Chapter 15
A Successful Early Warning System for Hydroclimatic Extreme Events: The Case of La Paz City Mega Landslide

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Introduction

The effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health. Adaptation measures are already required to adapt to the effects of climate change being experienced today (Haines et al. 2014).

Climate change is one of several direct and indirect factors that affect human life in cities. The urban areas are periodically affected by climate extreme events that are increasing in intensity and frequency (IPCC 2014). The frequency and severity

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of extremes inflicting exceptionally high economic and social costs have been linked to climate change. Moreover, there is growing scientific evidence that human action is responsible for warming the atmosphere and oceans, rising sea levels and some climate extremes (IPCC 2012).

Natural disasters are increasing in frequency and intensity. Between 2003 and 2012 there were more than 4000 worldwide; particularly worrying is the much greater incidence of hydrological and meteorological disasters, with a significant increase in hydrological ones. Although fatalities from natural disasters appear to be declining, the number of people affected is increasing (Guha-Sapir et al. 2014). This could be associated not only to the events themselves, but also with both the differential increase in adaptive capacity and exposure.

The need to create the project described in this chapter aroused from the occurrence of an extreme rainfall and mega-landslide event in La Paz city, Bolivia, in February 2002 (Aparicio et al. 2016). Which had a death toll was 63 persons plus 14 missing persons, in addition to losses in housing, public and private transport vehicles, urban infrastructure, and drainage. It also caused soil erosion and affected formal and informal trade. After this disaster La Paz city Autonomous Municipal Government (GAMLP) developed a project to improve the Standing Committee for Municipal Risk Management (SCMRM) which acts through the Special Office for the Integrated Management of Risks (DEGIR). It performs organisational preparedness exercises involving the population, in order to generate a timely response to an adverse event, protect public and private investment and the physical safety of the inhabitants. Accordingly, it has developed the early warning system for heavy rain, floods and landslides (EWS).

La Paz city, which lies in a mountain ecosystem between 3600 and 4000 m above sea level (masl), is experiencing rapid and uncontrolled population growth consisting of informal settlements and slums located on the slopes of the mountains on unstable soils. Extreme events occur within a framework of poverty, socio-economic inequality and climate-induced health inequity, compounded by failures in urban planning, illegal settlements, constraints on basic services and pollution of different environmental systems. The region is prone to soil erosion and the degradation and loss of biodiversity due to prevailing hydro-meteorological patterns, increased frequency and intensity of extreme weather events. La Paz city is at risk of a number of disasters, e.g., landslides, floods and sinkholes, population growth and adverse human activities have increased this vulnerability (Aparicio-Effen et al. 2010, 2016). These problems consist of issues of poor governance, lack of infrastructure and inequity that could increase in the next future.

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Tackling these issues requires scientific evidence from which to develop, policies, research techniques, tools and methodologies that can be standardised for use in different situations; such as reducing vulnerability and urban inequality, in order to enable socio-environmental systems to adapt and become more resilient.

Despite the continuous development of climate adaptation measures, the existent public adaptation policies and strategies are still insufficient to cope with the severity of impacts reflecting an overall adaptation deficit to climate variability and extremes events in South America (Villamizar et al. 2016; Nagy et al. submitted) in addition to the long-term continuity of adaptation processes (Bo Lim et al. 2005). This socio-environmental condition requires an effective response from the GAMLP through the SCMRM which is responsible for assessing threats, vulnerability and risks facing macro-districts.

The Adaptation Plan called "National Adaptation Bolivian Mechanism" (MNACC) (PNCC 2007) identified current and future vulnerability, encouraging a proactive attitude on the part of national sectorial system and social participation, in order to address climate threats. These elements were used as a basis for the design and implementation of climate adaptation measures focused to achieving urban resilience.

In February 2011 another hydro-climatic extreme event occurred in La Paz, the so-called "mega-landslide" which began on February 24th with cracks in 532 km^2 (26.4%) of urban area, and was followed by the activation of the early warning system (EWS) for the prompt evacuation of inhabitants at risk which prevented the loss of human life (Aparicio-Effen et al. 2016). The main preparedness and response differences with the event of 2002 were: (i) the communication did not fail (in 2002 phone cell lines were impacted), and (ii) the existence of an operational EWS.

Rainfall patterns are apparently changing, with variations in their quantity and frequency, and a greater tendency towards extreme events able to produce over short periods the rainfall that would normally fall over weeks or months, e.g. February 2002 and 2011, the latter during a La Niña event (Aparicio-Effen et al. 2016; Nagy et al. 2016), with serious consequences on the population's morbidity and mortality, leading to increased surface drainage, overflowing water collection systems and lower availability of water resources, since these events can occur during water shortages and droughts.

The work performed by the SCMRM during the mega-landslide of February 2011 led the authors to discuss in this chapter the success of the La Paz city EWS and to propose further VIA assessment focused on risk factors research, a list of adaptation measures to cope with hydro-climatic extreme events, and to improve EWS preparedness. An introduction to this case study was presented by Aparicio-Effen et al. (2016) supported by the South American Climate Vulnerability, Impact and Adaptation Network (CliVIA-Net) initiative (Nagy et al. submitted).

After the introduction the content of the chapter is as follows: the methodology and data used; the description of landslide area and extreme hydro-climatic event characteristics; the landslide risk factors as: the state of biodiversity conservation in the landslide watershed, land coverage and use, water and sanitation in the mega-landslide area; the conceptual framework of urban equity between

neighborhoods exposed to same climate extreme event; La Paz city EWS; the hazard, vulnerability and risk maps; the adaptation measures and actions; the summary and conclusions.

The limitations of the work and constraints of the paper are as follows:

- Climate scenarios and the occurrence of La Niña are not enough to have a good forecast of extreme events (Aparicio-Effen et al. 2016) but serve for preparedness of the EWS.
- The lack of updated building regulations based on the knowledge of landslide risks, populations' exposure, and the experience described in this paper.
- The success of the EWS could make it difficult to incorporate further adaptation measures to fill the adaptation deficit to cope with extreme hydro-climatic events.

Methodological Approach and Data Used

An interdisciplinary investigative approach was used to analyse climate-related risk factors and science-based (both natural and social) adaptation which focused on the experience of the EWS performance to prevent human life loses, draw valuable and useful findings for decision-making, and monitoring and evaluation of climate adaptation.

