3.5

Hydrological Risk: Landslide

__Nicola Casagli__, Fausto Guzzetti, Michel Jaboyedoff, Farrokh Nadim, David Petley

3.5.1 Introduction

The term landslide encompasses a wide variety of phenomena, from the simple fall of rock blocks from vertical rock faces, through to topples and landslides that are dominated either by a sliding motion or by flows of soil and/or rock. Landslides are strongly correlated with other types of natural hazards, such as floods, droughts, wildfires, earthquakes, tsunamis and volcanoes, and are often involved in cascading events of multihazard disasters.

Climate change, the increased susceptibility of surface soil to instability, anthropogenic activities, growing urbanisation, uncontrolled land use and the increased vulnerability of populations and infrastructure contribute to the growing landslide risk. In the Thematic Strategy for Soil Protection (European Commission, 2006), landslides are considered one of the main threats to European soils. In this framework, landslide disaster risk reduction should be properly undertaken in order to reduce the impact of landslides on humans, structures and infrastructures. In areas with high demographic density, protection works often cannot be built owing to economic or environmental constraints, and is it not always possible to evacuate people because of societal reasons. Forecasting the occurrence of landslides and the risk associated with them, and defining appropriate EWSs, are, therefore, essential needs.

> *The term 'landslide' describes a variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill or a combination of these.*

The societal and economic impact of landslide risk is difficult to assess and it is underestimated, since a relevant part of related damage is attributed to other natural hazards, in multihazard chains (e.g. seismically induced failures, rainfall induced debris flows, lahars and rock avalanches associated with volcanism).

An established worldwide scientific landslide community has flourished in the last decades, thanks to several international organisations, such as the International Consortium on Landslides and the Landslide Joint Technical Committee, which periodically organise the World Landslide Forums and the International Landslide Symposia, respectively. Regular landslide sessions are also organised at the General Assembly of the European Geoscience Union each year.

In this subchapter, the main causes and triggers of landslides and their socioeconomic impact at European level are described, before some general concepts and methodologies on landslide zoning (inventory, susceptibility and hazard maps) and EWSs based on the analysis of landslide monitoring data and rainfall data are introduced.

3.5.2
Landslide causes and triggers

The most recent landslide classification is found in Hungr et al. (2014). It discerns five main types of movement: falls, topples, slides, spreads and flows. Many landslides consist of a variety of movement types occurring in sequence. For example, large landslides in high mountainous areas often start as rock falls involving freefalling rock that detaches from a cliff, which upon impact at the cliff toe may spontaneously transition into a very high-energy rock avalanche (Hutchinson, 1988). The properties of the flow change further as the landslide entrains or deposits debris and water.

Landslides vary greatly in size. At the largest scale, a single landslide can involve up to some cubic kilometres of rock and soils. At the other end of the scale, a small boulder has the potential to cause loss of life, if it strikes an individual, or to cause mass fatalities if, for example, it causes a train to derail. In general, the potential to cause loss scales with size of the landslide, largely because of the scaling of the kinetic energy and the affected area.

A key causal factor for landslides is the topographic setting of the potential site. In general, the propensity to failure usually increases as the slope angle increases, from essentially zero on a flat surface to a significantly higher level when slopes are steep. However, the relationship with geological factors is highly non-linear, and below a key gradient, any given slope is likely to be stable under most conditions. Slopes naturally evolve into a stable state under any given set of environmental conditions, primarily through landsliding processes. External factors disrupt the slope equilibrium to induce instability; thus, for example, a migrating river channel or an unusual flood may erode the toe of a slope, increasing the slope gradient and the likelihood of failure. The slope will then naturally evolve back to its stable gradient through time, perhaps by means of another landslide that removes the excess material.

A second set of causal factors relates to the type of material involved in the potential instability and its geotechnical properties, such as internal friction and cohesion. In hard rock masses, stability is usually defined not by the intact strength of the material but by the joints, fractures and faults. The strength of these discontinuities may be dramatically lower than the intact rock strength, especially where they are lined with a weaker material. Where such a discontinuity has an orientation that promotes failure, the resistance of the slope to landsliding can be dramatically reduced. Therefore, in many cases, analysis of susceptibility depends on an understanding of the role played by these discontinuities. Furthermore, the strength of slope materials degrades through the processes of weathering, which may physically and chemically alter the constituent minerals or may break an intact mass into smaller, weaker pieces. Therefore, the susceptibility of a slope to failure may increase with time.

