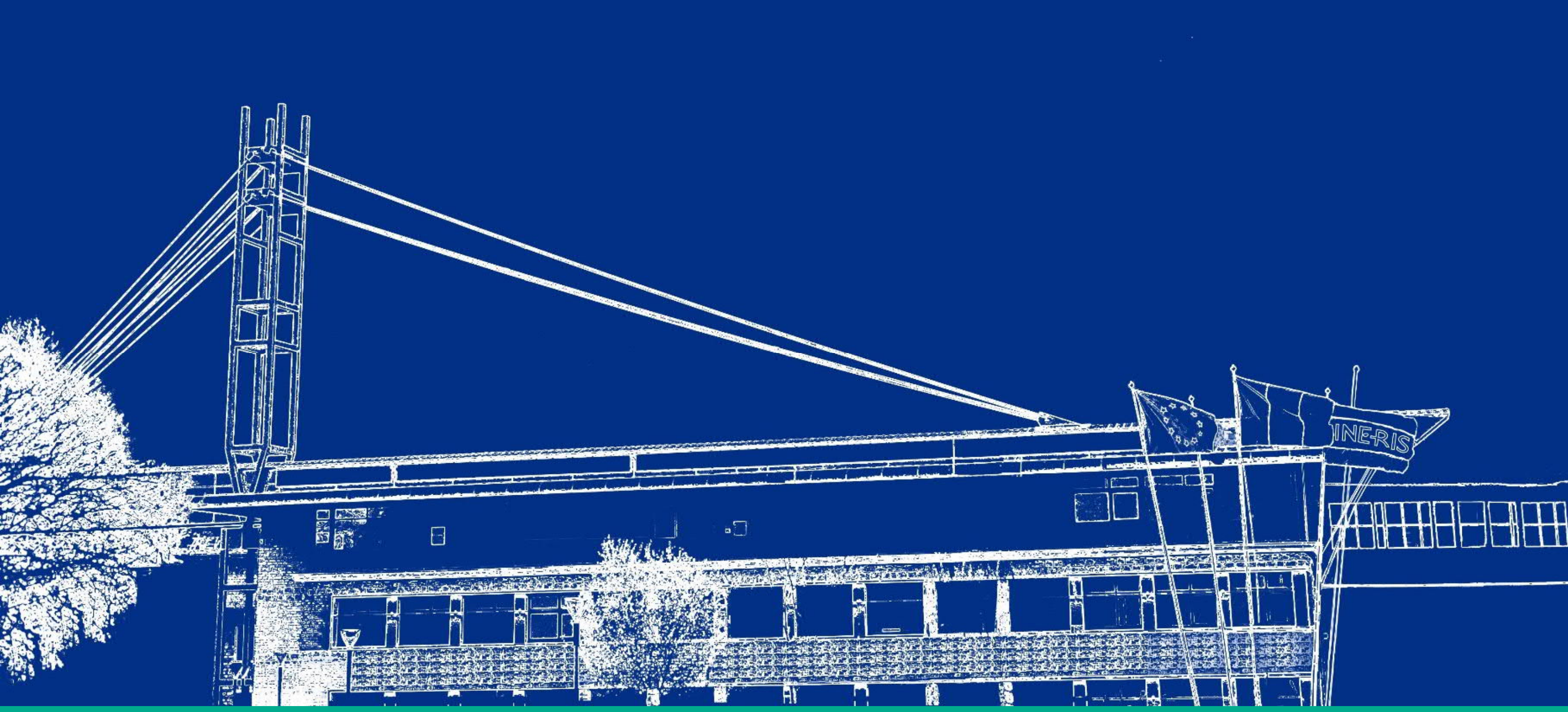

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26/06/2020

# Early warning systems for slope instabilities: concepts, feedback and perspectives

controlling risks
for sustainable development

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This report was reviewed by Mrs Margaret HERBAUX (Director of the ground movements mission, General Directorate for Risk Prevention SRNH/BRNT) and Mr Laurent DUBOIS (Head of the Geological Risk Unit, CEREMA Centre-Est), experts in ground movement monitoring. We thank them for their pertinent observations and comments that have contributed to improve this report.

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**Abstract**

In some contexts, the only solution to manage the risk of slope instability induced by precipitation is to set up an early warning system. Such systems are designed to issue warnings at the right time to enable action to be taken and to guarantee public safety. They are generally complex in nature and deployed according to the conditions and selected means. Each system is tailored made to the site, hazard, and the affected population. The oldest versions date back to the end of the 1970s and were, for the majority, introduced following a major catastrophe, generally under the auspices of government services or agencies.

They have developed progressively over the last few decades in line with climate change and the growing urbanisation of at-risk areas. Although they were originally hazard-centered, these systems are increasingly focusing on the affected populations since many now consider response capability to be the key to effective functioning.

Early warning systems for slope instabilities induced by precipitation can be deployed at two scales: local or regional. At the local scale of a single instability, they mainly function by acquiring and assessing in real time qualitative data describing the evolution of the hazard. At the regional scale (depending on the case, the ‘region’ can be a town, a region or even a country), the warning systems can simultaneously cover several types of instability and tend to function by monitoring weather conditions in conjunction with probabilistic instability models. Sometimes, these two types of system coexist in the same area, requiring a clear, coherent and transparent division of responsibility between the different stakeholders.

The examples from the literature show that the synergy between systems coexisting in the same area is still underdeveloped, often resulting from the lack of a comprehensive coordination framework. Competition between teams or even between different technical solutions, or the fear of issuing false alerts or failing to alert when needed, also inhibit synergy between systems and knowledge-sharing between peers. This can prevent methodological approaches or technological tools from being deployed and common standards from being established. Progress could thus be made by developing and generalizing feedback loops, drawing inspiration from approaches or action frameworks to be found in other domains, such as industry or in the context of other natural hazards.

This report ends with a few reflections on the need to develop a genuine risk culture within the civil society, with strong political support, to facilitate the integration and acceptance of early warning systems, among other solutions. Finally, some recommendations are also made concerning the prevention of major natural risks in France.

**Key words**

Landslides, early warning, risk, management, climate change.

**Territory**

France, Europe, World.

**Résumé**

Dans certains contextes, la seule solution pour prévenir le risque d'instabilité de pente induit par les précipitations repose sur la mise en œuvre de dispositifs d'alerte. Leur but est d'émettre des alertes au moment opportun, pour permettre d'agir et garantir la sécurité publique. Ces dispositifs sont généralement complexes et déployés selon des conditions et des moyens ciblés, adaptés au site, au phénomène redouté ainsi qu'aux enjeux et aux populations exposées. Les plus anciens remontent à la fin des années 1970 et ont pour la plupart été mis en œuvre après une catastrophe majeure, généralement sous l'égide de services ou d'agences gouvernementaux.

Avec le changement climatique et l'urbanisation croissante de territoires à risque, leur développement a progressé au cours des dernières décennies. D'abord aléa centré, ces dispositifs sont aujourd'hui davantage tournés vers les populations exposées, la capacité de réponse étant considérée par beaucoup comme la clé de leur efficacité.

Les dispositifs d'alerte appliqués aux instabilités de pente induites par les précipitations peuvent être déployés à deux échelles : locale ou territoriale. A l'échelle locale d'une seule instabilité, ils reposent principalement sur l'acquisition et l'expertise en temps réel de données qualitatives permettant d'appréhender l'évolution de l'aléa. A l'échelle territoriale, le territoire étant selon les cas une ville, une région ou même un pays, les dispositifs d'alerte peuvent couvrir plusieurs typologies d'instabilités à la fois et reposent principalement sur la surveillance des conditions météorologiques couplées à des modèles probabilistes d'instabilité. Parfois, ces deux types de dispositifs coexistent sur un même territoire, ce qui nécessite une répartition claire, cohérente et transparente des responsabilités entre les différentes parties prenantes.

Les exemples tirés de la littérature montrent que la synergie entre les dispositifs, y compris sur un même territoire, est encore trop peu développée du fait souvent de l'absence de cadre de coordination globale. La compétition entre les équipes voire les solutions techniques, ou encore la crainte de communiquer sur les fausses alertes et les alertes manquées nuisent aussi à la synergie entre les dispositifs d'alerte et au partage de connaissance entre pairs. Cela peut pénaliser le déploiement d'approches méthodologiques ou d'outils technologiques et empêcher l'émergence de standards communs. Un élément de progrès consisterait donc à développer et généraliser le retour d'expérience en s'inspirant de démarches ou cadre d'actions déjà existants dans d'autres domaines, comme le domaine industriel par exemple, ou encore dans le contexte d'autres aléas naturels.

Ce rapport se termine par quelques considérations sur la nécessité de développer une véritable culture du risque au sein de la société civile, portée par une forte volonté politique, pour entre autres faciliter l'intégration et l'acceptation des dispositifs d'alerte. Enfin, quelques recommandations applicables au contexte de la prévention des risques naturels majeurs en France sont également formulées.

**Mots-clés**

Mouvements de pente, alerte précoce, risque, gestion, changement climatique.

**Territoire**

France, Europe, Monde.

# 1 Introduction

At global scale, our societies are becoming increasingly vulnerable to natural risks, independently of the effects of climate change (for example Haiti in 2010, Japan in 2011 and 2016, Nepal in 2015 and Switzerland in 2017). This growing vulnerability can be explained, notably, by demographic dynamics and the increasing urbanisation of at-risk areas.

In terms of harmful natural events occurring globally (source: catnat.net), earthquakes and ground movements represent ~15 % of economic and human losses, and landslides account for 17 %. Additionally, it is notable that the many recent landslides that resulted in significant human deaths and economic losses (Yin et al., 2009) occurred following climate events classified as extreme. These events are characterised by heavy rain, sometimes over a long period.

In some contexts, typically in cases of large-scale movements or major risks, the only solution to prevent the risk of slope instability induced by precipitation is to implement an early warning system. The aim is to issue precise warning information, at the right time, to enable action to be taken and to reduce damage and loss. Generally, these risk mitigation measures are deployed according to the conditions and selected means. Each system is adapted to the site, hazard and affected population it covers.