A quantitative multi-phase approach was followed (including the assessment of bio-physical, socio-economic and health factors) to analyse a mega-landslide that occurred from 26 to 28 February 2011. A retrospective study was carried out for climatic time-series analysis, water supply, social, demographic and epidemiological variables in order to perform a comprehensive assessment of the human impacts. Thirty-year time-series of monthly temperature and rainfall variables were compiled for two weather stations, Laikakota and San Calixto. The San Calixto weather station data were used for total precipitation, maximum daily precipitation (representative of maximum concentration), and the number of rainy days, as well as for daily temperature maximum and temperature minimum.

Other analysed landslide risk factor variables were as follows: (i) conservation state of watershed head, (ii) coverage and use of ground, (iii) climate extreme events, (iv) water and sanitation in the area of the mega-landslide, and (v) social variables (education and access to health services). Each one was studied using specific methodology before being compiled and comprehensively analysed in terms of their impact on human vulnerability, such as literature review, meetings with municipal government, national and local organisations, and partner organisations working in the areas of climate change, extreme events and water and sanitation, e.g. PAHO/WHO, UNICEF, GTZ.

The authors made a compilation of demographic and socioeconomic information and analysis (National Institute of Statistics-INE), weather and climate data from National Meteorological and Hydrological National Directorate (SENAMHI 2015), municipal statistics (GAMLP 2011), and epidemiological statistics (La Paz Departmental Health Department (SEDES).

To analyse the State of Biodiversity Conservation in the landslide watershed an exhaustive literature review was carried out and biodiversity samples were lifted, applying standard biological methods for the study of wild flora and fauna (Burnham et al. 1980). The survey began in the highest part of the basin (Ajuan Khota dam) descending to the urban area of Bolognia in an altitudinal transect. It was followed by preparation of maps and images using remote sensing images and geographic information system (GIS) to identify epidemiological risk for human settlements, epidemiological methods and multivariate analysis.

The Urban Health Equity Assessment and Response Tool ("Urban HEART") methodology (WHO 2010) was applied to assess equity, adjusting it to the effects of climate change and variability, in particular to mega-landslides (Aparicio Effen et al. 2016). This research used relevant Municipal databases from 2011 (GAMLP 2011), governance, social and environmental data. The knowledge, attitudes and practices (KAP) surveys (Handicap International 2009) were carried out among a sample of affected families and of a control area (Alto Irpavi neighborhood).

A risk map for 2011 was developed by the GAMLP which combines the vulnerability and hazard maps, obtaining specific geographical areas in which there is a risk of damage due to extreme events based on topography, geology, active geological faults, geo-mechanical characteristics of the soil, and also envisages the potential social, political or economic impact. It determines the probability of each system to be affected facilitating to plan adequate protective measures, to regulate the use of the different geographical areas (depending on the level of risk), and to govern land-use so as to ensure sustainability over time. The landslide-prone areas were assessed by expert judgment of risk-factors of soil instability and landslide risk for building purpose as follows: high soil humidity saturation (40%), the slope (30%), the geomorphology (20%) and geotechnical factors (10%) to the landslide risk which is expressed in the following hazard Eq. (15.1):

$$\text{Hazard} = (\text{Geology} * 0.4) + (\text{Slope} * 0.3) + (\text{Geomorphology} * 0.2) + (\text{Geothechnics} * 0.1)$$

$$(15.1)$$

Based upon all the above sources of information and tools, participatory methods for climate VIA assessment (Bizikova et al. 2008; Droesch et al. 2008; UNEP 2009; Nagy et al. 2014), as well as EcoHealth (2014) and KAP surveys, as adapted by Aparicio-Effen et al. (2014, 2016) for human well-being and health, were used to propose, select and prioritise a wide range of adaptation measures to address extreme events, climate change and variability.

The participatory methodological approach is based on the following concepts and steps (modified from Nagy et al. 2014) to include human well-being and health according to Aparicio et al. (2014, 2016):

- The application of scientific knowledge on VIA assessment and climatic trends.
- The assessment of the existing capacity and its strengthening allows prioritising measures and identifies windows of opportunity for carrying out the process.
- The elaboration of institutional agreements at several levels.

- The assessment of human well-being and health vulnerability and impact at affected families' camps.
- Semi-structured and in depth interviews with selected identified EWS managers, practitioners and institutional stakeholders (DEGIR, GAMLP, INA, SCMRM SEDES, SENAMHI), experts (La Paz University-UMSA, CliVIA-Net).
- Analysis of adaptation literature review by the authors of the chapter.
- Focus groups meetings and workshops with stakeholders where a multiple question matrix based on the Vulnerability Reduction Assessment (VRA)-UNDP and UNEP guidelines was developed. The matrix included the numerical assessment (scale 1–5) of climatic stressors, threats, harms, obstacles, and supportive factors to implementing adaptation, and written comments.
- A dialogue between natural and social scientists and attendants was held at each step.

The measures were prioritised based on categorisation according to whether they are institutional (I), social (S) and technical capacities (T), and whether they are high-priority (HP), i.e. to be implemented in the short term; medium-priority (MP) or low-priority (LP), i.e. to be implemented in the medium or long-term respectively, for decision-making, management, public policy, institution and La Paz city inhabitants.

Landslide Description Area and Climate Extreme Event Characteristics

The Landslide

The city of La Paz is situated 16°29′ Latitude South, 68°8′ longitude West, at an average altitude of 3640 masl. La Paz is very complex in terms of its geological and geotechnical setting, and steep topography. Up to 35% of the urban area consists of steep terrain on a gradient of more than 50% with high potential instability, which hampers the provision of basic services and generates high urbanisation costs. The southern part of the city is very hilly, the slope is moderate (a gradient between 10 and 49%) in 28% of the land, located in transitional zones between the terraces and steep slopes and consisting of alluvial fans; these areas are now urbanised. The remaining 37% of the land is gently sloping (a gradient of less than 10%), corresponding to the southerly neighbourhoods of Obrajes, Irpavi and Achumani, which are prone to flooding. The urban population of La Paz and El Alto is 1,476,412 which represent 18.94% of the total national population. It has a growth rate of 2.84%/year and an average of 3.9 persons per household.