Earth materials interact closely with hydrology and hydrogeology. Water is probably the most important factor that promotes slope instability. In many cases, water influences the strength parameters of geological materials, generally reducing strength when materials become saturated. Pore water pressure changes the effective stress state of a slope, typically reducing resistance to shear forces, and promoting instability. The lack of understanding of hydrological conditions is a frequent cause of failure in managed slopes; the 1966 Aberfan disaster in South Wales for example (Bishop et al., 1969), in which more than 140 people were killed by a landslide from a mine waste tip, was primarily the result of the construction of the tip on a spring and watercourse, which promoted conditions of full saturation after periods of heavy rainfall. However, water can also have more complex relationships with instability. For example, in some materials partially saturated conditions can provide additional strength through the generation of suction forces, while in others saturated conditions can promote soil liquefaction after failure, turning a slow landslide into a highly mobile and highly destructive flow.

Land use can also be a key factor in landslide causation. Some types of vegetation can improve stability by providing additional strength to the soil via root systems, and by regulating the infiltration of water and drawing down pore water pressures through transpiration. In general, forested slopes are more stable than those left bare, and there is a large body of evidence to support the argument that there is increased mudflow activity after fires have removed vegetation (Cannon and Gartner, 2005; Shakesby and Doerr, 2006) and increased landsliding after careless logging (Jakob, 2000). In general, the removal of vegetation promotes instability. Growing new vegetation is a difficult (but effective where successful) way to restore stability. Deforestation highlights the action of humans as the final key factor. As people modify the landscape, the likelihood of landsliding changes. In many cases, humans promote instability by cutting slopes to steeper angles, removing vegetation, changing hydrology and increasing weathering rates.

Landslide occurrence is related to causal factors, which create a propensity for a slope to fail, and triggers, namely the specific external event that induces landslide occurrence at a particular time.

In most cases, the timing of failure is associated with a trigger event. This is not always true, however; there is increasing evidence that slopes can fail through progressive mechanisms that involve the weakening of slope through time until stability is compromised, but such events are rare, although they can be destructive. However, most landslides are associated with a clearly defined trigger. Heavy rainfall is a key factor in generating landslides, primarily through the generation of pore water pressures and thus a reduction in the effective normal stress. For example, the annual global landslide cycle is dominated by the effects of rainfall associated with the South Asian and East Asian monsoons (Petley, 2010). The impact of the South Asian monsoon on the southern edge of the Himalayas, allied with the topography and materials of the region, makes this the global hotspot for landslide occurrence. However, the same correlation holds true everywhere.

The second key factor, and possibly the most important in terms of loss of life, is the impact of seismic events. Large earthquakes in mountain chains can trigger extraordinary numbers of landslides. Recent events include the 2005 Kashmir (Pakistan) earthquake and the 2008 Sichuan (China) earthquake, both of which killed more than 20 000 people in landslides. The Sichuan earthquake alone triggered more than 100 000 landslides. At present, the nature of the interaction between seismic waves and slopes is poorly understood, and forecasting the impacts of a future earthquake in terms of landslides is fraught with difficulty. However, the high levels of loss suggest that this will be a key area of research in the future.

Humans can also be a key trigger of landslides. The construction of hydroelectric stations can be significant. The Three Gorges Dam in China, the world's largest hydroelectric project, is expected to lead to the ultimate relocation of 1.4 million people owing to the construction of a 650-km long reservoir and the increased landslide risk; similar problems can be also found in Europe but to a lesser extent. The Vajont rock slide (Italy) resulted in the deaths of more than 2 000 people in 1963, when rock fell into the reservoir impounded by the highest arch dam in the world at the time. Humans trigger landslides through slope cutting (especially for road construction), deforestation, irrigation, undercutting and changes in hydrology and blasting, among many other activities. Mining activities have a particularly large impact. In more developed countries, mining is therefore strictly regulated; sadly, in less affluent countries, regulation lags considerably, and losses are much higher.

