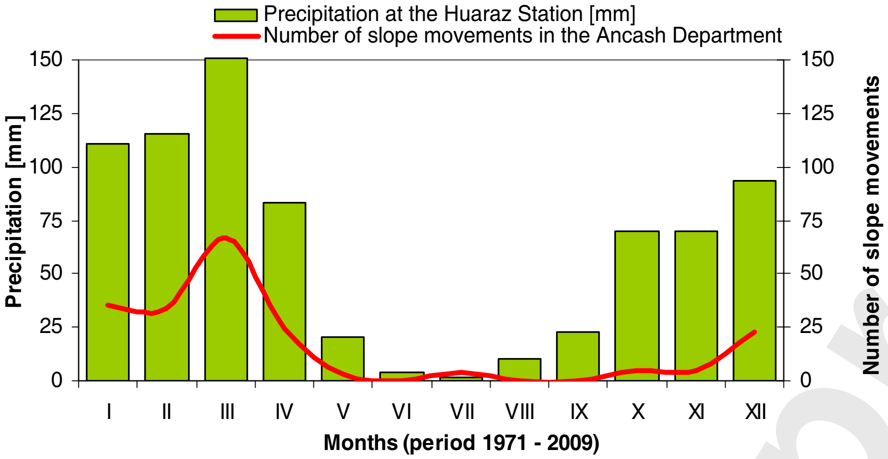

Figure 9.8 Average monthly precipitation at Anta Station (Huaraz) as related to the frequency of mass movements caused by rainfall in the Ancash Department, during the 1971–2009 period (source: NCDC, 2006; TuTiempo, 2006; DesInentar, 2011; Senamhi, 2001; own calculations)

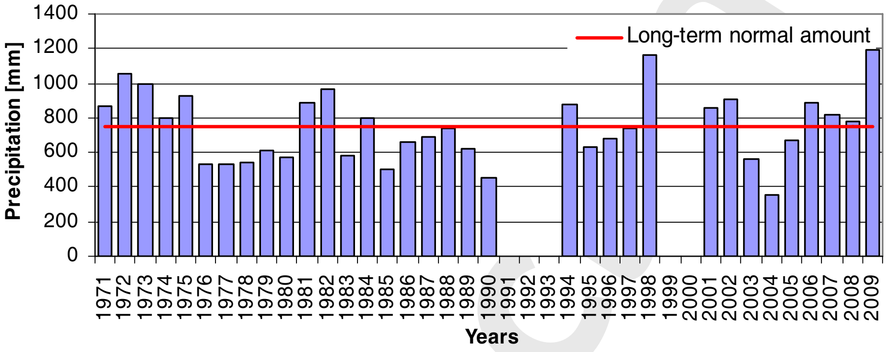

Figure 9.9 Annual precipitation at the Anta Station (Huaraz) during the 1971–2009 period (source: NCDC, 2006; TuTiempo, 2006; Senamhi, 2011; own calculations); note: incomplete data for 1991–1993, 1999, 2000; the station was moved in 2000 (from 2750 to 3052 metres above sea-level)

(Huaraz, Huaylah, Yungay). During the 1982/83 El Niño, extreme precipitation also affected the coastal areas, where it caused a series of mass movements on western slopes of the Cordillera Negra Mountains. For that period, the more northern provinces of Santa and Casma even registered the highest frequency of catastrophic alluvion occurrence (16 total) in the entire department. The high amount of risks during this period caused a rapid increase in the total number of hazards in these provinces. Casma and Santa Provinces thus exhibited, during the 1971–2009 period, levels of events comparable with provinces on the eastern slopes of the Cordillera Blanca Mountains (Sihuas, Pomabamba), where the impact of El Niño is least intense.

With a national spatial comparison, we obtained a picture of the distribution of the frequency of slope movements caused by El Niño that is similar to that of the Ancash Department. We thus observed an evident dominance of the occurrence of mass movements in mountain departments. There is an evident decrease in the frequency of slope processes in mountain departments with increasing distance from the coast (i.e. from the maximum altitudes of the Cordillera Occidental Mountains, through the Cordillera Central to the lower altitudes of the Cordillera Oriental Mountains). Records show a higher number of mass movements in departments on the western coast, during strong El Niño episodes. This is the reason behind several significant increases in the number of catas-