Influence of Precipitation

One of the causes of the mega-landslide in February 2011 identified by both the inhabitants during the meetings and by the SCMRM was the heavy rainfall. This led the authors to analyse the time-series of total precipitation, maximum daily precipitation (representative of maximum concentration) and the number of rainy days at the San Calixto Observatory from 1919 to 2011 (Figs. 15.1 and 15.2).

February 2011 was the sixth most rainy month of February, with the highest number of rainy days (25), since 1919, and the second most rainy over the last 30 years (157 mm/month), reaching 39.2 mm on 25 February 2011, a day before the mega-landslide. These figures are able to cause flooding and riverbank erosion (Chow 1994, 2004) in addition to non-controlled sewage emissions and upwelling of subterranean water, which saturate the soil, lubricate the slope, and overload it hydraulically, increasing the probability of landslide disaster.
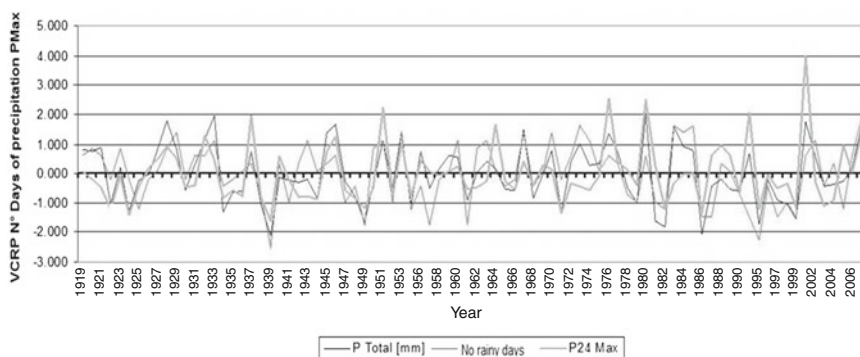

Fig. 15.1 Number of rainy days (*black line*), compared with total precipitation (*dashed line*) and rainfall maximum 24 hours (*grey line*)
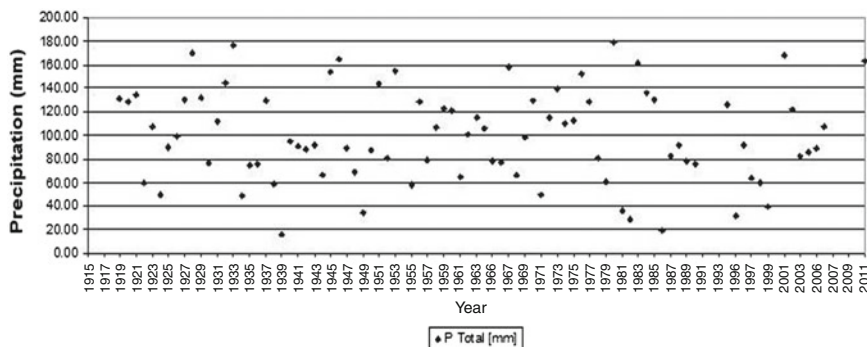

Fig. 15.2 Total past precipitation (for February). Elaborated by the authors from SENAMHI data base

The mega landslide of February 2011 coincided with a moderate to strong La Niña event (CIIFEN 2011). The Intergovernmental Panel on Climate Change suggests some degree of correlation of the tendency of global warming to exacerbate extreme events throughout the world (IPCC 2012, 2014), a factor, which could explain this behaviour as a result of Climate Change. The perception of the inhabitants of the Altiplano was that in recent years the rainy season had become shorter and more concentrated (PNCC 2007), which would provide ideal conditions for the erosion of river beds and slopes.

Landslide Risk Factors

In this section the authors present the state of biodiversity conservation in the land-slide basin, land coverage and use of urban soil, water and sanitation in the area of the mega-landslide.

The State of Biodiversity Conservation in the Landslide

Considering that ecosystem services contribute to human health in multiple ways and can act as buffers, increasing the resilience of natural and human systems to climate change impacts and disasters, an integral assessment of the State of Biodiversity Conservation in the landslide basin of the Irpavi-Callapa river was developed based on biological criteria and its impact on the availability of water resources for local inhabitants, and on biodiversity.

Changes in climate place considerable additional pressure on land ecosystems that have already been affected by human pollution, greenhouse gas emissions, over-exploitation of natural resources, the fragmentation of habitats, and the survival of many species and ecosystems endangered by global warming, changes in humidity or general instability (IPCC 2002; Llorente et al. 2004). These pressures introduce changes in the ecosystem's structure and function (decomposition, nutrient cycle, water flow, composition and interaction of species) and of their distribution in landscapes, with an indirect effect on the population of plants and animals (IPCC 2002; Llorente et al. 2004). Water condensation is closely linked to the state of conservation of woodland in upper basins.

The La Paz valley was formed through the heavy erosion of the Altiplano formations, with debris being carried down to the Amazon basin. The valleys developed their own individual characteristics as the Cordillera Real underwent two strong glacial periods. The valley runs from north to south, with drainage towards the Amazon basin and a marked difference in altitude from 4000 m amsl at the basin headwaters, to 2600 m near the La Paz river. These differences create various natural environments, which determine the varied structure of the vegetations and of the various ecosystem components (Lorini 1991). Zones of potential vegetation are the

northern Prepuna, high dry inter-Andean valleys of the upper river Beni basin, and sub-humid–northern humid Puna. The variations in altitude, the different slope gradients, varying exposure of the sides of the valley to the sun, the direction of winds, available humidity and the variable temperatures create various microclimates in the basin, which account for the varied vegetation in this region (Lorini 1991).

The area of Callapa-Irpavi is found in the upper part of the La Paz river basin. Wasson and Barrere (1999) identify two water eco-regions, the glacial Cordillera, above 3400 m, with mountains rising above 5000 m, which result in permanent snow cover being a fundamental factor in the regulation of the rivers' water cycle and the dry valleys, where basins are protected by the axis of the glacial Cordillera and the humid mountains. The gradient of the mountainsides, the highly erodible rocks and the dry climate vegetation contribute to the high erosion levels in these valleys.