Finally, in active volcanic areas, landslides can be a major problem. Some of the highest levels of loss have occurred as a result of the high-mobility volcanic landslide known as a lahar, and volcanic flank collapses, which can be tsunamigenic, may be the largest terrestrial landslides possible. Some of the deadliest landslide events on record have occurred in volcanic areas. Active volcanism promotes instability (the 1980 Mount St Helens eruption started with a landslide that depressurised the volcano), and dome collapse is common. Volcanic deposits regularly mobilise into high-energy flows, and hydrothermal activity can cause material strength degradation over large areas. Major debris avalanches, partially submarine, were triggered by the 2002 eruption of Stromboli volcano (Italy) and they caused tsunamis, in a typical multihazard domino effect (Tinti et al., 2006).

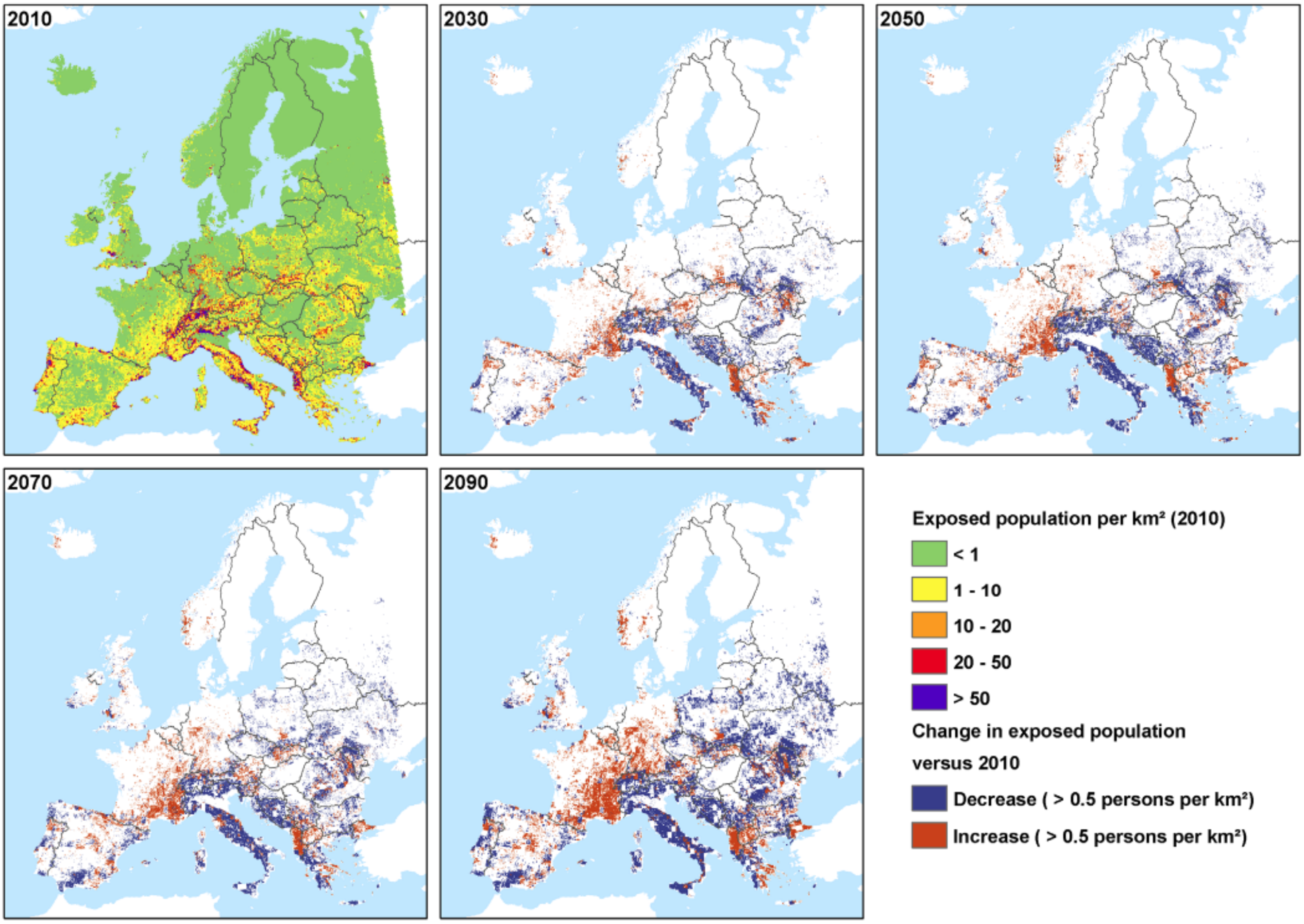
3.5.3

The socio-economic impact of landslides in Europe and climate change

The fast-paced changes in society, climate change and the human impact on the environment have a major impact on the frequency and spatial distribution of landslides. Annual climate data in Europe for the last two centuries demonstrate a shifting pattern in frequency and intensity of extreme weather events (IPCC, 2012, 2013). Along with the changes in climate and weather patterns, demography, land use and other factors driving the landslide risk are changing rapidly (UN, 2015). Indeed, projections through the 21st century for Europe indicate that societal changes may lead to a larger increase in the impacts from landslides and other natural hazards than climate change. Therefore, the changes in the socioeconomic impact of landslides should be considered at two different timescales. The influence of climate change on the spatial and temporal characteristics of landslide risk will be noticeable by the end of the century. At a shorter timescale of one to two decades, the rapid changes in anthropogenic factors such as urbanisation and land use change drive the dynamic risk pattern that we face today.

FIGURE 3.26

Estimate of changes in the exposure of Europe's population to landslides in the 21st century
Source: SafeLand (2013)



Regional climate model (RCM) simulations from the EU FP6 project ENSEMBLES (Van der Linden and Mitchell, 2009) predicted a consistent large-scale pattern of heavy precipitation changes in Europe. The simulations generally showed an increase in heavy precipitation over northern and central Europe in winter, although some inconsistencies were found among the predictions from different models in mountainous regions and at the foothills of the mountains. In summer, most models agree on an increase in heavy precipitation over Scandinavia and reduced precipitation in southern Europe. The largest inconsistencies were found in the transition zone across central Europe, which separates areas with positive trends in the north and areas with negative trends in the south. Considering both the expected changes in patterns of extreme precipitation events and changes in other factors driving the landslide risk, the EU FP7 project SafeLand (www.safeland.no) assessed the expected changes in climate-driven landslide activity (magnitude, frequency) in Europe in the next 100 years.