Currently, the best documented systems are those for instabilities induced by precipitation.

This report, produced in the context of Ineris' mission to support the public authorities, aims to consolidate the internationally-available literature and feedback on early warning systems for slope movements induced by precipitation. It is based on the available scientific literature alongside information collected during discussions with the operators responsible for the management of the early warning systems in operation in Europe.

To provide some background for this study, this report begins with a description of the general context of early warning systems and their basic components. We will thus see that since the end of the 1970s when the first systems were introduced, the characteristics of these systems have changed significantly. A warning system today is a package of integrated tools and processes which include informing populations and preparing them for action. Thus, this study does not cover scientific observation systems (for example the OMIV in France), nor the monitoring systems that do not address the issue of response capability. These distinction and approach are in line with those proposed by Guzzetti et al. (2019).

An early warning system can be deployed at the scale of a single slope or at regional scale, following different approaches. We will see that there are no completely automated systems; human appraisal is always a fundamental factor in ensuring the effective functioning of these systems. Sometimes, local and regional systems coexist in the same area, which can lead to difficulties in the absence of an overall coordination framework. In order to illustrate the conditions and frameworks in which these different systems operate, this report focuses on four exemplary systems: the Ruines de Séchilienne in France and Ancona in Italy at the local scale, and Norway and Hong Kong at the regional scale.

The report concludes by addressing the issues of effectiveness and synergy between systems and approaches, and by discussing the current innovations under development. These innovations focus on technology, such as the expected contribution of learning techniques based on artificial intelligence to support human appraisal, and the predictive models based on the physics of the phenomena in question. We also present some reflections on assessing and improving system efficacy. This report concludes with some recommendations concerning the prevention of major natural risks in France.

# 2 Context

## 2.1 Landslides

The term landslide covers several types of instability that differ by the nature of the materials in question, the volumes involved, the evolution mechanism and the kinetics.

There are several classifications in the literature (Varnes (1978), Flageollet (1988) and Dikau et al, (1996a)). The details of these classifications will not be explored here, but the best known is doubtless that of Varnes.

From the point of view of analysing and mitigating risk, the determining factor is the velocity of the movement. In fact, velocity directly influences the appraisal of the level of vulnerability. The latter increases as the movement velocity increases. In other words, rapid slope movements incur more victims than slow movements when the same volumes are involved (Maquaire, 2002). Moreover, the consequences of rapid movements are all the more destructive when significant volumes are mobilized.

The velocity of movement can be estimated and measured more or less precisely. Cruden and Varnes (1996) propose seven categories of velocity (from extremely slow to extremely rapid; from under 16 mm/year to over 5 m/sec). There are different types of impact that correspond to each category in terms of loss of human life and building damage. Category 1 describes movements that are imperceptible to the human eye and can only be identified by instrumental monitoring. Category 7 corresponds to a major catastrophe.

## 2.2 Large-scale movement and major risk

A major natural risk arises from the combination of a natural hazard and a vulnerability at a particular location, meaning that all the present people and goods could be affected by the natural phenomenon in question.

It is characterised by a low frequency of occurrence and by its extreme gravity. Its effects can affect a large number of people, incur significant damage and overwhelm the response capacities of the authorities directly concerned.

Two types of measures are generally used to reduce the risk, i.e. structural and non-structural, as illustrated in Figure 1. The decisions are taken on a case-by-case basis depending on the technical feasibility or allocated budgets.

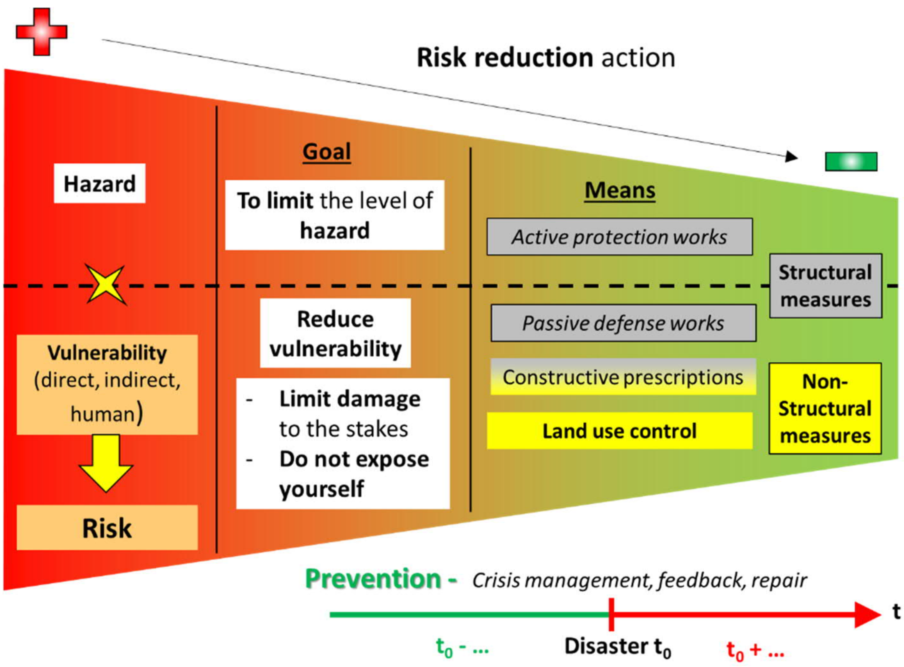


*Figure 1: notion of risk and reduction measures, derived from Tacnet, 2004.*

The structural measures involve the implementation of protective measures aiming to actively limit the intensity of the phenomenon (hazard) by acting on the causes of the phenomenon or by limiting the consequences or effects on the stakes in the context of passive strategies.
The non-structural measures include building regulations, managing ground occupation and deploying early warning systems (Tacnet, 2004 and Fell et al., 2015).

## 2.3 General information on warning systems

The first developments in early warning systems for natural risks date back to the 1970s. It is now accepted that these systems have led to a significant decrease in the number of victims of ground movements.

Although they were originally centred on specific hazards, these systems are now focused on the affected populations and prove to be an effective solution for reducing the risk. The governmental authorities and international institutions are therefore paying increasing attention to these types of system.

Since the 2000s, the European Commission has been supporting the development of early warning systems for natural risks (Alfieri et al., 2012). The aim is now to improve prevention, preparedness, protection, and response to natural disasters and to promote research and societal acceptance of the preventive measures for natural risks.

In 2005, the United Nations launched their 2005-2015 framework for action via the UNISDR[1], aiming in particular to introduce a "global early warning system for all natural threats" (Revet, 2009). In 2009, the UNISDR defined warning systems as "*the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss*".

International institutional support is also accompanied by the launch of two information platforms:

1. one by the UNISDR[1] focusing on promoting and developing these systems, accessible via http://www.unisdr.org/2006/ppew/;
2. the other by UNESCO[2] which lists the early warning systems for natural risks http://www.unesco.org/new/en/natural-sciences/special-themes/disaster-risk-reduction/geohazard-risk-reduction/early-warning-systems/.

## 2.4 The 4 components of warning systems

Following the principles of the United Nations, an early warning system is effective if it triggers an adapted reaction in the affected population. To do this, it should be based on the following four tightly linked components (UNISDR, 2006a et 2006b; Basher et al., 2006, etc.):

I. Good knowledge of risk: this requires adequate knowledge of both the hazard and the vulnerability;

II. Monitoring and warning services: these require a precise identification of the parameters to monitor in terms of instruments, and an estimation - with the greatest possible precision - of their evolution in order to enable a definition of alert thresholds compatible with the risk reduction measures;

III. Dissemination and communication to the affected populations: this is achieved through specific information channels using means that are known and understood by all. This also requires a high level of preparation prior to the alert;

IV. Response Capability: this relies on building and implementing response/emergency plans that are regularly tested for their pertinence/feasibility and accepted by all the stakeholders, including the authorities.

[1] United Nations Office for Disaster Risk Reduction

[2] United Nations Educational, Scientific and Cultural Organization

We should note that with its 2015-2030 Sendai Framework for Action, the UN[3] intends to put even more emphasis on preventing, managing, and reducing the risks of catastrophes rather than on reacting to catastrophes after they occur. In this sense, improving the understanding of all parties of the risk factors for a catastrophe is considered a key element in risk reduction.

## 2.5 Application to landslides

Figure 2 illustrates changes in the approaches deployed in cases of slope movements between 2007 and 2013. In 2007, the warning systems were centred on hazards and the main difficulty identified in their implementation was the setting of appropriate alert thresholds (Di Biagio & Kjckstad, 2007). In 2013, the approach was redirected towards improving the participation of all stakeholders, notably the affected population (Intrieri et al., 2013) now considered as an actor in risk prevention.

This change of approach, specifically for cases of landslides, thus aligns with the general considerations outlined in the preceding section. It was made possible by the technological developments of the last decades, and by feedback from and analysis of cases carried out, in a few countries. For example, in northern Italy (in Valtellina di Tirano), research carried out for the European project “Mountain Risks” (Garcia, 2011; Garcia et al., 2012) showed that the key factor in reducing the impact in society of landslides and natural risks in general is indeed the response capability, meaning society’s preparedness to respond that is developed through education and communication.

| UNISDR (2006) | Di Biagio and Kjekstad (2007) | Bell et al. (2009) | Intrieri et al. (2013) | Calvello et al. (2015) | Fathani et al. (2016) | Calvello (2017) |
|---|---|---|---|---|---|---|
| Risk knowledge | | | Planning | Decision making | Risk knowledge | Components of landslide model (part of warning model and warning system) |
| Monitoring and warning service | Monitoring | Monitoring | Monitoring | Monitoring | Monitoring and Warning | |
| | Analysis and forecasting | Modelling | Forecasting | Modelling | | |
| | Warning | | | Warning | | Components of warning model (part of warning system) |
| Dissemination and communication | | Implementation | | | Dissemination and communication | Other components of warning system |
| Response capability | Emergency plan | | | Emergency plan | Response capability | |
| | | | Education | Education | | |

*Figure 2: comparison between the UNISDR (2006) definition for all natural risks and the different schemas proposed in the literature for landslides, expressed in terms of the similarities and differences (modified from Piciullo et al, 2018).*

## 2.6 Local scale and regional scale

In the case of large-scale movements, the early warning systems are generally deployed at the local scale and mainly rely on collecting data in near real time on the most relevant physical dimensions to assess the evolution of the site, as well as on the external triggering factors.