Upper Basin (Area of Hampaturi "4203 m"–Ajuankhota "4429 m")

This area is situated on the High-Andean shelf and in the upper Puna (Beck and García 1991) over 4200 m and up to 4500–5000 masl, over periglacial sediments in the highest places (>4500 m) and glacial/interglacial deposits lower down (Calvario formation). A large part of the area above 4500 m is covered by bare ground. Vegetation includes low grasses (very low grasses with plants at ground-level). The vegetation in the lowest regions (4200–4400 m) includes grasslands. Bushes and low grasses also grow here (in rosettes at ground level), often related to larger plants. Below this altitude, vegetation looks drier. At around 3900–4000 m the vegetation contains an increasing number of bushes and a great abundance of grasses. A large number of pre-Columbian terraces can be found at these altitudes and further down. They are still in use today alongside large human settlements, bringing about considerable changes in the natural vegetation. Pine trees, eucalyptus, cypresses and brooms are some of the non-native woody species here, along with smaller plants related to farming.

The Chicani area is located lower down the basin, containing the Irpavi, Chicani and Chinchaya terraces. These are in the highest parts of the dry valley and on the Puna (Beck and García 1991). Below 4000 m, vegetation appears to be drier and below this point bushes are increasingly frequent, along with a great abundance of grasses.

The Mid Basin Area

The Chicani Hill is found halfway up the basin at approximately 3550–3600 masl and is characterised by strong gully erosion (cliffs). There are large urbanised areas on its northern slope, where vegetation is practically non-existent. There are a number of small slopes that create ponds and flooded ditches that are home to

Pleurodema cinereum frogs, which are widely spread in the lower La Paz valley, especially in the rainy season (Fig. 15.3).

The Lower Basin Area

The lower basin contains the Bolognia forest, which lies over a substrate of the heavily urbanised La Paz/Purapurani area, containing remains of open Pinus radiata (pine) forest and examples of other non-native species such as acacias, cypresses and brooms. Some areas are dominated by Stipa ichu tall grasses intermingled with native bushes, which appear as patches on the landscape. The northern slope is home to dry valley or mesothermal species (Beck and García 1991). The basin, in particular the headwaters (area of *Hampaturi and Ajuankhota*), provides an important service for the ecosystem by providing water for the southern region of La Paz. A large number of flora and fauna species have been identified in the basin, including indigenous regional species and introduced or migrant species. The Irpavi-Callapa basin is affected by a number of human activities: agriculture and livestock, urbanisation and the construction of major damn projects. However, a number of areas still preserve their vegetation (both native and introduced species), which supports the native biota of these high-Andean environments. Other semi-natural ecosystems protect the basin from landslides and continue to enable water collection for the city of La Paz.

Land coverage and use of urban soil

Part of the upper basin was analysed in order to identify any significant change in the land coverage and use that might have affected or provided the exposure conditions for the extreme event. Two Landsat 7 (001–071) satellite images were used (www.landcover.org and http://glovis.usgs.gov/) for the months of July 1999 and August 2010 to analyse the land coverage change and use within the basin of the disaster area. The study area was identified and a surface of 10,000 km^2 was defined (Fig. 15.4), using a 90 m resolution digital elevation model (DEM).

Once the area of the basin had been outlined, a classification analysis was carried out for each of the Landsat 7 satellite images (1999 and 2010). The classification of

Fig. 15.3 River Callapa (*left*) and dry vegetation found in Irpavi basin cliff areas (*right*) (Photographs J. Aparicio)

coverage followed the classifications proposed by the Map of Coverage and Actual Usage of the Soil 2010 (preliminary version), provided by the Ministry of Rural Development and Land Vice-Ministry of Land. This analysis indicates two layers of land coverage and use (Fig. 15.5).

These two classifications were used to calculate the areas (km^2) in each of the categories presented in Table 16.1 for 1999 and 2010. To avoid any mistake that might be caused by seasonality (dry or wet season), the two analysed satellite images were taken during the same season.

A decrease in area was observed from 1999 to 2010 in "snow fields" and "water bodies" of 3.33 and 1.13 km^2 respectively, which could be related to annual seasonal changes and/or to an increase in evaporation due to higher temperatures. The human elements, e.g. "farming" and "urban structures" increased by 0.37 and 12.25 km^2 respectively, with farming areas growing to thirteen times their area and urban structures growing to 2.4 times their area. The areas of "Scrubland" and "Scrubland with bushes" decreased by 50%, probably as a result of the growth in the urban area,
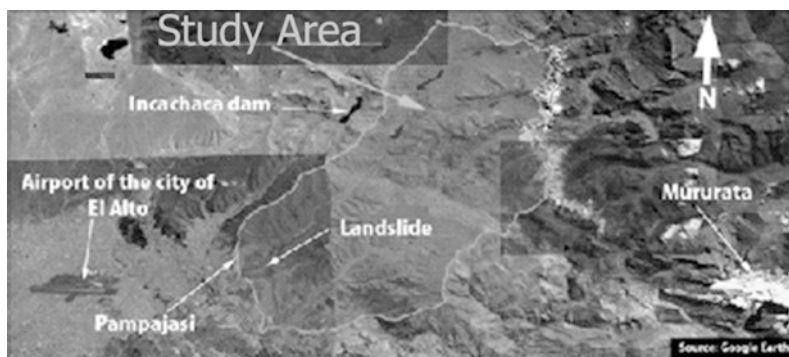

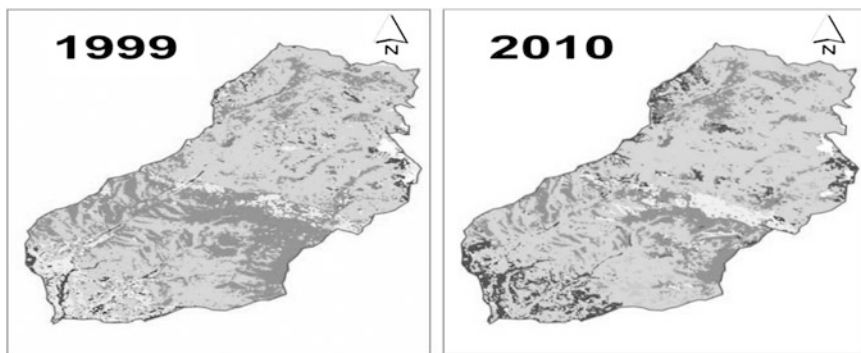**Fig. 15.4** Study area outlined by the limits of the basin. The *red* area shows the landslide area