It must be emphasized that any prognosis of the changes in the socio-economic impact of landslides due to climatic change involves a high level of uncertainty.

The SafeLand study estimated that landslide hazard threatens about 4 % of European citizens today. In addition to the people directly threatened in their homes, 8 000-20 000 km of roads and railways are exposed to high landslide hazard, causing additional direct threats to life and economic assets as well as problems for emergency response and recovery operations (Jaedicke et al., 2013). The SafeLand prognosis was that about 0.7% of the total European population will experience an increase in landslide risk by the end of the century, although in some parts of Europe the risk will be reduced. The spatial pattern of the expected change in the European population exposed to landslide risk is depicted in Figure 3.26. The main changes in landslide risk at the European scale shown in the figure are due to the changes in population pattern caused by migration and urbanisation.

The SafeLand project also made a detailed study of the changes in landslide risk pattern at local scale for selected sites in Europe for the period 1951-2050. For these studies, the climate simulations were downscaled to simulate localised heavy precipitation events in regions where rain-induced landslides occur on a regular basis. The downscaled climate models predicted an increase in landslide hazard at all sites. These results differed from the predictions provided by larger scale climate models at some locations. These differences might be explained by the refinement in the climate model used, which, for example, considered the influence of local topography on precipitation. This demonstrated that large-scale models are useful to evaluate the relative spatial variations of landslide activity, while local scale models are necessary for urban planners and local authorities to estimate the future risks associated with landslides and other hydro-meteorological hazards in their communities or regions of interest.

In addition, the large uncertainties in population and traffic evolution scenarios, land use changes and political decisions regarding urban development require that the key parameters driving landslide risk are accurately monitored and that the prognosis of landslide risk is continuously updated as new information becomes available and more accurate and refined climate change models are developed.