The so-called local scale (Thiebes, 2011; Thiebes et al., 2012; Calvello et al., 2015b, 2016; Thiebes and Glade, 2016, Piciullo et al, 2018 and Pecoraro et al., 2018) is thus applied at the scale of a slope where a single type of landslide can be found.

The so-called regional scale (Thiebes, 2011; Thiebes et al., 2012; Calvello et al., 2015b, 2016; Thiebes and Glade, 2016, etc.) or territorial scale (Piciullo et al., 2018) applies to a region, a municipality or even a whole country. It can thus cover several types of instability at the same time (Cloutier et al., 2015). The approach taken is then mainly based on weather monitoring and consists in estimating the probability of occurrence of landslides.

In regional early warning systems, it is thus more difficult to identify the exact slope(s) where the failure occurred (Thiebes et Glade, 2016).

[3] United Nations

## 2.7 Details of major natural risk prevention policies

### 2.7.1 In France

In France, the natural risk prevention policy is based on an evolving legislative framework, for which the main provisions were adopted following major catastrophes.

The milestones of this evolution are presented in Figure 3. The first milestone came with the 1982 law that introduced Risk Exposure Plans (*plans d'exposition aux risques,* PER) and created a natural catastrophe compensation scheme. The second came with February 1995 law that replaced the PERs with more flexible PPRs (*plans de préventions des risques,* risk prevention plans) and set up the major natural risk prevention funds (*fonds de prévention des risques naturels majeurs,* FPRNM), known as the Barnier funds, to reinforce and unify preventive action. Then in July 1987, article L 125-2 of the Environmental Code stipulated that citizens have the right to be informed about the major risks to which they are exposed and about the safety measures concerning them. Finally, in July 2003, the law on technological risks also applied in the domain of natural risks.

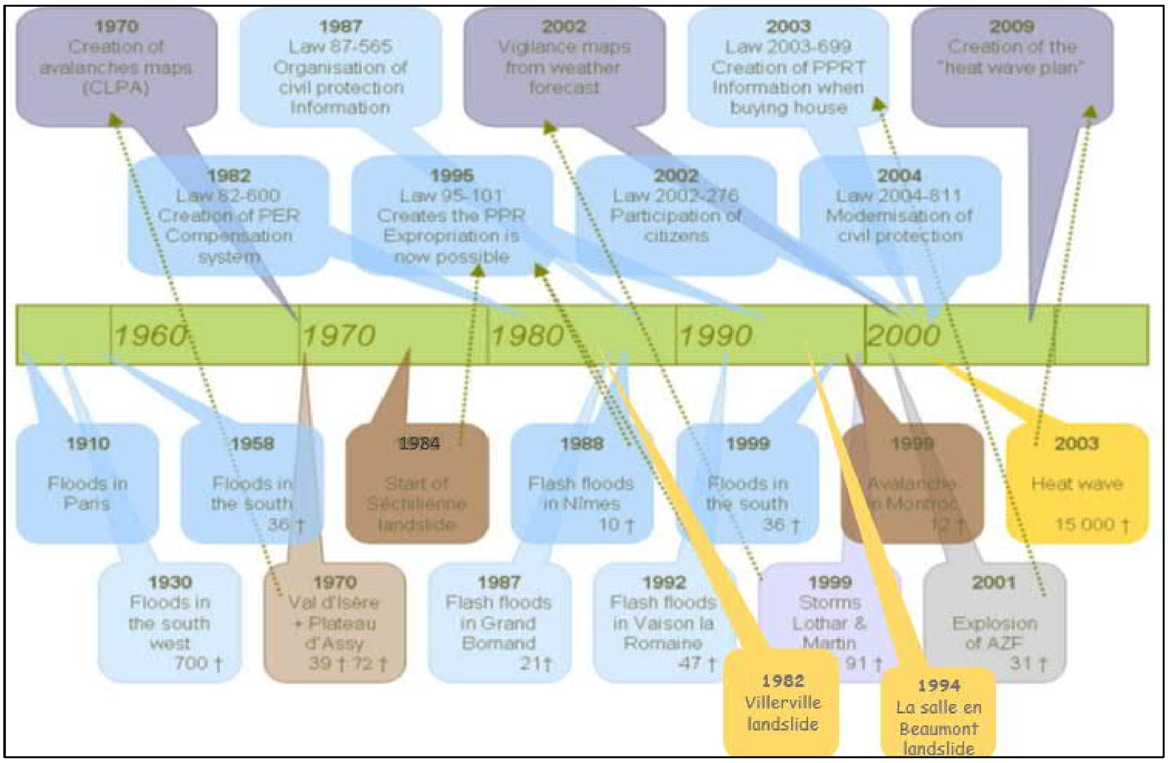


*Figure 3: evolution of the legislative framework in France from 1960 to 2010 (source: projet FP7 Safeland).*

The implementation of this natural risk prevention policy is still based on a centralised organisation and shared competencies, involving the State and its devolved services, regional authorities and citizens.

In response to a major risk of large-scale ground movement, the State organises monitoring and warning actions. The State thus participates in deploying and managing the early warning systems through interventions by its services or through subsidies granted to local authorities. These systems generally constitute a temporary solution to control the risk, aiming to guarantee people's safety until permanent solutions are found (expropriation of affected populations, reinforcements, protective structures, etc.).

Among the different landslides and rockfalls, four major active land movements can be found in France today: Roquebillière, Combelouvière, Ruines de Séchilienne (presented in section 4.1) and La Clapière (Trielli, 2014). The latter two were subject to studies and works funded by the Barnier funds (cf. article

38 of the Amending Finance law in 1997). They also received DGPR funding[4] (Bop 181 and subsidy through the national programming of State operators).

### 2.7.2 In Italy

The situation in Italy is very different from that in France due to its geomorphological and geological context which is conducive to slope and hillside instabilities.

The very first regulations thus appeared very early, in 1904, and have been repeatedly strengthened over the last century, often following catastrophic events. In 1982, the legislative framework was marked by the creation of the National Civil Protection Department. It then refocused on a more integrated approach to manage the risk of flooding and ground movements. We should also note that since the start of the 2000s, the centralised organisation has been abandoned in favour of governance at several scales which recognises the contribution of a large number of stakeholders.

This risk prevention policy and its organisation have led to the development of early warning systems at different scales (at the scale of municipalities, provinces and regions), under the authority of different bodies. Thus, Italy now has 21 early warning systems including those of Emilia Romagna (Berti et al., 2012; Lagomarsino et al., 2013), Piedmont (Tiranti et Rabuffetti, 2010), Campania (DPGR n. 299/2005), Tuscany (regional laws DGR n. 895/2013 and DGR n. 395/2015), Umbria (regional law DGR n. 2312/2007, Ponziani et al., 2013; Francesco, 2010) and Sicily (regional law DPRS n. 626/2014), etc.

This situation led the DPCN to publish an operational guide[5] in 2016 intending to harmonise the levels of criticality and alert, as well as the warning messages. They are now colour-coded (yellow, orange and red) and for each level, the associated event and risk scenario is described. However, no specific criteria have been established to set the thresholds or the warning criteria. Each authority is thus free to make its own decisions based on the information available on the phenomenon and the acquired expertise.

### 2.7.3 Elsewhere in Europe

In general, we can note that the most affected countries are more advanced in terms of legislation and organisation, but plenty of work remains to be done at a global scale. Regrettably, progress in national natural risk management policies is generally only made following traumatic events. In this sense, Norway is a textbook case, since some measures, such as the introduction of a prototype early warning system at the Aknes site, were taken under intense pressure from the population and the media.

# 3 The early warning systems across the world

## 3.1 General overview

Figure 4 presents a non-exhaustive map of early warning systems deployed at regional scale, created by Piciullo et al. (2018) from the scientific literature available. Half of these were deployed following a catastrophic event induced by intense rain (see the red rectangles in Figure 4). We can also see that the different cases greatly vary in terms of the size of the zones they cover: the systems can cover a region (12 systems), a large metropolis (6 systems) or an entire country (5 national systems). Then at this scale, the types of instability vary and also include artificial slope instabilities, such as in Sri Lanka, Bangladesh and Hong Kong.

Pecoraro et al (2018) created a map of the local-scale systems from the available scientific literature (Figure 5). We note that information on the type of monitored hazard is not always available, but the majority of systems cover natural slopes: most of them are superficial landslides and fast-moving mudslides (Cruden et Varnes, 1998).

Some of these systems were set up following a research project. The transition from research to operation occurs when knowledge of the hazard is satisfactory and the conditions and means of issuing alerts are perfectly understood by the experts. Let us cite for example, the work carried out in 2007 by

[4] General Directorate for Risk Prevention

[5] See http://www.protezionecivile.gov.it/jcms/it/view_prov.wp?request_locale=it&contentId=LEG56184

the German project ILEWS (Integrative Landslide Early Warning Systems), where the main aim was to develop and implement a new system design that more fully integrates the human component (Bell et al., 2008; Thiebes et al., 2012).

The maps below show that Italy constitutes a unique case since the national warning system (called SANF[6]) coexists with the regional systems, which themselves integrate the local systems applied at the level of a single slope (see also section 2.7.2).