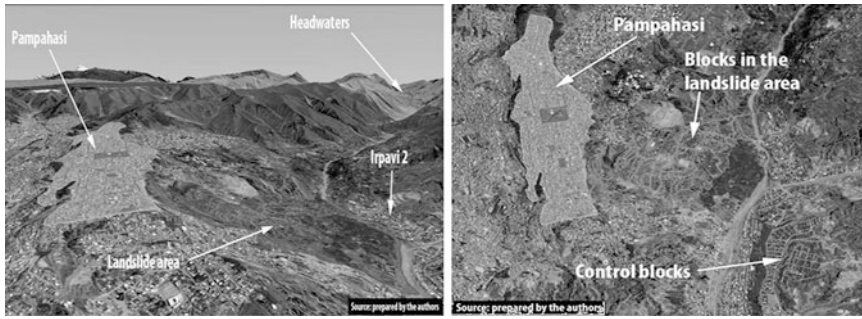**Fig. 15.5** Land coverage and use in 1999 (*left*) and 2010 (*right*)

Fig. 15.6 North-easterly view of the landslide area and of the Pampahasi district from a height of 4.17 km (A, in *light grey*) View of the landslide and Irpavi area (B, in *dark grey*)

given that the "Scrubland" lost a significant area to the landslide. Half-way up the basin, "Scrubland" increased but not in proportion to losses, while the "Scrubland and bushes" areas decreased drastically and were replaced by "Scrubland" and "Scattered Vegetation", which may be developing as a result of the loss of vegetation clusters. Lastly, the growth in the area of "Forest Plantations" to almost double the size could be a result of urbanisation, where clusters of eucalyptus or pine trees are planted for their benefits. Alternatively, this could be the result of an error in the interpretation of the model, since the shadows of ravines in the images could be interpreted as "Forest plantations", due to the similarity in their respective reflectivity. The analysis of the direction of water drainage in the landslide area shows that the upper basin had little influence on water levels, since most of the water came from Pampahasi, and flowed at the top of the landslide area from west to east.

The landslide occurred on the Eastern slope in the north of the city of La Paz. Given its characteristics, the Municipal Government had already listed it as a risk area, but did not prevent people from settling there (Aparicio-Effen et al. 2016). To analyse this situation, the built-up section of the landslide area was assessed by comparing constructions at 8-year intervals. To that end, digital images of the blocks of buildings were digitalised with images obtained from Google Earth. The areas were overlapped and shapefiles were used to incorporate the calculation of the area of the blocks. The same method was used to calculate the built-up area on the opposite slope, where the Alto Irpavi district is located, to carry out a comparison and analyse the difference and similarities (Fig. 15.6).

The built-up areas (houses) had almost doubled (1.8 times) in 8 years. This means that the area built in landslide area was of 74,945 m^2 in 2003 and 137,953 m^2 in 2011. The built-up area in Irpavi—selected as the test area being located in the same basin and opposite the landslide area (Aparicio-Effen et al. 2016) has a construction area of 71,983 m^2, slightly less than the area of Callapa in 2003 (Fig. 15.6). In order to analyse the density of the landslide area, the total area of the collapsed blocks (843,267 m^2) was compared with the built-up area (137,953 m^2), which indicated a density of 0.16 m^2 of buildings per m^2 of blocks.
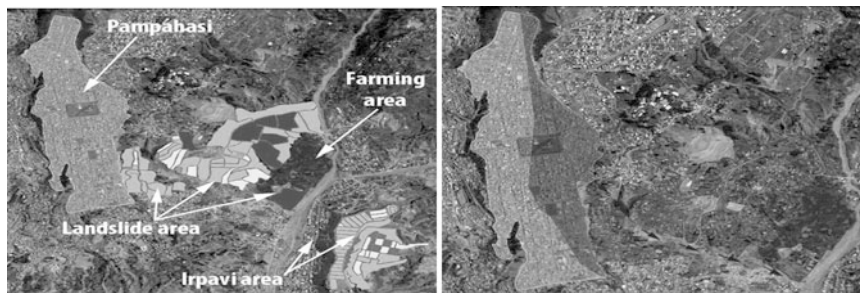
Fig. 15.7 Classification of blocks by construction area (*Left*) Water drainage from Pampahasi to the landslide slope (*Right*). a) small (*light grey*), b) regular. The *dark grey* area is the landslide area receiving water from Pampahasi (in *grey*); the arrows follow the river (in *light grey*), c) medium (*grey*), d) large construction area (in *white*). Irpavi control quarter (*light grey*)

The density of the Irpavi area is of 0.20 m² of buildings per m² of block, which indicates a greater building load in Irpavi than in the landslide area

The classification of the blocks of building with the largest or smallest built-up areas identified the areas of greatest pressure. Blocks were classified under (a) small built-up area (<500 m²), (b) regular built-up area (between 500 and 1000 m²), (c) medium built-up area (between1000 and 5000 m²), and (d) large built-up area (>5000 m²). Figure 15.7a shows that the largest proportion of the category "(d) large built-up area", was concentrated in the middle of the area of the landslide in large blocks of buildings. This category was not found in the Irpavi area.

The lower part of the landslide had a large crop area (256,215 m²) which was sown, consequently the soil was constantly disturbed and irrigated, hence not providing adequate support to the urbanised area higher-up. In comparison, the lower part of Irpavi is well settled with houses and embankments. Lastly, the water running from the district of Pampahasi contributed to the irrigation of the upper part of the area that collapsed due to water drainage. Using the basin model, the drainage area of water running from Pampahasi to the slope where the landslide occurred was calculated at 429,490 m² (Fig. 15.7b). This river was not channelled and, according to the inhabitants, its bed was full of solid debris, which could have contributed to the underground infiltration of the water in this area.

Water and Sanitation Services Access Around Landslide Area

The water supply to the landslide area comes from the Pampahasi treatment plant, the sources of which are the Hampaturi and Incachaca basins. It draws on three large-capacity reservoirs, Incachaca, Hampaturi and Ajuankhota, as well as other smaller reservoirs. However, there were also a number of watercourses directed to private individuals and communities. The extreme event damaged a large capacity

pipe that provided water to the whole southern area, which was not repaired until three months later due to the scale of the damage.

The knowledge, attitude and practice (KAP) surveys carried out among the persons affected by the mega-landslide showed that 92% benefitted from the municipal waste collection service, 85% of the families had drinking water in their houses, and only 69% had drains at home. Fifty one per cent of the population interviewed had noticed infiltrations in the affected districts over the last 4–7 years, these being only noticeable in the rainy season (90% increase). This had been attributed to the presence of drinking water reservoirs belonging to the company EPSAS.