3.5.4

Landslide zoning: inventory, susceptibility and hazard maps

The mapping of landslides underpins disaster risk reduction strategies, integrating socio-economic impacts, and therefore the challenge is to analyse their causes and triggers in our changing environments. Owing to the extraordinary breadth of the spectrum of landslide phenomena, no single method exists to identify and map landslides and to ascertain landslide susceptibility and hazard.

In addition to predicting 'where' a slope failure will occur, landslide hazard forecasts 'when' or 'how frequently' it will occur, and 'how large' it will be (Guzzetti et al., 2005).

The simplest form of landslide mapping is a landslide inventory map, which shows the location and, where known, the date of occurrence and the types of landslide that have left discernible traces in an area (Guzzetti et al., 2012). Landslide inventory maps can be prepared by different techniques, depending on their scope and the extent of the study area. Small-scale inventories (≤1:200 000) are compiled mostly from data obtained from the literature, through inquiries to public organisations and private consultants, by searching chronicles, journals, technical and scientific reports, or by interviewing landslide experts. Medium-scale landslide inventories (1:25 000 to 1:200 000) are most commonly prepared through the systematic interpretation of aerial photographs at scales ranging from 1:60 000 to 1:10 000, and by integrating local field checks with historical information. Large-scale inventories (>1:25 000) are prepared, usually for limited areas, using both the interpretation of aerial photographs at scales greater than 1:20 000, very high-resolution satellite images or digital terrain models, and extensive field investigations.

An archive inventory shows information on landslides obtained from the literature or from other archive sources. Geomorphological inventories can be further classified as historical, event, seasonal or multitemporal inventories. A geomorphological historical inventory shows the cumulative effects of many landslide events over a period of tens, hundreds or thousands of years. In a historical inventory, the age of the landslides is not distinguished, or is given in relative terms (i.e. recent, old or very old). An event inventory shows landslides caused by a single trigger, such as an earthquake, rainfall event or snowmelt event, and the date of the landslide corresponds to the date (or period) of the triggering event. Examining multiple sets of aerial or satellite images of different dates, multitemporal and seasonal inventories can be prepared. A seasonal inventory shows landslides triggered by single or multiple events during a single season, or a few seasons, whereas multitemporal inventories show landslides triggered by multiple events over longer periods (years to decades).

Landslide susceptibility is the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions. Landslide hazard is the probability that a landslide of a given magnitude will occur in a given period and in a given area.

Conventional methods to prepare landslide inventory maps rely primarily on the visual interpretation of stereoscopic aerial photography, aided by field surveys. New and emerging techniques, based on satellite, airborne and terrestrial remote sensing technologies, promise to facilitate the production of landslide maps, reducing the time and resources required for their compilation and systematic update. These can be grouped in three main categories, including the analysis of surface morphology, chiefly exploiting very-high-resolution digital elevation models captured for example by LiDAR (light detection and ranging) sensors, the automatic or semi-automatic interpretation and analysis of satellite images, including panchromatic, multispectral and synthetic aperture radar (SAR) images, and the use of new tools to facilitate field mapping.

Qualitative and quantitative methods for assigning landslide susceptibility can be classified into five groups (Guzzetti et al., 1999): (1) geomorphological mapping, based on the ability of an expert investigator to evaluate and map the actual and potential slope instability conditions; (2) analysis of landslide inventories, which attempts to predict the future landslide spatial occurrence from the known distribution of past and present landslides (typically, this is obtained by preparing landslide density maps); (3) heuristic or index-based approaches, in which investigators rank and weight the known instability factors based on their assumed or expected importance in causing landslides; (4) process-based methods that rely on simplified physically based landslide modelling schemes to analyse the stability/instability conditions using simple limit equilibrium models, such as the 'infinite slope stability' model, or more complex approaches; (5) statistically based modelling contingent on the analysis of the functional relationships between known or inferred instability factors and the past and present distribution of landslides. Regardless of the method used, it is important that the susceptibility zonations are validated using independent landslide information, and that the level of uncertainty associated with the zonation is given (Rossi et al., 2010).