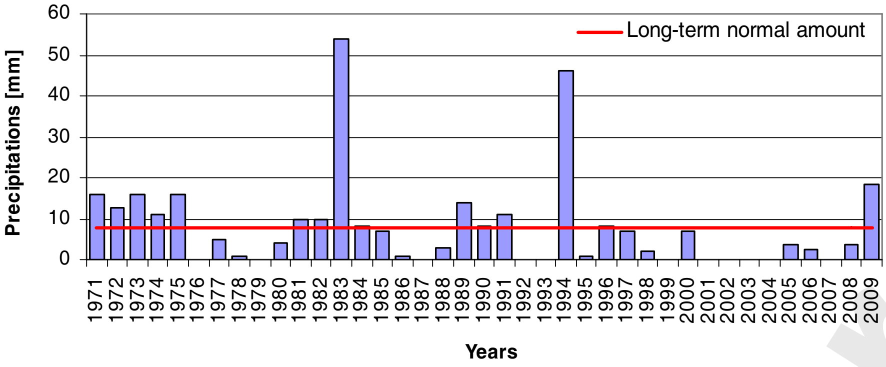

Figure 9.10 Annual precipitation at the Chimbote Station from 1971 to 2009 (source: NCDC, 2006; TuTiempo, 2006; Senamhi, 2011; own calculations); note: incomplete data for 1991–1993, 1999, 2001–2004

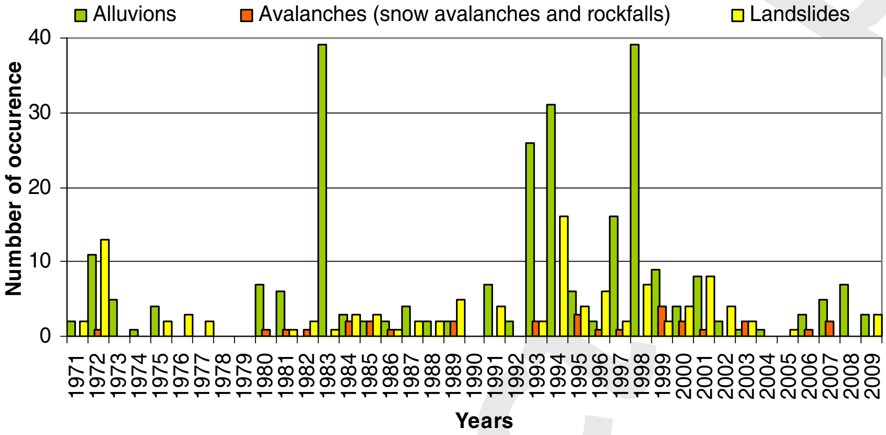

Figure 9.11 Temporal distribution of the occurrence of the three basic types of mass movement in the Ancash Department from 1971 to 2009 (Source: DesInventar)

trophes in these areas from 1971 to 2009. These coastal departments manifest a higher total frequency of slope processes caused by precipitation than departments in the Cordillera Oriental Mountains. According to the DesInventar database, the lowest number of mass movements occurred in departments on the southern coast, which are least influenced by El Niño. Figure 9.12 best illustrates the spatial distribution of the frequency of mass movements caused by precipitation in Peru and in the Ancash Department.

We can say that the territory of the Ancash Department is, as far as the occurrence of mass movements is concerned, one of the most at-risk areas of Peru, followed immediately by the Lima Department. From the total number of 3,066 catastrophes caused by mass movements, nearly 13% (399) occurred here. This level is well above the national average. If we consider only mass movements caused by El Niño, we obtain a similar proportion 1638 (Peru): 201 (Ancash) – 12.3%. In this comparison, the Ancash Department also ranks as the third most risky department, after Lima and Junín.

All of the findings discussed in this section correspond with the conclusions written earlier in the text, concerning the degree of El Niño's impact on temperature and precipitation in various areas of the Ancash Department and of Peru. The findings presented in this section confirm that different levels of El Niño impact contribute identically to the overall frequency as well as the temporal and spatial distribution of slope processes.