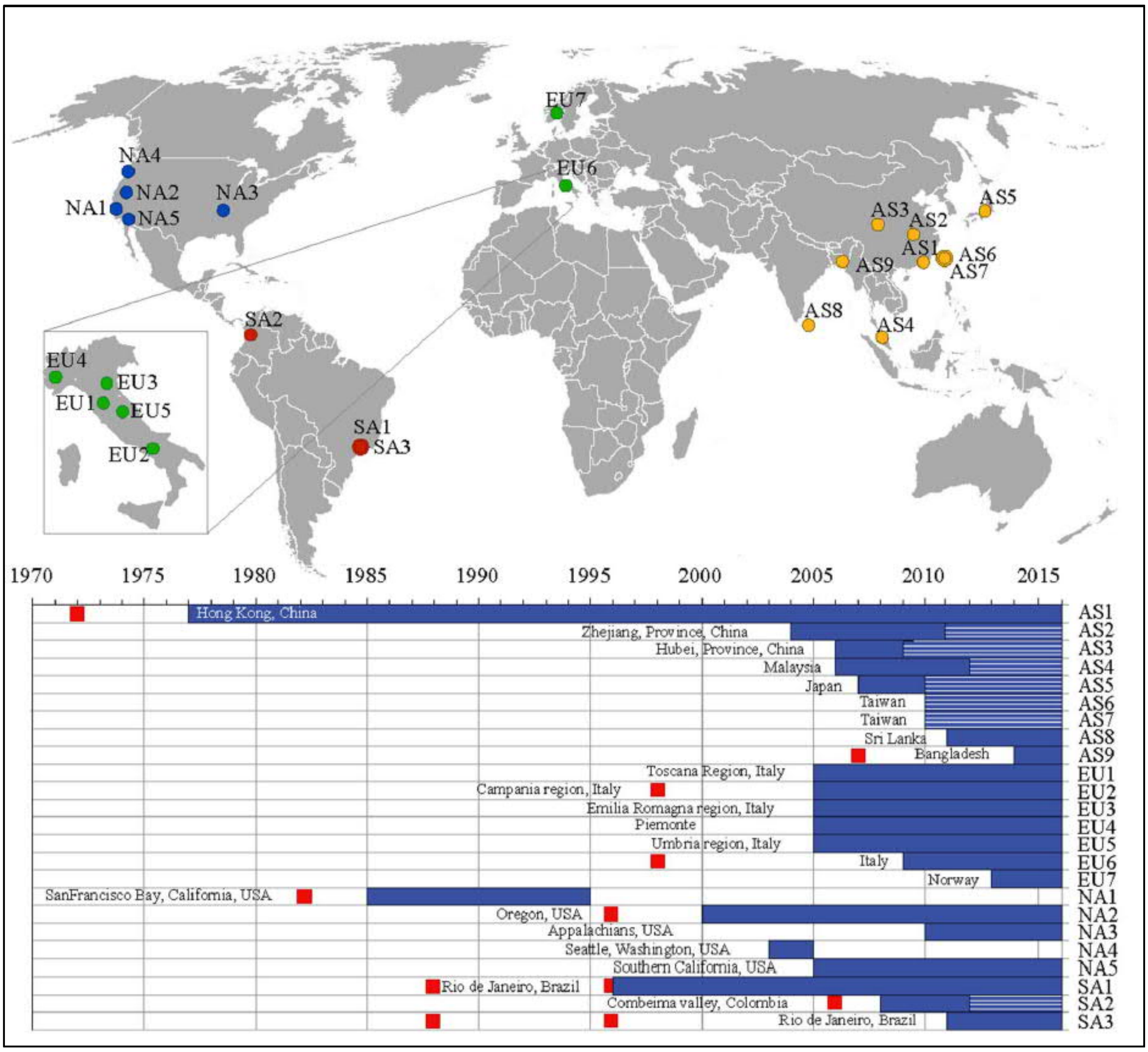


*Figure 4: above, map of <u>systems deployed at regional scale</u>; below, information on their functioning, the red rectangles indicate the systems introduced following a catastrophe, the catastrophe date is shown by the position of the rectangle (from Piciullo et al., 2018).*

6 Sistema d'allertamento Nazionale per la previsione di frane indotte dalla pioggia in Italia (National warning system to predict slope movements induced by rainfall in Italy) http://sanf.irpi.cnr.it/

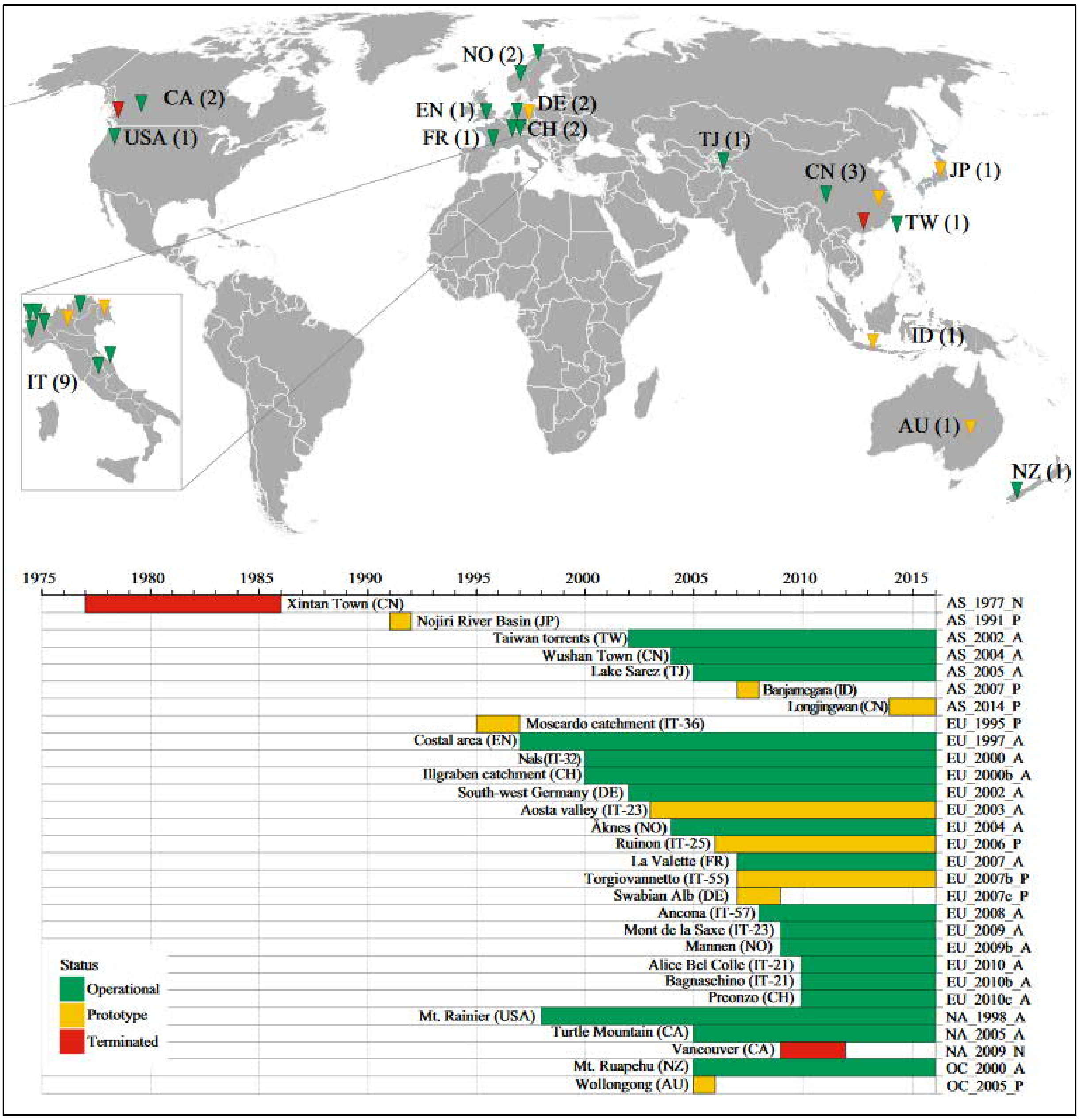


*Figure 5: above, map of warning systems deployed at the local level; below, activity status of the systems (from Pecoraro et al., 2018).*

## 3.2 Used sensors

At the local level, it is now commonplace to use multi-parameter monitoring systems to track all the physical interactions likely to precede and trigger the feared phenomenon (Ornstein et al., 2007, Klein et al., 2013, Klein et al., 2014, etc.). The exact choice of instruments, their numbers, positioning, etc., are defined according to the conditions of each site, including the stakes in question, the technical environmental constraints and the financial means available. Given this, two types of variables are generally measured (Ifsttar et Cerema, 2016):

- the dimensions needed to categorize the movements, such as translational or rotational landslides, the velocities or accelerations, and the deformations;
- the influencing variables, such as meteorological and hydrological variables (precipitation, temperature, etc.), hydrogeological variables (piezometric levels, pore pressure values, suction, etc.) and external anthropogenic vibrations (mine blasting) or natural vibrations (earthquakes). These variables do not directly represent the slope activity and the decision to measure them

depends on the knowledge of the site's behaviour. They can be useful in managing the risk when well assessed.

Figure 6 presents the types of sensors according to the parameters to be measured. The measurement principles for these different sensors are presented in Bouffier et al. (2016) and in the Ifsttar and Cerema technical guide (2016).

| Physical quantities | Sensors | Applications |
|---|---|---|
| Displacement and strain | Fissurometer, extensometer, vernier pattern | Opening of a crack between two blocks |
| | Distance meter | Distance from a point to a reference point |
| | Reverse pendulum | Transversal displacement of the surface relative to a sealed area at the bottom of the hole |
| | Optical fiber | Strains distributed over a large line |
| | Tacheometer | Relative position of a point in space |
| | GPS | Relative and absolute position of a point |
| | RADAR | Distance of a multitude of points from a reference point |
| | Laser scan | Position of a multitude of points |
| Rotation | Clinometer | Rotation from horizontal |
| | Inclinometer | Rotation from vertical |
| Vibration | Velocimeter / accelerometer | Velocity / Particle acceleration |
| | Geophone | Particle velocity |
| Precipitation | Rain gauge | Rain level |
| | Snow gauge | Snow depth |
| Water level | Stream gauge | Water level of a waterway |
| | Piezometer | Water table level |
| Pore pressure | Pore pressure sensors | Pore pressures |
| Flow | Flow meter | River or drain flow |
| Temperature | Temperature sensor | Temperature |

*Figure 6: physical dimensions measured and associated sensors for the operational monitoring of an unstable slope (source Ifsttar and Cerema technical guide 2016).*

At regional scale, the most frequently used sensors are automatic rain gauges (Piciullo et al., 2018). However many systems use meteorological radars, particularly in Asian countries affected by monsoons and typhoons (such as Japan and Hong Kong).