Landslide hazard is more difficult to obtain than landslide susceptibility, since it requires the assessment of the temporal frequency of landslides and the magnitude of the expected failures (Guzzetti et al., 2005). The temporal frequency (or the recurrence) of landslides, or of landslide-triggering events, can be established from archive inventories and from multitemporal landslide maps covering sufficiently long periods. Furthermore, where a landslide record is available, an appropriate modelling framework needs to be adopted (Witt et al., 2010). Alternatively, for meteorologically triggered landslides, one can infer the frequency of landslide events from the frequency of the triggering factors, for example the frequency (or the return period) of intense or prolonged rainfall periods. The uncertainty inherent in the prediction of triggers that may result in landslides adds to uncertainty inherent in the prediction of occurrence of landslides.

To determine the magnitude of an expected landslide, investigators most commonly revert to determining the statistics of landslide size (area or volume). Accurate information on landslide area can be obtained from high-quality geomorphological inventories. Determining the volume of a sufficiently large number of landslides is more problematic, and usually investigators rely on empirical relationships linking landslide volume to landslide areas (Guzzetti et al., 2009; Larsen et al., 2010; Catani et al., 2016). Finally, when determining landslide hazard as the joint probability of landslide size (a proxy for magnitude), the expected temporal occurrence of landslides (frequency) and the expected spatial occurrence (landslide susceptibility), great care must be taken to establish if, or to what extent, the three probabilities are independent. In many areas, given the available information and the local settings, this may be difficult to prove (Guzzetti et al., 2005). We expect that the quantitative assessment of landslide hazard will remain a major scientific challenge in the next decade.

Such identification of areas susceptbible to landslide hazard is essential for the landslide risk assessment and possible implementation of effective disaster risk reduction strategies. These strategies (Dai et al., 2002) include land-use planning, development control land, the application of building codes with different engineering solutions, acceptance, and monitoring and early warning systems. Land planning control reduces expected elements at risk. Engineering solution is the most direct and costly strategy for reducing either the probability of landsliding or the probability of spatial impact of a landslide. One approach is correction of the underlying unstable slope to control initiation of landslides (such as stabilisation of slope, drainage, retaining walls or planting), and the other is controlling of the landslide movement (such as barriers/walls to reduce or redirect the movement when a landslide does occur). The acceptance strategy defines acceptable risk criteria (Fell, 1994;Fell and Hartford, 1997); and the monitoring and warning system strategy reduces expected elements at risk by evacuation in advance of failure.

3.5.5 Landslide monitoring and early warning

These systems require a fine assessment of the socioeconomic impact of landslides, which must be based on accurate landslide mapping, as well as an understanding of their causes. EWSs for landslides are based on the reliable continual monitoring of relevant indicators (e.g. displacements, rainfall, groundwater level) that are assumed to be precursors to triggering landslides or reactivations. When values for these indicators exceed predefined thresholds, alarms are transmitted directly to a chain of people in charge of deciding the level of warning and/or emergency that must be transmitted to the relevant stakeholders, following a predefined process (Figure 3.27). In some cases, warnings can also be automatically transmitted. Usually, one to five alert levels are used (Blikra, 2008; Intrieri et al., 2013): the highest level may lead to emergency warnings to the population, evacuations or the use of sirens and loudspeaker messages in several languages to force people to move to a safer place, as in the case of tsunamis induced by landslides.