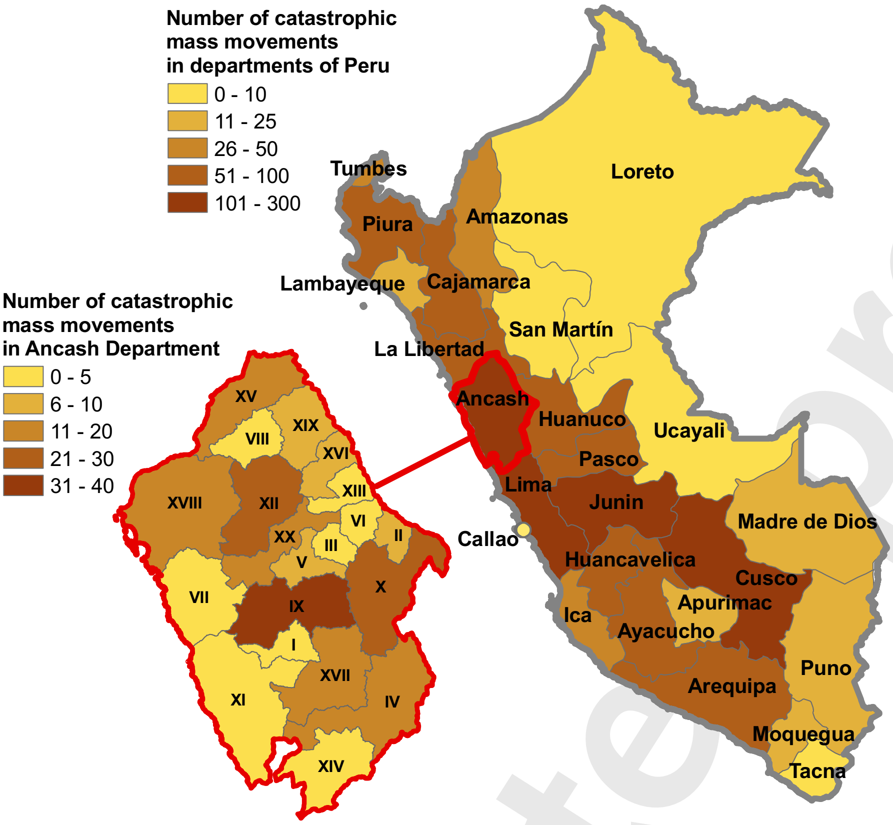

Figure 9.12 Spatial distribution of mass movements caused by precipitation, during El Niño, in Peru and in the Ancash Department, during the 1971–2009 period (source: DesInventar). *Peru:* Amazonas (46), Ancash (201), Apurimac (23), Arequipa (82), Ayacucho (53), Cajamarca (59), Prov. Constitucional del Callao (1), Cusco (169), Huancavelica (70), Huanuco (57), Ica (33), Junin (234), La Libertad (61), Lambayeque (17), Lima (299), Loreto (6), Madre de Dios (13), Moquegua (12), Pasco (71), Piura (61), Puno (12), San Martín (10), Tacna (9), Tumbes (30), Ucayali (9); *Ancash*: I – Huaraz (34), II – Aija (2), III – Antonio Raymondi (7), IV – Asunción (4), V – Bolognesi (11), VI – Carhuaz (9), VII – Carlos Fermín Fitzcarrald (3), VIII – Casma (3), IX – Corongo (5), X – Huari (26), XI – Huarmey (3), XII – Huaylas (24), XIII – Mariscal Luzuriaga (3), XIV – Ocros (4), XV – Pallasca (12), XVI – Pomabamba (7), XVII – Recuay (11), XVIII – Santa (12), XIX – Sihuas (7), XX – Yungay (14).

9.4 Discussion

Different types of natural hazards are often compared to discuss which of them is most frequent or most dangerous, both at global and regional levels. It is clear that the database, on which such analysis is based, will inevitable influence the result. Frequently, the regions or time periods analysed are not comparable, or the data collection methods are incompatible. No unified, universal approach exists in this field. It is, for instance, important to consider whether data are collected to make a record of victims or damages for the needs of insurance companies or for entirely different purposes; whether missing persons are included as victims or not, etc. The credibility of the data is also sometimes problematic. It is evident that remote and difficult to reach areas provide less credible data. It is, therefore, not by chance that different publications come to different conclusions. For instance, Shah (1983) considers (based on the number of victims) earthquakes to be the most problematic events for South America, during the 1947–1980 period, distantly followed by floods and avalanches (38,837 : 4,396 : 4,350). The ISDR database for South America for the period from 1973 to 2002, floods predominate, followed by extreme droughts. Nevertheless, according to WMO data, so-called hydrometeorologic risks make up nearly 90% of all natural hazards (Vilímek 2007). And, in the future, even greater risks can be expected, both in terms of the intensity of risk events as well as the frequency of their occurrence (Jeggle ed. 2005).