## 3.3 Thresholds, warning levels and zones

### 3.3.1 Setting the thresholds

One of the main difficulties in implementing warning systems lies in setting the thresholds. A threshold is defined as the limit after which a process is manifest, or a change of state occurs (White et al., 1996). This step is critical in order to correctly detect a risky situation while minimising the number of false alerts.

To correctly set the thresholds, the collected measurements must be reliable and the system must be able to predict the time when this threshold will be reached. Thus, the method should take into account the available feedback and rely on a good understanding of the considered hazard. Above all, this threshold should be based on algorithms and standard procedures that are known and accepted by all. The aim is to ensure the objectivity and reproducibility of the proposed method in order to quickly and easily update the thresholds at regular intervals (Segoni et al., 2018).

For precipitation-induced landslides, the rainfall thresholds can be determined at local or regional level (in this case there is also an overall threshold), empirically (statistical or historical) or deterministically (based on physical models that take infiltration models into account).

The empirical thresholds are less complex to determine and for this reason they are the most commonly used (Guzzetti et al., 2017). To set these thresholds, the main requirement is a historical record of precipitation over periods of 15 to 90 days. Two parameters are generally considered: rain intensity, which is the amount of rain accumulated over a period and the rain rate, which is generally measured in millimetres per hour, also called Intensity-duration (ID) threshold, as introduced by Caine (1980). A study carried out by Guzzetti et al. (2007) presents the different ways of calculating empirical Intensity-duration thresholds for different types of landslides and for 52 zones in Europe. Some of these thresholds, calculated as described above, have been integrated into the warning systems presented in Figure 4. This is the case for 14 of the 22 systems presented.

At local scale, the rain measurements are generally coupled with movement measurements, which define how the hazard is evolving (Pecoraro et al., 2018). The criteria considered as the most meaningful is based on movement velocity, obtained by measuring the movement over a defined period (hour, day). However, movement acceleration is more difficult to calculate and is not always representative of an evolution that can be critical (Maquaire, 2002).

We should note that at local scale, the use of effective rainfall or pore pressure is recommended over gross rainfall where possible, since they take into account rainwater infiltration in the ground better. However, this requires a hydrogeological model and piezometric monitoring.

Other information can also be coupled with the thresholds set, such as susceptibility mapping, landslides inventories, ground surveys, etc.

### 3.3.2 Warning levels and zones

One or several thresholds can be used to establish the warning level. There are at least 2 warning levels to cover situations that surpass normal variation: a ‘be aware’ level and an ‘imminent danger’ level. The highest level is commonly referred to as ‘alarm.’ In other words, the ‘alarm’ level announces imminent danger and triggers emergency measures.

In practice, we note that the number of warning levels greatly varies from one system to another. Based on the literature available (cf. Figure 7), we can say that at local scale, there can be up to 6 warning levels and that the majority of systems comprise 2 to 3 warning levels. They mainly aim to set a scale of risk levels from low to high, or very high, and thus a state of ‘no alarm’ to ‘alarm’.

At regional scale, only 3 systems out of 22 have just 2 warning levels. This is the case for example for the favelas of Rio de Janeiro, where the restriction to 2 levels is the result of the social context: they aim to avoid complicating the understanding of the warning in a poorly developed social situation.

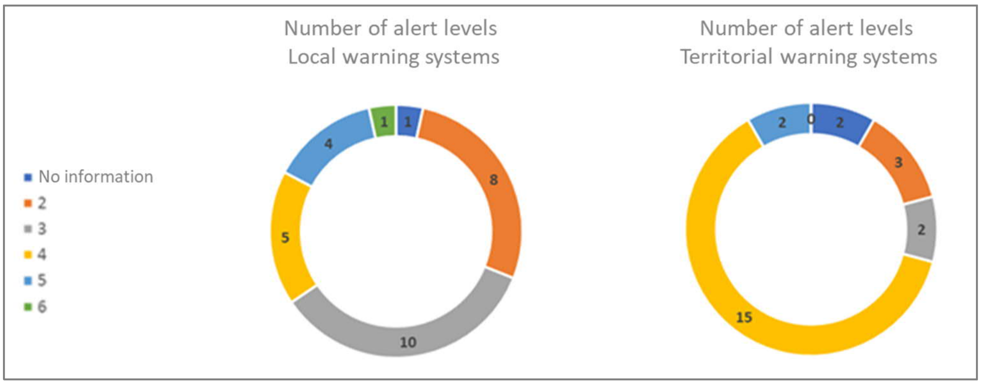


*Figure 7: number of warning levels set at local and regional scale (from Pecoraro et al., 2018 and Piciullo et al., 2018).*

Most of the regional systems now comprise 4 warning levels (15 out of 24 systems). They are generally linked to the occurrence probability of the hazard and lead to the activation of different emergency plans depending on the affected zone.

At regional scale, the warning levels can also be associated with two types of warning zone (Piciullo et al., 2018): fixed zones and variable zones. The so-called fixed warning zones follow geographical boundaries and do not change over time. A variable zone is composed of a group of different regional units for which, in a given event, the warning level may be the same.

We can observe, however, that most systems are based on fixed zones (20 of the 24 systems), which simplifies and accelerates the distribution of administrative tasks and the triggering of emergency plans. Only two systems, in Zhehiang (China) and Norway (cf. section 4.4) cover variable zones.

## 3.4 Organisation and management of warnings

### 3.4.1 The decisional and organisational algorithm

In order to manage a warning system, a decisional and organisational algorithm must be created. It should detail all the information on the number of warning levels, how to activate them, and to follow-up in a precise timeframe. It also details the actors responsible for managing the system based on information sharing and decision-making procedures, and exhaustively describes the roles and responsibilities of the people involved.

The decisional and organisational algorithms are thus specific to each system. They can vary in complexity depending on the scale covered by the system and stakes at play. Some examples are presented in chapter 4 of this report, which details a few exemplary systems.

### 3.4.2 Communicating and warning

A great variety of practices can be observed in the local-scale systems. For most of them, warning is almost immediately launched to the affected populations, while in other cases, experts or entities responsible for managing the site (such as the Prefect, or the Mayor in France) receive the information first, and then decide whether to warn or not. Therefore, warning can sometimes be delayed by the time it takes for the experts to verify the facts and dispel any doubts, and, if needed, it can be issued later.

For the regional systems, most warning alerts are issued following human appraisal, since they are always issued by the central body/decision maker responsible for civil protection and security (for example the USGS[7] in the United States, the Civil Protection in Italy).

The warning messages for the population known as “studied messages” (Glatron, 2008), are prepared in advance, using vocabulary that is understandable to all. These messages (made available in different forms - written, oral, electronic, visual, etc.) are always produced through consultation between the institutions and the scientists. The communication strategies differ depending on the gravity and warning level.

Most of the time, they are relayed via the media and internet technologies. Digital communication via the social networks is clearly growing - which leads to new practices. The population can now actively participate by sharing, commenting and even contributing to the information circulating on social media.

### 3.4.3 Response capability

As seen above (see section 2.4), response capability is one of the four important components of early warning systems. This involves raising awareness and preparedness in the affected populations concerning the actions to be taken when a warning occurs in order to limit the consequences of the risks and the damaging effects.

Unfortunately, this component is often little addressed in the scientific literature and in operational feedback, as it also applies to the more recent systems which are supposed to be focused on the people involved. This can partly be explained by the fact that the response capability must be implemented according to the cultural and social levels of the population, which is far from simple. The challenge is to minimise misunderstandings of the messages issued to avoid distorting risk perception which can lead to insufficient cooperation or even inaction in the populations (Garcia, 2011).

Today, Asian countries are the ones that have made most progress on this matter. Sri Lanka, Bangladesh and Indonesia (system in prototype phase), for example, have heavily invested in response capability. We can also cite Rio de Janeiro city which has introduced a large educative project adapted to all cultural and educative levels, including inhabitants of the favelas. This type of approach is inspired by studies aimed at integrating socio-cognitive models in risk management (Paton, 2003; Lindell and

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[7] United States Geological Survey

Perry, 2012 and Glatron, 2008), where the goal is to target attitudes and participation levels in the affected populations.

## 3.5 Performance of these systems

### 3.5.1 Missed alerts and false alerts

Whatever its scale, the system should be able to generate credible warning alerts and avoid situations leading to:

- missed alerts or no risk reduction actions taken when the hazard is triggered;
- false alerts leading to enactment of emergency measures when the expected instability does not occur.

These two situations can induce significant economic, legal and social problems. For example, the population can refuse to believe the system and so not react in the case of a proven warning or react with less urgency. Moreover, Wilson (2004) observed that missed alerts can also be experienced as a dereliction of duty of the actors responsible for managing the risk, which is also problematic.

It is accepted that the credibility of the warning can be improved either by producing amalgamated warnings, meaning those based on a combination of thresholds (such as rain intensity and displacement velocity), by comparing identical measurements of physically redundant sensors or by achieving analytical redundancy using supplementary sensors. These aspects linked to redundancy are now well integrated in the local systems, as highlighted by Pecoraro et al. (2018).

Finally, many consider the systematic intervention of an expert to be essential to avoid most false alerts. Because of this, it appears difficult to completely automate early warning systems.

### 3.5.2 Assessing the effectiveness

It is crucial for an operational early warning system to be effective. It can be described as the capacity to timely predict the occurrence of a hazard and to trigger adequate responses.

In practice, it is difficult to measure the performance of these systems, since this requires human expertise, alongside technical, administrative and social criteria. For the time being, moreover, there are no universally-shared standards (Sättele et al., 2015a; Sättele et al., 2016; Segoni et al., 2016; Piciullo and Calvello, 2016; etc.).