Of the persons affected, 40% indicated that they did not perceive any decrease in water availability due to climate change, while 30% said that water availability had decreased, 15% pointed to a loss of water sources and 12% referred to increased disease due to global warming. The microbiological water quality of the rivers near the mega-landslide area showed that the sanitary level of the water (from the Jillusaya river) was extremely low, so that the water from the river Jillusaya and its continuation, the Achumani and Irpavi rivers (studied area) were unfit for human consumption and farming (in the case of vegetables) in particular (Flores et al. 2010).

The districts affected by the landslide were poorly served by sanitation facilities which were in any case substandard due to lack of maintenance, therefore uncontrolled sanitary discharges and groundwater outflows might have contributed to the landslide. This was noted by people who were affected by the event.

Urban Equity Assessment in the Area of the Mega-Landslide and in Its Control Area

The Urban Health Equity Assessment and Response Tool (WHO 2010) methodology was applied to assess equity, adjusting it to the effects of climate change, environmental and health determinants, and to mega-landslides based on municipal statistics from 2011 (GAMLP 2011; Aparico-Effen et al. 2016). KAP surveys were carried out among 200 affected families from San Antonio, Sur and Hampaturi macrodistricts and among a representative number of families in the control area (Alto Irpavi). An equity assessment was carried out for the landslide area (9 macro-districts) and it was compared with the opposite slope, in the Alto Irpavi district. Both the landslide area and the control area are found in the same basin and were exposed to the same extreme precipitation event as well as to same governance determinants but with different results. A brief summary of results presented by Aparicio-Effen et al. (2016) is as follows:

- In the affected districts, 50% of the houses were built with bricks (mostly in the Sur macro-district) compared to the other two macro-districts, which used "adobe" and "adobe with brick", explaining their fragility and their unsuitability in a "very high risk" area.

- About 60% of houses affected by the mega-landslide were "house/shacks". The households in the control district (Alto Irpavi) were often of better quality and their average income was significantly higher.

These results show that the districts where the mega-landslide occurred were in an inequitable situation compared to the control area, due to the higher quantity of cases requiring improvement. In general, the Irpavi-Callapa drainage basin is affected by anthropogenic processes (farming, urbanisation in a number of districts including the construction of large-scale water-retaining dams).

La Paz City Early Warning System: An Adaptation Measure to Hydro-Climatic Extremes

EWS Development

Due to the extreme hydro-climatic event in February 2002, when 63 persons died and 14 people was missing, in addition to 4 million dollars of losses in public and private infrastructure, transport, formal and informal trade, urban infrastructure and landscape services, e.g. surface drainage, soil stabilisation and control of gullies, La Paz municipality risk-management was improved, acting through the Special Office for the Integrated Management of Risks (DEGIR), whereas an Early Warning Operations Centre (EWOC) was created.

The alerts generated and issued by EWOC allow for coordination with authorities and emergency response personnel. The EWS for heavy rain, floods and landslides consists of permanent monitoring systems using rain gauges, radar measurement of rivers water levels, weather stations, video surveillance cameras and a weather radar local area. The equipment generates real-time wind direction speed information, the approach or formation of humid air masses that could cause heavy rain or hail and changes in river levels and other useful data. It performs organisational preparedness exercises involving the population, national police, La Paz Fireman Unit in order to generate a timely response to an adverse event, protect public and private investment, and the physical safety of La Paz inhabitants.

La Paz Early Warning System (EWS) Components

Geodynamic Monitoring

Geodynamic Monitoring through GPS satellite tracks the movement of land in La Paz municipality areas, classifying it as being at high or moderate risk of landslides. The objective of this component is to monitor soil in areas vulnerable to landslides and provide early warning of a likely event. According to the monitoring, DEGIR

carries out prevention work in susceptible areas. It uses a variety of techniques including demolition, the main concern being to reduce risk and minimise population danger. The municipality has been divided up and 39 landslide-susceptible areas have been identified, one of which has already suffered a landslide (Pampahasi Central Bajo-Callapa). Surveillance in this area should therefore be stepped up, incorporating advanced techniques.

Technical and Scientific Support

The technical and scientific support facility has a laboratory for analysing cements, soils and water quality. This is a strategic component of EWS which helps to detect possible adverse events, provide data for project development and monitors project quality. The information processing system provides real data to operative emergency teams, to generate a timely response to an adverse event, protect the physical safety of La Paz inhabitants preventing human loss.

Hydro-Meteorological Monitoring

The EWS hydro-meteorological monitoring facility is aimed at generating information in real-time regarding the status of 36 weather stations located in La Paz drainage basin prior to hydrological events. The monitoring responses allows updating hazard, vulnerability and risk maps to incorporate all the threats and vulnerabilities, given the dynamic nature of the risks involved.

EWS Tools

Risk assessment relied on the reinforcement of tools previously developed by the La Paz municipal authorities, taking into account the following maps:

Hazard Maps

The hazard map of La Paz (Fig. 15.8) incorporates endogenous and exogenous geodynamic processes (only the latter are taken into account here); it incorporates large-scale movements, e.g. landslides, flooding and hydrological analysis of the drainage network. The 1:1000 scale geological map of the valley of La Paz was used to draw a geomorphologic and geotechnical map on the same scale. A 10 m pixel digital elevation model was used to draw a slope map. The geological, geomorphological and geotechnical maps were rasterised from the base vector, using a 10 m pixel. The hazard from large-scale soil movements was evaluated using Eq. (15.1) where hazard was weighted on a 1–5 scale, where 1: very low, 2: low, 3: moderate, 4: major and 5: very major hazard.
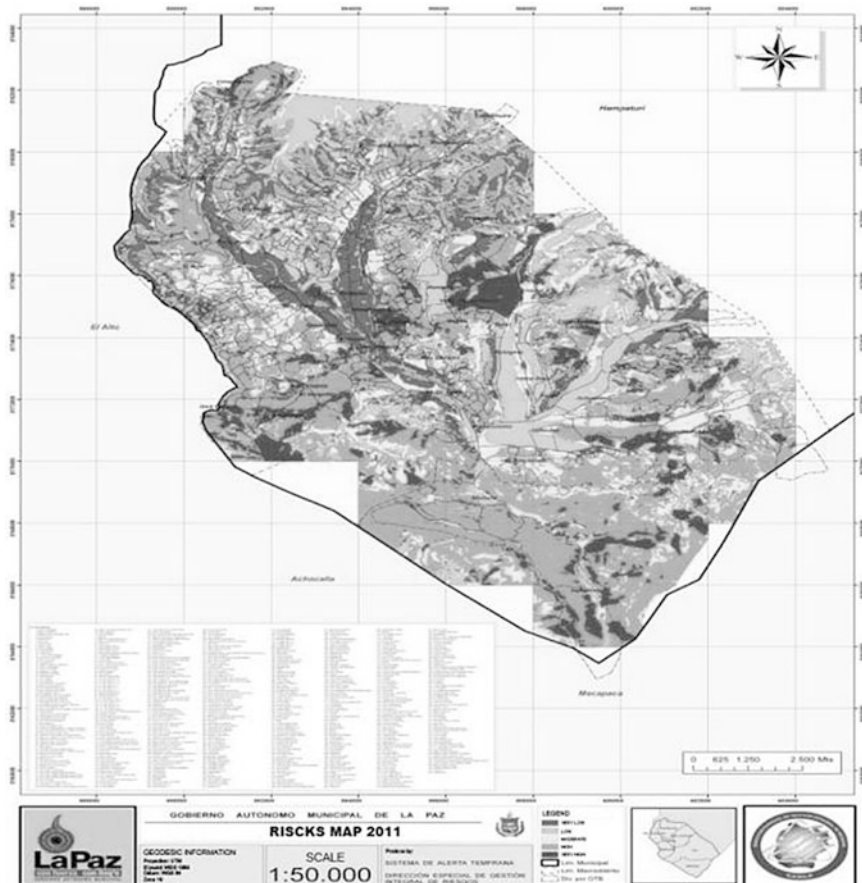
Fig. 15.8 La Paz Hazard map 2011. *Source:* DEGIR 2011

Vulnerability Map

Urban vulnerability is determined by a complex relationship including multiple factors where the level of exposure depends on the sum of economic, political, social, demographic, migratory and cultural elements. These are compounded by unplanned expansion of the city and result in increased population exposure. With these considerations in mind, two analytical approaches were adopted: direct mapping of variables and qualitative mapping (both of which are applied in combination). Direct mapping involved transposition of the INE tables and specialisation of the variables weighted by experts (expert judgment in risk analysis). The most vulnerable macro-districts in La Paz and the factors examined are shown in Table 16.2.
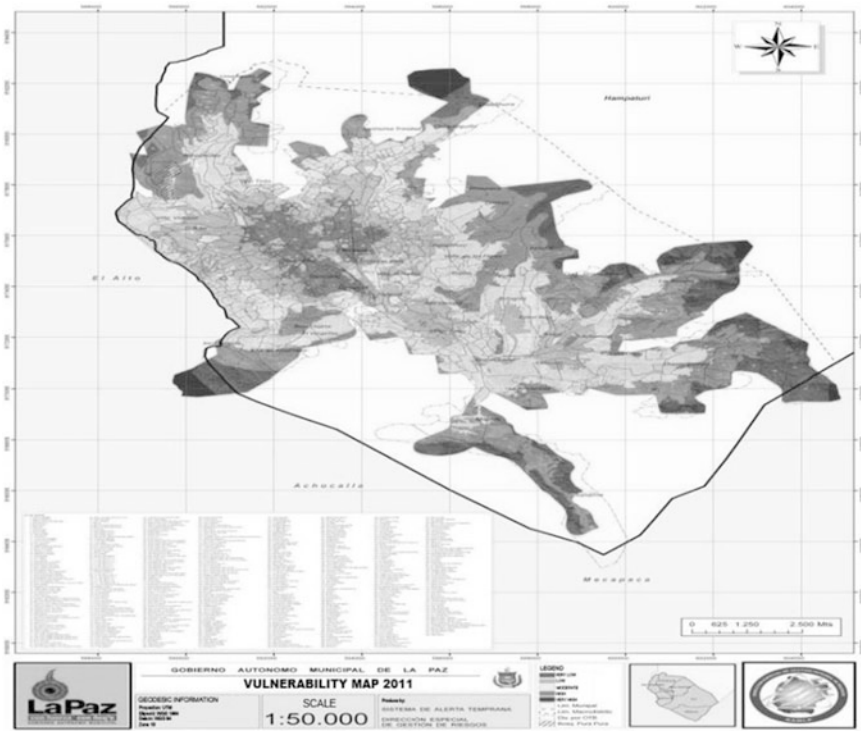
Fig. 15.9 La Paz Vulnerability Map 2011. *Source:* DEGIR

Index of Reclassified Socioeconomic Vulnerability

On the basis of the vulnerability map the values were reclassified into five categories to make it easier to visualise the levels of vulnerability (Fig. 15.9). According to this index the city was classified as follows: moderate: 34.9%, high: 27.1%, very high: 16.3%, low: 16%, very low vulnerability: 5.6%. The areas with a very high level of vulnerability are located on the outskirts of the city.