The periods compared are another important variable. The longer an analysed time period is, the greater its informative value will be, because the possibility for extreme and sporadic events to influence averages is eliminated. On the other hand, the credibility of data decreases with time, particularly if, for instance, personal observation is taken into consideration.

The database we have analysed is homogenous, in terms of methods for collecting data, although, from a global perspective, it only describes a relatively small region. Certain inaccuracies can result from the fact that the register of natural hazards is related to the people's exposure to hazards or to property damage. In any case, it is true that more densely populated and more intensively exploited areas (e.g. denser infrastructure) register more natural hazards, as opposed to the scarcely populated departments of eastern Peru (at the national level) or the sparsely populated districts of the Ancash Department. This could lead to partial overestimations regarding the Lima Department – at the national level, or the region of Huaraz – in the Ancash Department, due to their residential structure. Nevertheless the basic processes and natural mechanisms are evident from the analysis, for instance, the progressive decrease of ENSO impact or the portion of various types of natural processes within the total amount of natural hazards. The analysis also confirms the principal impact of basic processes.

During analyses of this type it is also important to classify various types of natural processes when collecting input data, i.e. correlations between different types of natural processes in the sense of a cause-effect relationship. In the event that, for instance, slope processes are caused by an earthquake, will the particular event be classified in a given region as an earthquake or a landslide?

Although we have presented several disputable things here, it is true that analyses of this type, whether regional or global in nature, help us recognise basic natural processes in a given area from the perspective of their degree of hazard. And, when compared over time, they can also contribute to an appreciation of whether the findings, under the impact of global changes (e.g. climatic change, human migration), represent or fail to represent shifts in terms of the causality of events. Such findings may result in the implementation of practical measures for determining the level of vulnerability and for protecting populations and property.

9.5 Conclusion

During the analysed period, from 1971 to 2009, the most frequent type of natural hazard in the Ancash Department was alluvion (a local term for debris flow). This was followed by flooding, extreme rainfall, earthquakes and landslides. Altogether, these phenomena represented 80% of all naturally conditioned catastrophic events. If we combine the various forms of mass movement (alluvions, landslides), they clearly comprise a dominant portion of natural hazards in the given region and during the given period. However, we should recognise the interconnection of various natural processes in the sense of a cause-effect relationship, wherein hydro-meteorological events or earthquakes could be the primary cause and different forms of mass movement are merely a subsequent effect.

The significance of extreme climatic phenomena, as the factor causing catastrophically developing processes, is confirmed by the following fact. With the exception of earthquakes (relative frequency 3.39%) and a negligible quantity of mass movements caused directly by seismic activities or anthropogenic factors, the majority of natural hazards (i.e. about 68 %) are caused by the direct impacts of extreme climatic events. We must, however, take into consideration the fact that truly extreme catastrophic events can, at least partially, distort the above statistics – e.g. the earthquake of May 31, 1970. Therefore, monitoring a longer time series in the future should have an even greater informative value, as it will be possible to eliminate the impact of any one truly extreme event on the statistical average.

Five important El Niño episodes, which occurred in 1972/73, 1982/83, 1986/87, 1991/92 and 1997/98, are the direct generators of nearly half (41%) of the catastrophes caused by extreme weather in the given region and during the observed period.

The above analyses are important both for regional planning and protection of population, i.e. for civil protection needs (Defensa Civil in Peru).

9.6 Social Impact

The results obtained through the research work in the frame of the IPL Project M 129 ("Evaluation of natural hazards associated with rapid glacial retreat in Cordillera Blanca, Peru") and the World Centre of Excellence on Landslide Risk Reduction, registered in the Czech Republic ("Landslide field research and capacity building through international collaboration") are expected to have an impact on both on the society and administration engaged in natural hazard management. Disasters have to be considered as complex phenomena of multi-causal origin occurring within the complex frame of the Earth's system. They may have a chain-like form of successive occurrence of individual disastrous phenomena (e.g. heavy storm, flood, landslides, agricultural disaster, some disease epidemic, social disorder). Moreover, increasing nature – human/technical interaction within globally connected human activities have brought another aspect – the aspect of coupled human and natural systems (Vilímek et al., 2010). To protect society we have to understand the natural processes first of all. Apart of the direct impact on the society we have to consider the influence on the important archaeological sites like that ones protected by UNESCO as well (e.g. Vilímek et al., 2010) – this has been also the subject of a previous IPL Project (C101-1).

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