The effectiveness of the regional systems is often statistically estimated, following the matrix illustrated in Figure 8 from which different indices can be extracted.

| | No Threat | Threat |
|---|---|---|
| Alert | False Positive (FP)<br>->false alert | True Positive (TP)<br>->true alert |
| No Alert | True Negative (TN)<br>-> no alert | False Négative (FN)<br>->missed alert |

*Figure 8: classic 2x2 confusion matrix.*

In Hong Kong, the system's effectiveness was assessed during the 2001-2005 period (Cheung et al., 2006). This confirmed that the majority of the alerts issued were justified, none were missed and the rate of false alerts was considered low. The system's effectiveness has also been qualitatively assessed in terms of the reduction in the number of fatal accidents since its introduction (cf. section 4.3).

Statistical studies have also been carried out for the Italian systems (i.e. Martelloni et al., 2012). During the 2008 - 2010 period for example, the rate of justified alerts for the Emilia Romagna system was at 84% and the rate of missed alerts at 30%. For South California, the system's performance was estimated in the 2005/2006 period, during which 39 alerts were issued and 11 resulted in mudslides indeed (Restrepo et al., 2009). For the Rio favelas system, no thorough study has been carried out on the correspondence between alerts and occurrences of instability. However, a large number of false alerts was noted for the 2011/2012 period (Calvello et al., 2014).

A more in-depth statistical approach has recently been proposed by Calvello and Piciullo (2016) to reflect the effectiveness of regional systems better. This approach, called EduMap (for Event, Duration Matrix, Performance), functions by calculating a duration matrix linking several parameters; it accounts for simultaneous occurrences of several instabilities in the alert zone, and the duration and warning level issued in terms of the spatial density of the landslide in the warning zone. It also takes into consideration the uncertainty in the predictive models.

Yet we can note that this in-depth approach, as well as the simplified approach presented above, are focused technology, since they do not take the response capability into account.

## 3.6 Costs

Many consider the warning systems to be a good alternative to structural measures used to mitigate the risk, since they often have the advantage of being cheaper compared to any reinforcement works that require substantial inputs, and that can in some cases be difficult to achieve.

The example of the Ancona system (cf. details in section 4.2) illustrates this point. The cost was estimated at 3.3 million euros. This includes the early warning system as well as its management and maintenance during the 10 years of operation (communication with S. Cardellini, Ancona Municipality). This sum can be compared to the costs of reinforcement measures, estimated at 60 million euros, for which technical feasibility is not guaranteed considering the urban and industrial configuration of the city.

More generally, we can observe that the emergence on the market of low-cost sensors and the technological developments have clearly decreased the implementation costs and fostered the development of early warning systems.

Today the largest expense items are the technical maintenance and staff costs to manage the system.

# 4 Focus on a few exemplary systems

## 4.1 Local systems: The example of Séchilienne in France

**Context**

The Ruines de Séchilienne slope is located in the Belledonne mountain range, around twenty kilometres south east of Grenoble, in the Isère department (38). The ground movements are concentrated on the south slope of Mont Sec which overlooks the former RN 91 (currently RD1091), between Grenoble and Briançon, and borders the Romanche river upstream of the village of Séchilienne (Figure 9).

Rock falls have been observed on this site since 1726 (Lenoir, 2010). Occurrence of the phenomenon accelerated during the 1960s to the 1980s, leading the State to pay increasingly urgent attention to the site. From 1984 onwards, the site was subject to technical and scientific investigations. The results of these made it possible to establish a first assessment of the geological and hydraulic hazard (i.e. Antoine et al., 1987; Alfonsi, 1997 and Lefort, 1998) and to identify the many stakes and their vulnerability. The geological hazard was then based on the hypothesis of a massive collapse, involving several millions of $m^3$.

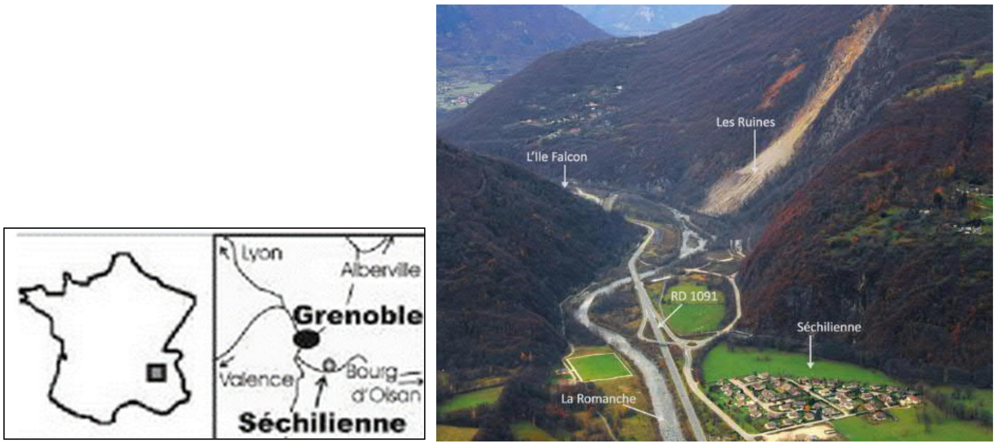


*Figure 9: (left) location of the village of Séchilienne; (right) the Ruines de Séchilienne and the Romanche valley viewed from the uplands of the Saint-Barthélemy-de-Séchilienne municipality © S. Gominet, photothèque Irma.*

Starting in 1985, the site was rapidly put under operational monitoring by the CETE[8] of Lyon, upon request of the State, while different protective measures were considered. Notably, the construction of a rock-fall protection project was proposed to stop a rock fall of a total volume of 1 million m³ (built in 1986 when the road was deviated for the first time). It also proposed to preventatively expropriate the inhabitants of a hundred houses in the Ile-Falcon area, in accordance with the law of 2 February 1995 (Figure 9).

We should note that the assessment of the geological hazard evolved in line with the appraisals and deliberations of the Expert Panel. This panel was formed in 1999 at the behest of the DGPR[4] and made permanent in 2004 (Einhorn, 2010). Several technical studies were also achieved on road and hydraulic barriers between 2005 and 2010 (Einhorn, 2010). Introducing these defences and moving the affected population (progressively between 1997 and 2011) led to a reduction of the risk, and the early warning system was consequently downgraded in 2016.

Some information provided below has, therefore, become obsolete at the publication date of this report.

**Components of the early warning system**

The monitoring of the Séchilienne slope movements was initially based on manual strain and geodetic measurements. The system was successively partially automated and improved with additional measurements (Panet, 2000). The frequency of the manual strain measurements (every year) and the geodetic ones (every 3 years) was reduced in 2016 and 2019. These measurements are still being taken to verify the automatic measurements and to study the surface deformations in some of the zones having less active slope movement.

To summarise, the monitoring is based on a set of 5 automated measurement systems that comprise 27 strain gauges (opening up of large fractures), 54 reference points for the laser distance meter and 40 reference points for the laser distance meter installed on the opposite slope (Pothérat et al, 2009, Duranthon et al., 2003), a real-time GPS system (i.e. a mobile antenna and a fixed antenna) and a meteorological station (rain/snow gauge, sensor to measure the total snow cover accumulated during the winter).

Many other observations were also made on the site. We can cite for example those made by OMIV[9], with spontaneous polarisation measurements on the surface and in the exploratory tunnel starting from 2005, microseismic monitoring from May 2007, improvements in understanding the hydrogeological context and cross-tests of the new measurement procedures (actions still underway). We can also cite the contribution of Ineris, between 2009 and 2016, to the investigations to understand the involved

[8] CETE: Centre d'Études Techniques de l'Équipement (Public Works Engineering Centre) today known as Cerema: Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Centre of Expertise and Studies of Risks, Environment, Mobility, and Town Planning).

[9] https://omiv.osug.fr/SECHILIENNE/index.html

mechanisms deeply underground using an experimental multi-parameter observation system (geodetic, geotechnical and microseismic), for which a summary[10] was published in 2017 (Coccia et al., 2017).

**Thresholds and warning levels**

In 2013 PSS[11], two warning levels (pre-warning and warning) were set, based on four main criteria linked to the movement velocity, i.e. the occurrence and volume of landslides, the occurrence of heavy rain (combined with the vigilance or weather alerts) and the occurrence of a seism of magnitude ≥ 4 near the site.

<u>The pre-warning alert is defined in 2 phases:</u>

- 1st level of vigilance, when at least one of the four criteria is fulfilled;
- Heightened vigilance, obtained when the landslides persist or when the displacement velocity surpasses thresholds higher than those set to activate the 1st level of vigilance.

<u>The warning alert is also defined in 2 phases:</u>

- The serious concern phase, activated by the Prefect after the technical experts have analysed the phenomenon's behaviour. It is triggered in the case of a strain number acceleration, a potential risk of large-volume landslides, an announcement of a ten-year flood of the Romanche river at the foot of the slope or a situation of weather vigilance or warning.
- The imminent danger phase, also activated by the Prefect when a major landslide is predicted in the very near future (approx. 36h).

| Décisions De PREALERTE OU ALERTE | PREALERTE VIGILANCE DE 1ER NIVEAU ET VIGILANCE RENFORCEE | De la PREALERTE à l' ALERTE PREOCCUPATIONS SERIEUSES | ALERTE DANGER IMMINENT OU EBOULEMENT(s) MAJEUR(s) |
| --- | --- | --- | --- |
| | Situation d'accélération du phénomène ou événement particulier **sans notion de délai et d'évènement majeur.** Cette phase est réversible.<br><br>**vigilance de 1er niveau:**<br>**suivi CETE DE LYON** au vu des critères d'activation sur site<br><br>**vigilance renforcée :**<br>suivi CETE DE LYON / experts - échanges **PREFET** | Situation: tous éléments pouvant indiquer le passage à une logique de divergence, de non réversibilité du comportement de la zone des 3 millions de mètres cubes.<br>Les données disponibles sur l'évolution du mouvement font craindre que le **délai avant la rupture passe à moins de 72 heures.**<br><br>**Décision: préfet** au vu des critères de suivi et des avis du CETE DE LYON*** et des experts | Situation: une divergence rapide du phénomène est possible.<br><br>**Le pronostic du déclenchement de l'éboulement : 36h**<br>**Le cas d'un éboulement instantané est improbable mais néanmoins considéré.**<br><br>**Décision: préfet** au vu des critères de suivi et des avis du CETE DE LYON*** et des experts |

The Prefect, under advice from technical experts, decides when to trigger the warning phase, before returning to normality. A 5th phase corresponding to the occurrence of a major landslide, was also planned.