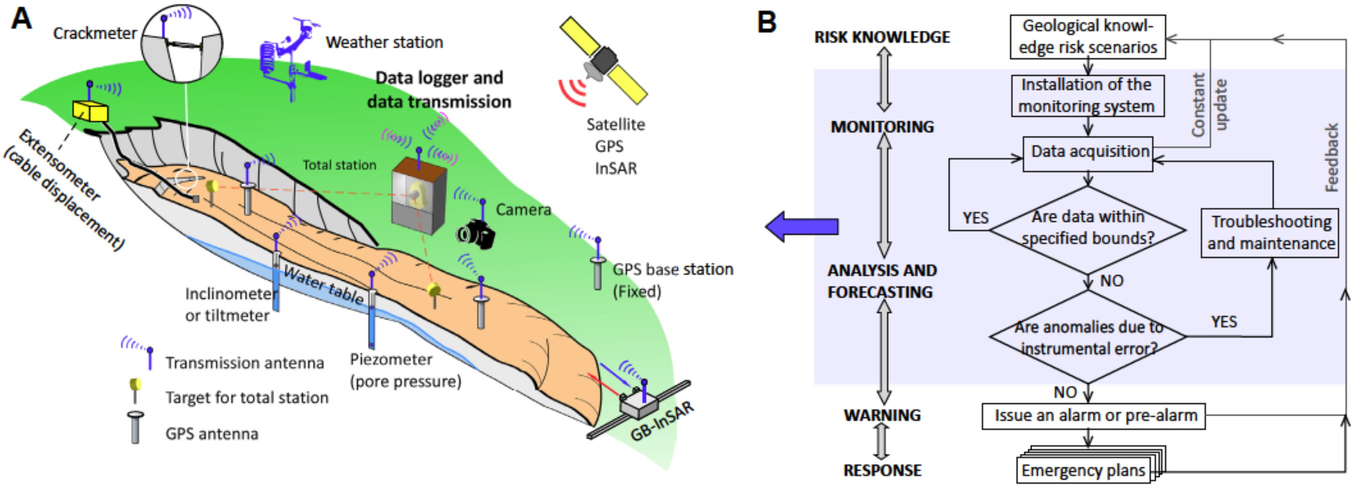
An EWS needs to be set up with specific requirements. First, the potential impacts must be defined based on a risk analysis informed by hazard mapping, including the impact of global changes (Corominas et al., 2014). In addition, the causes and triggers of disasters must be thoroughly analysed and the development of local coping capacities must be included (Dash and Gladwin, 2007).

The number of EWSs dedicated to landslides has greatly increased since the beginning of the 21st century because of the progress made in electronics, communication and computer programs for monitoring and imaging. In addition, the innovations in satellite technologies and ground remote sensing have greatly improved the capacity of remote imaging measurements versus in situ point measurements (Tofani et al., 2013). Implementing an EWS depends on the context, namely (1) the type of landslide (Hungr et al., 2014), (2) the disaster scenarios considered, (3) the degree of awareness of the stakeholders, including populations, and (4) the allocated resources (e.g. budgetary, human). Landslide types determine, first, if the appropriate EWS must be site specific or regional (Intrieri et al., 2013), and also if it is dedicated to identifying triggering conditions and/or to detecting an ongoing event (Sättele et al., 2016). For example, monitoring systems of debris-flow or shallow landslide EWSs are usually based on thresholds of rainfall amount over a period of time. These thresholds are based on rainfall intensity-duration, cumulated event rainfall-duration (Guzzetti et al., 2008), or antecedent precipitation (including snow depth) measures and soil moisture (Baum and Godt, 2010; Jakob et al., 2012). An extended monitoring of those indicators usually makes it possible, therefore, to set regional alarms. Landslide types also constrain the maximum lead time or time of reaction after the alarm transmission (Sättele et al., 2016). In some specific cases, debris-flow catchments are equipped with monitoring systems such as ultrasonic and seismic sensors that detect the debris-flow movements (Marchi et al., 2002) and automatically send a warning message to shorten the reaction time as much as possible.

For site-specific systems, displacements measured by different sensors and pore water pressure and/or precipitation are usually used (Michoud et al., 2013). Various sensors can be set to monitor displacements, including extensometers (cable or laser) and crackmeters that measure the distances between two points, and total stations that are also used to provide distances and 3D positions using targets positioned on site. Moreover, GPSs