By combining the hazard and vulnerability maps a risk map was obtained (Fig. 15.10) on which 36 areas of very high risk were identified (10% of the urban area of La Paz). The 2011 risk map determines geographical areas in which there is a risk of damage due to extreme hydro-climatic events and takes into account topography, geology, active geological faults, geo-mechanical characteristics of the soil, as well as the potential social, political or economic impact (Table 16.3). It determines the probability of each system being affected. The risk map makes it possible to plan protective measures, to regulate the use of the different geographical areas, and to govern land-use so as to ensure sustainability over time.
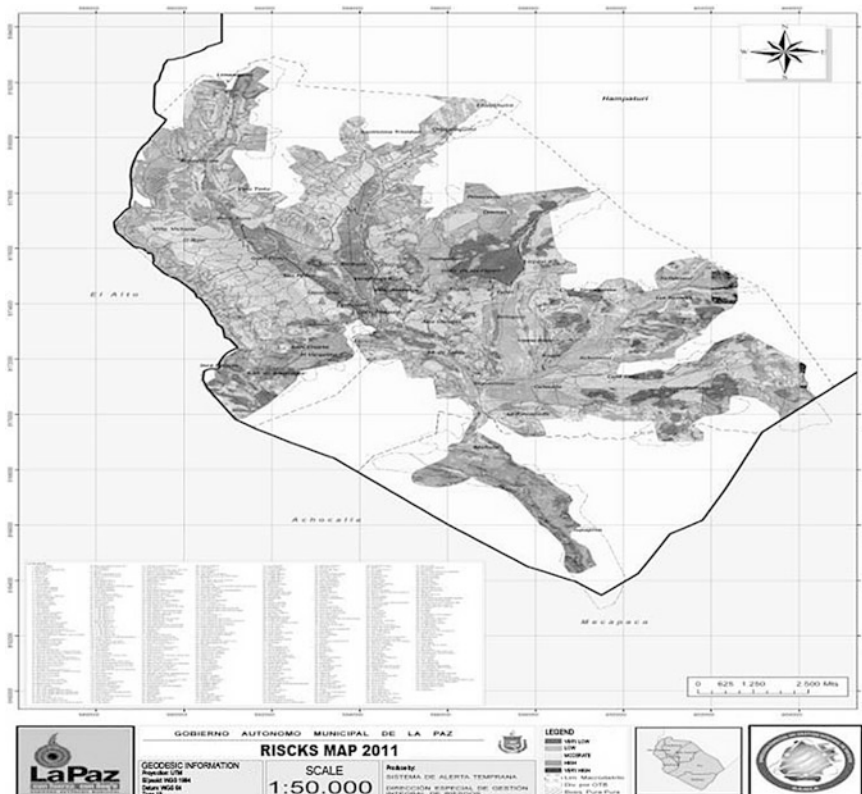
Fig. 15.10 La Paz Risk map 2011. Very high risk: 10% (*dark grey*), high: 21% (*gray* in south and southwest areas), moderate: 41% (*light grey* dispersed in the study area), low: 22% (*light grey* dispersed in the middle of the study area), and very low risk (*grey* in the middle and northwest of the study area): 6% (*dark green*). *Source:* DEGIR

Adaptation Measures

To achieve an integrated adaptation and risk-management approach we intended to inter-link the practices for analysing human and environmental systems, both in the fields of the social and the natural sciences.

Climate adaptation and vulnerability, and risk-reduction remains fragmented given the different scientific approaches and disciplines involved. In order to modify this situation the authors applied an interdisciplinary participatory approach aiming to include multiple stakeholders, population, municipal authorities and researchers. A list of measures has been selected based on consultation with experts, surveys and collaboration with the institutions. Table 16.4 shows a description of the wide range of adaptation measures proposed to address extreme events and climate change and variability, categorised according to whether they

are institutional (I), social (S) and technical capacities (T), and whether they are high-priority (HP), i.e. to be implemented in the short term; medium-priority (MP) or low-priority (LP), i.e. to be implemented in the medium or long term respectively.

Conclusions, Main Lessons and Future Prospects

La Paz city is experiencing climate change with hotter summers. A decrease in snow-fields and water bodies has been observed. Also, extreme hydro-climatic events have been recorded in February 2002 and 2011, the latter related to a La Niña event. Rainfall patterns are apparently changing with variations in their quantity and frequency, and a greater tendency towards short-term extreme events.

The quantity of precipitation and soil saturation—attributable to the number of rainy days, possible non-controlled sewage emissions, upwelling of subterranean water, and to the quantity of maximum precipitation registered in the days before the landslide, have very likely been the cause of the landslide. Moreover, there are reports of leaks in the drinking water system, water erosion in the area due to its natural drainage network, the over-exploitation of dry land at the foot of the slope, the construction of housing in the risk area leading to an increase in the weight supported by the foot of the slope, and the area's abrupt and unlevel landscape preventing the consolidation of the slope.

The observed increases in heavy rainfall, overflowing and landslides, in addition to urbanisation, have affected houses at instable soils in addition to the preexistent house deficit. Nevertheless, there are no new building regulations to reduce the impact of landslides. This is a priority planning for La Paz city.

The basin and in particular the headwaters provide an important service for the ecosystem by providing water for the southern region of La Paz. A large number of flora and fauna species have been identified in the basin, including indigenous regional species and introduced or migrant species. The Irpavi-Callapa basin is affected by a number of human activities: agriculture and livestock, urbanisation and the construction of major dam projects. However, a number of areas still preserve their vegetation (both native and introduced species), which supports the native biota of these high-Andean environments. Other semi-natural ecosystems protect the basin from landslides and continue to enable water collection for the city of La Paz.

Several factors played a role prior to the landslide: housing had increased the weight of the soil; there had been a history of landslides since the 1930s; there were leaks from the water system, coupled with an abnormal rainfall profile in February 2011 (thick water films after rainfall, with maxima recorded days before the landslide, combined with soil saturation due in part to 25 days of precipitation), in addition to possible uncontrolled sanitary discharges and groundwater outflows, could all have caused the landslide. Nor should the overexploitation of barren land and agriculture at the foot of the slope be discounted.

The Early Warning System and Mapping developed after the mega-landslide of February 2002 showed to be effective to strongly reduce impacts during the mega landslide of February 2011. The latter led the authors to analyse the success of the EWS and propose further VIA assessment focused on risk factors research, adaptation measures and to improve its preparedness.

The main lessons are:

Professional capacity and leadership of the DEGIR (Risk Management Directorate) of the GAMLP (La Paz city government) enabled the development of an integrated early warning system, which shows the importance of applying before-event science-based knowledge, monitoring, hazard, vulnerability and risk map tools, as well as after-event preparedness. This experience was particularly successful in avoiding the loss of human lives.

The occurrence of La Niña events—which evolution can be followed on real-time—is useful for preparedness of the EWS, particularly during summer. Nevertheless, the lack of updated building regulations remains as a barrier to achieving a better adaptation.

An expert judgment based on interdisciplinary scientific knowledge and previous mapping was coupled with a participatory process including consultation with municipal experts, and meetings and interviews with stakeholders. As a result, new composed risk maps were produced, and adaptation actions were proposed.

Future prospects:

The integrated VIA assessment approach, tools and actions presented in this chapter should be useful for municipal planning and further decrease of landslide harms and losses. The implementation of the adaptation measures proposed herein will contribute to further reduce infrastructure harms and losses, and the population at risk.

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