*Figure 10: extract of table summarising the main PSS actions for Séchilienne landslide (source PSS, 2013).*

**Organisation and management of the alerts**

The Séchilienne early warning system was structured around the main actors presented in the table hereafter.

[10] https://www.ineris.fr/fr/bilan-mise-oeuvre-expertise-dispositif-telesurveillance-experimentale-versant-ruines-sechilienne-38

[11] Plan de Secours Spécialisé (Specialised Emergency Plan)

*Table 1: name and role of the stakeholders in the Séchilienne warning system; also applies at a national level in France.*

| Actors in the warning system | Main Roles |
|---|---|
| **Technical expert (consultants or agency)** | Managing the monitoring system (data collection and interpretation, maintenance etc.)<br>Detecting anomalies and triggering warning alerts to the relevant State services and the Prefect.<br>Technical support for the Prefect. |
| **The Prefect** | Drafting and disseminating documents providing information on the risks.<br>Transmitting the warning alert, coordinating the State services regarding the safeguarding measures and rescue operations. |
| **The Mayor and regional authorities** | Contributing to preventative information on the risks and educating the affected populations, including drafting municipal safeguarding plans.<br>Implementing the means of information, the warning and the safeguarding operations.<br>Assisting in the organisation of rescue efforts in collaboration with the Prefect and the competent State services. |
| **The Media (Transmitters)** | Communicating warning alerts and information, improving knowledge of the catastrophe. |
| **Public network managers** | Maintaining/reinstating functions to ensure that priority needs are met (water, electricity, etc.). |
| **Citizens and local actors** | Applying the instructions relating to the warning. |

### Social aspects, results and feedback

Several emergency simulation exercises were in fact organised to validate the successive PSSs, to test whether the involved actors successfully coordinated, and to validate the organisational and decisional procedures of some phases. In 2005, after the deployment of the PSS in 2003, three crisis simulation exercises were organised, the first two for elected officials and agents and the last for the population of the Hameau du Grand Serre. In 2012, an emergency simulation exercise was also run for the schools in the area and involved the triggering of their PPMS [*Plan Particulier de Mise en Sûreté* - Specific Security Plans] (keeping pupils indoors to prevent "dust" risk). As an example, the report of the PSS triggering exercise of November 2005 can be accessed on the Isere prefecture website [12].

Equally, the minutes of the CLAIRS (*Commission Locale d'Analyse et d'Information sur le Risque Séchilienne* - local commission for analysis and information regarding the Séchilienne risk) commission meetings between 2005 and 2011 are available on the prefecture website. They relate the main developments at the site and their discussions on the construction of defences.

Regarding evolution of the site, three separate periods or situations were found (communication L. Dubois, Cerema[8]):

1. In November 2006, a landslide of over 35 000 $m^3$ occurred, fulfilling criteria 2.2 of phase 2. Analysis of the sensor data made it possible to reliably predict the date of this event. This landslide was not followed by other significant landslides and did not officially trigger a PSS (the CETE[8] of Lyon geologists were on-site on the day of the landslide);
2. In March 2009, the opening velocity of the main fractures delimiting the frontal zone was between 12 cm/month and 17 cm/month for the A13, A16, C2 and E3 strain gauges (compared to 10 - 14 cm/month in February 2009), an increase of between +21% and + 28%, which is still very small considering the increase in water inflows of +63 % i.e. 134 mm in February 2009 and 218 mm in March 2009. The velocities remained under the thresholds of criteria 1.1 of phase 1 (1.0cm/d - 1.5cm/d depending on the sensor in question). Consequently, phase 1 was not triggered;
3. In Autumn 2012, it was noted that the surface movements were accelerating, the fractures opening, and rockfalls were occurring. December 2012 was particularly worrying: the opening velocity of the main fractures delimiting the frontal zone was between 35 cm/month and 52

[12] http://www.isere.gouv.fr/Politiques-publiques/Risques/Risques-naturels/Ruines-de-Sechilienne

cm/month for the A13, A16, C2 and E3 strain gauges For most of the time, the velocities remained under the thresholds of criteria 1.1 of phase 1 (2.1 cm/d to 3.1 cm/d depending on the sensors in question), at no point did 3 out of the 7 sensors simultaneously present velocities above the criteria 1.1 thresholds. Consequently, phase 1 of the PSS was not triggered.

These situations were not mentioned in any specific communication thereafter. More widely, there is no overall summary of the work carried out and the data collected on the site. The reason is that phase 1 was never formally triggered. For the same reason, the sliding thresholds were never revised as they were considered as efficient; the velocity criteria thresholds 1.1 and 2.1 are however automatically updated every year on the 1st July.

**Some cost considerations**

Some specific means for the acquisition and the management of the monitoring data had to be developed when the Séchilienne monitoring and early warning system was introduced. The main developments were carried out or supervised by the CETE[8] in Lyon. We can cite, for example, the development of the ONERA radar in 1999 and the GeSSRI software in 2000 (*Gestion de la Surveillance des Sites Rocheux Instables*, Management of the Monitoring of Unstable Rocky Sites). The associated development costs are not known.

In 2004, the annual working budget for the monitoring was estimated at 600k€/yr (pre-tax) (Durville et al., 2010). Reduced to automatic geodetic measurements only, the working budget is now at 100k€/yr (pre-tax). The yearly working budget for a classic and automatic geodetic measurement campaign is 135k€/yr (pre-tax). This working budget includes the maintenance of the automatic tacheometer, sensors, access paths, software, computers, buildings and generators, and the electricity and telephone subscriptions. The maintenance of the ULB radar and its software costs an additional 30k€/yr (pre-tax).

Finally, the cost of installing the hydraulic defences was estimated at 24.6 million euros (cf. CLAIRS commission report dated 29th June 2011) and the cost of the road deviation was 26.3 million euros (cf. minutes of the Isere department meeting of 2007).

## 4.2 Local systems: The case of Ancona in Italy

**Context**

On the night of 12 December 1982, the city of Ancona in Italy was subject to a landslide (Figure 11) of 220 hectares (approx 11% of the urban area of the city was affected). Fortunately, there were no victims, but 3661 people were evacuated and 500 people lost their job as a result. The roads, railways and water and gas pipelines were damaged, and 208 houses were destroyed or damaged (Cardellini and Osimani, 2008). The landslide occurred 10 years after a severe earthquake (magnitude 4.7), which separated part of the future instability zone into several compartments, and following 6 days of intense rain with a mean intensity of 30mm/day, corresponding to a return period of under 10 years. The most probable hypothesis for what triggered this event was infiltration of this rain, facilitated by a long period of drought which had created large fissures (Uzielli et al, 2015). Later, clear correlations were found for the limited instabilities occurring in 2008, 2010 and 2011, between accumulated rainfall and movements (Baroň et al., 2012).

The Ancona slope instability is a deep and complex landslide with four 30-to-110m-deep slide surfaces (Figure 11). The whole slope is unstable (safety factor close to 1). The triggering factors are rainfall in the higher part of Mont Montagnolo (Figure 11b) and the presence of direct faults in the lower part of the slide.

However, after 1982 catastrophe, geological reconnaissance studies and scientific works were carried out in parallel with the interventions to reinstate daily life. The results showed that it was not possible to carry out stabilisation and consolidation works, both because of the cost (approx 60 million euros) and the large environmental impact. Following this observation, a regional law (R.L n.5 of 03/04/2002) was enacted, defining the need to introduce a permanent warning system.

**Components of the early warning system**

The installation of the local warning system began in 2006, on the initiative of the Ancona municipality, which also worked on establishing an emergency plan. These actions were supported by a wide-reaching preventive communication policy for the population.

This system was completed in 2009 and included multi-parameter instruments: 33 inclinometers, 34 GPS stations, 8 complete stations and 3 DMS - Differential Monitoring of Stability (columns for geotechnical monitoring, including a piezometer, a thermometer and an inclinometer) in three 100m-deep boreholes.

The total cost of this monitoring system was estimated at 1.5 million euros.

The system’s management centre is located in the premises of Ancona city hall, it is managed by the city’s head geologist who is the technical director.

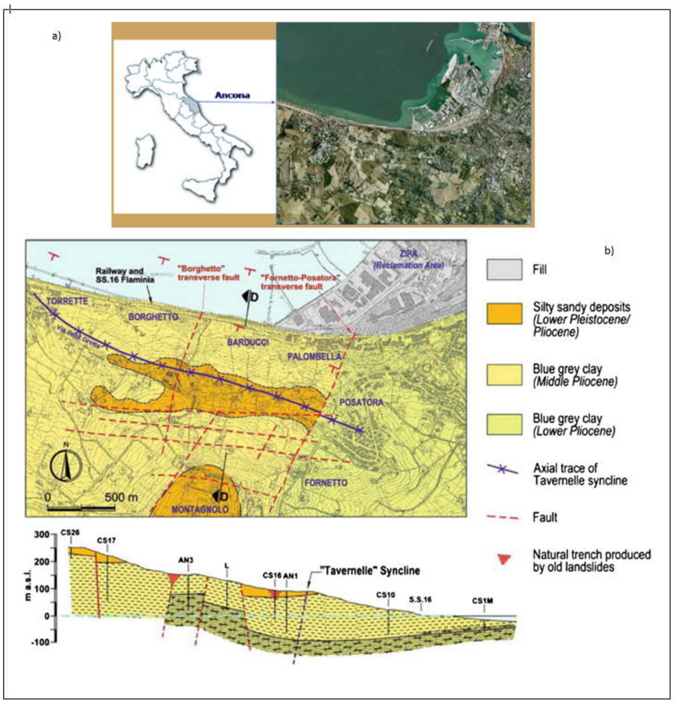


*Figure 11: a) location of landslide, b) geology, from a communication by S. Cardellini, Ancôna Municipality.*

### Thresholds and warning levels

The thresholds selected to trigger the warning are based on multiple parameters. They take into account the amount of rain (over 3, 5 and 20 consecutive days), the piezometric level at the three DMS stations and the surface movements (Figure 12).