FIGURE 3.27

(A) Illustration of the components of a modern EWS that does not show the energy sources and the two or three levels of redundancy. (B) Flow chart of the activities of the implementation and operation of an EWS (modified from Intrieri et al., 2012). The blue box in (b) indicates the action linked to the monitoring system. Source: courtesy of authors



are nowadays widely used, which can give the real 3D position of a point (Gili et al., 2000). All the above techniques usually provide data only at specific point locations; thus, several of them must often be set up in a network to monitor areal deformations. Inclinometers give deformations at depth along boreholes, providing essential data on the changes in depth of landslide behaviour (Blikra, 2008). For the last few years, ground-based interferometric radar (GB-InSAR) has been used for the most critical landslides (Casagli et al., 2010; Blikra, 2012; Rouyet et al., 2016). It provides a map of the distance changes, from the GB-InSAR to the landslide surface, at a millimetre scale and with a time resolution of a few minutes. Satellite InSAR images are also used to monitor long-term displacement trends, with results being strongly dependent on the type of treatment. In optimal cases, the time resolution is about 6 days, with millimetre precision and metre spatial resolution (Berger et al., 2012). Finally, as landslides react to water infiltration, many instruments are dedicated to monitor water: rain gauges, piezometers, thermometers, barometers, moisture content sensors and other meteorological data. Pore water pressure changes monitored with piezometers usually have a good correlation with slope movements (Michoud et al., 2013).

Behind the implementation of the monitoring part of EWSs is the understanding of the landslide mechanisms, that is, the identification of the main parameters controlling the movements of the landslide (Intrieri et al., 2012 and 2013). For this purpose, the design of a landslide conceptual model (LCM) is fundamental, since it will guide the type and the location of the sensors to install, and it is required to forecast landslide failure scenarios. The updating of an LCM must be continual during the whole life of an EWS. In addition, landslide failures may trigger other hazardous events in a cascade effect, such as tsunamis or dam breaks, that have to be considered in the EWS. The reasons why an EWS is implemented are either the identification of an unacceptable risk level or an increase in, or abnormal, landslide activity. Although the LMC implementation process provides reasons to fix appropriate sensors that will monitor the most significant failure initiation indicators, there are usually many practical constraints, such as topography, access, visibility and available resources.

> *Landslide monitoring and EWSs are tools to forecast the potential occurrence of disasters, thus contributing to the implementation of effective disaster risk-reduction strategies.*

Ideally, the first data from a monitoring system are used to calibrate and fix alarm thresholds usually based on displacement velocities or accelerations, or pore water pressure or precipitations (Cloutier et al., 2015). This approach can be supported by failure forecast models, such as the Fukuzono method, or by more complex models (Crosta and Agliardi, 2003; Federico et al., 2012). The alarm thresholds will be used to trigger chains of actions that will involve different levels of people depending on the alert level, from technicians and experts to officers and politicians who will be involved in the assessment of the abnormal situations and who will have to make decisions (Froese and Moreno, 2014). This starts from the initial check of the situation and the coherence of the movement detection of the sensors (to avoid false alarm), and it can end with an evacuation decision. It requires that the monitoring system is reliable and is therefore redundant in terms of sensors, communication and the stakeholders involved. Pre-defined crisis units must follow decision trees to propagate or stop the warning at each level. This also necessitates the requirement to verify constantly that the observed landslide behaviour is still following the expected course, which also implies that the threshold and alarm levels can be reassessed by the crisis units.

The most important actions that can be prompted by EWS high-alert levels are evacuations and a rapid set-up of protection measures. They imply that all stakeholders, including the relevant population, must be prepared through education and training to implement the appropriate response.

In addition, the methods used to emit and communicate the emergency situation must be adapted to the local population culture. It must be stressed that all stages of implementation or operation must include feedback to the other stages. Frequent feedback and updates are a key point. They must also include the reappraisal of the indirect effects (cascade). A final problem relates to communication to the general population, which, to be effective, needs trust and training and must be an efficient means by which to communicate and emit warnings and actions within the noise of our 'connected world'. It appears that only 38 % of the EWSs have more than one communication vector to inform the population (Michoud et al., 2013).

3.5.6
Conclusions and key messages

Partnership

Understanding landslide risk requires a multihazard approach, based on networking and partnership between different scientific disciplines, with transdisciplinary research that aims to identify those socioeconomic and institutional elements that require attention in landslide DRM.

Knowledge

Knowledge of landslide risk is a multidisciplinary task that requires an understanding of processes and mechanisms, spatial and time prediction, vulnerability assessment, monitoring and modelling of the effects related to environmental and climate change.

Innovation

The effectiveness of landslide risk mitigation measures critically depends on scientific innovation and technological development for rapid mapping, monitoring and early warning.