These thresholds are coupled with other information from ground surveys (presence of fissure, collapse, etc.). All together, they give rise to 5 warning levels (Figure 12): carefulness, pre-alert, alert, pre-warning, and warning.

| INDICATORS/ INFORMATION | CAREFULNESS | PRE-ALERT | ALERT | PRE-WARNING | WARNING |
|---|---|---|---|---|---|
| SEGNALAZIONI | new on road surface fissures | on road surface fissures in development with openings> 5 cm and steps | subsidence of roads, detachment and marginal crevasses on land | cracks on houses; cracking noise | Very evident movements of homes and land |
| RAIN | rain for most consecutive of 3 days rain> 90 mm in 3 days (hold for 20 days) | | rain for most consecutive 'of 5 days rain> 120 mm in 5 days (hold for 20 days) | rain for most consecutive of 6 days rain> 180 mm in 6 days (hold for 20 days) | |
| GPS | | | displacement of 1 house (validated by the first measures to tca and inspection) | displacement of 2 houses in the same area (validated by the first measures to TCA and inspection) | displacement of more than 2 houses in the same area (validated by inspection) |
| TCA | | | displacement of 1 house (validated by the first measures to tca and inspection) | displacement of 2 houses in the same area (validated by the first measures to TCA and inspection) | displacement of more than 2 houses in the same area (validated by inspection) |
| NIVEL | | | 2mm displacement (validated by inspection) | 4 mm displacement (validated by inspection) | 8 mm displacement (validated by inspection) |
| DMS | piezometric dms1 > 7 m dms3 > 5 m | piezometric : dms1 > 5 m dms3 > 4 m | inclinometers: displacement of 6 mm in 1 day (validated) | inclinometers: displacement of 6 mm in 3 h (validated) | inclinometers: displacement of 6 mm in 1h (validated) |

*Figure 12: the different warning levels and associated thresholds for each type of sensor (decisional algorithm) that make up the permanent monitoring system (from Cardellini, 2016).*

**Organisation and management of the alerts**

The authorities directly involved in managing the different warning and criticality levels are: the mayor in his/her role as responsible for civil protection in the municipality, the regional civil protection body and the technical director of the system's management centre who informs the mayor about the reached criticality levels.

A permanent on-duty team, 7 days a week, composed of technicians, geologist and engineers , is responsible for monitoring the data and triggering the warning alert.

The decisional algorithm relies on systematically interpreting and verifying the detected alarms (the technical experts go to the site to validate/invalidate the alerts). In case of a validated alert, the technical director of the system's management centre decides on the warning level, the communication actions to take and whether to activate the emergency plan in collaboration with the Civil Protection body.

**Social aspects, results and feedback**

The Ancona municipality enacted wide-reaching information campaigns and training projects for the population from the start of the project with the aim of increasing the population's resilience by getting them used to actively live/coexist ("*convivenza attiva*") with the slope instability.

These information campaigns targeted all ages, from schools to retirement homes. The Ancona municipality won the international *Sasakawa* [13]*Award for Disaster Reduction* prize in 2011 for this campaign. This prize is awarded by UNISDR[1].

Indeed, it is important to stress that to date, no false alerts have been issued thanks to the work of the duty team in systematically verifying any threshold overrun. This reinforces the population's trust in the early warning system.

## 4.3 Regional scale systems: the case of Hong Kong

**Context**

The metropolis of Hong Kong is highly vulnerable to the risk of rainfall-induced slope instabilities because of two factors: the geomorphology of the region that is more than 70% hilly, and the climate marked by monsoons and typhoons.

[13] See https://www.unisdr.org/we/campaign/sasakawa

Many natural and anthropogenic slope instabilities have occurred in the history of Hong Kong, causing the death of more than 470 people since 1947 (Choi et Cheung, 2013). The tragic events in 1972 in the Po Shan and Sau Mau Ping districts (67 and 71 deaths respectively), and then another deadly landslide in 1976 in Sau Mau Ping (with 18 deaths) led the local authorities to introduce significant measures to reduce the risks.

In 1977, the LPM programme (*Landslip Preventive Measure*) was launched to map and secure where possible all the unstable slopes in the territory, or at least to contain the debris and mudflows. The cost of the programme was 14 billion dollars, and it was completed in 2010.

Also at the end of the 1970s, the Geotechnical Engineering Office (GEO) was created in order to implement a regional warning system (LWS, Landslip Warning System[14]). This system was jointly managed by the GEO[15] and the HKO[16] since 1984 and it is now integrated in the general system managed by the HKO[16] that covers all types of climate-related disasters. This change was made after projections of climate changes in Hong Kong, which predict a rise in day and night temperatures, a rise in mean rainfall intensity, increased frequency of extreme events, sea level rise, changes to coastlines and a rise in storms resulting from cyclones.

**Components of the early warning system**

Hong Kong's warning system comprises a dense network of automatic rain gauges (approx. 120 measurement stations, or 1 for every 4 km$^2$-area on average). The measures are monitored in real time and coupled with those obtained by HKO's meteorological radars.

It relies on partitioning the area (approx. 1000 km$^2$) in a relatively fine mesh (Yu et al., 2004 et Cheung et al., 2006). For each mesh a correlation model is launched between the frequency of slope instabilities and the maximal run-off (known for each type of instability) over 24 h (Figure13). 1, 2, and 3-hour rainfall predictions provided by KHO are used to decide whether the warning criterion has been reached or not (Cheung et al., 2006).

To support the LWS, a system of very short-term weather forecasts, called SWIRLS[17], was developed to continuously analyse the meteorological radar echoes between two successive measurements and to calculate the direction and velocity of the rains (Figure13).

**Thresholds and warning levels**

As mentioned above, the warning criteria are based on the correlation between the run-off (rainwater run-off 24 hours a day) and the frequency of slope instabilities in the affected mesh. It integrates the latest available meteorological data and the short-term precipitation forecasts.

The GEO started to calculate and integrate a Landslide Potential Index (LPI) into the LWS since the end of the 1990s. This index is used to describe the severity of a rain event and its potential to induce landslides. There is no predictive value and the index is calibrated on the most severe rainfall events of the last 30 years.

In summary, there are two warning levels: no danger and danger.

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[14] See http://hkss.cedd.gov.hk/hkss/eng/landslip_info.aspx

[15] GEO, Geotechnical Engineering Office

[16] HKO, Hong Kong Observatory, seehttp://www.weather.gov.hk/contente.htm

[17] SWIRLS, Short-range Warning of Intense Rainstorms in Localized Systems

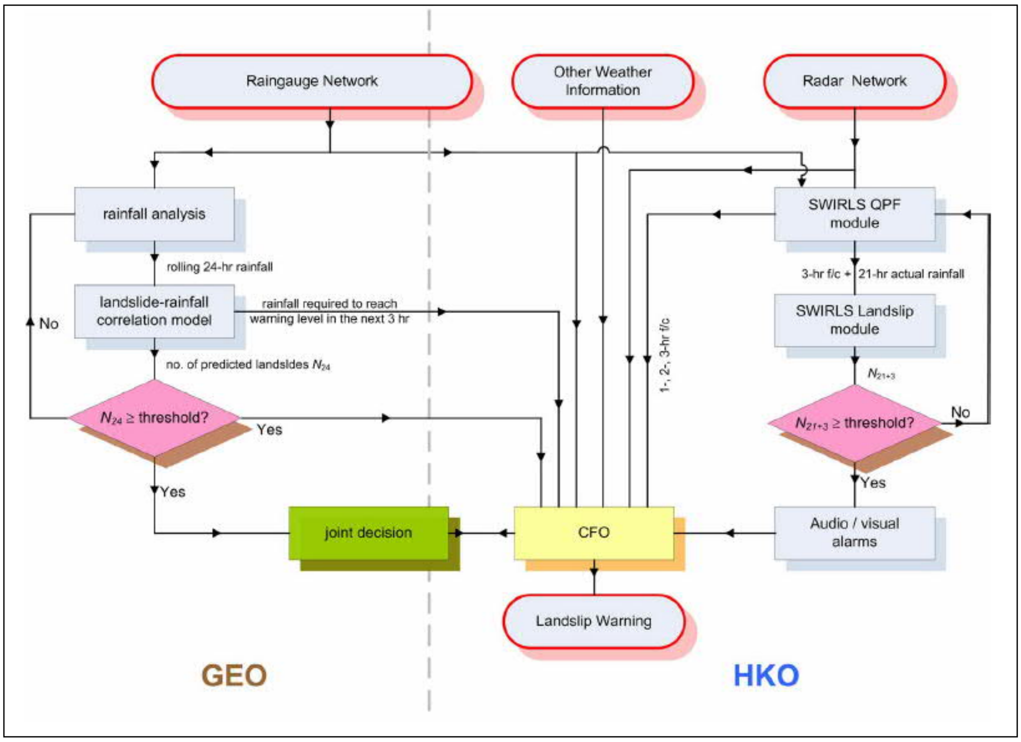


*Figure13 : decisional and organisational algorithms for the Hong Kong warning system and synergy between the GEO and HKO services (Cheung et al., 2006).*

**Organisation and management of the alerts**

The GEO and HKO jointly take the decision to issue or cancel a warning (cf. Figure13). The warning alert is issued in the form of a bulletin and disseminated by the media (radio and television) and on the dedicated website[14]. Since 2010, warning alerts have also been relayed via the dedicated application, MyObservatory[18]. The number of daily visits to this application exceeds 100 million. That is more than 14 pages consulted on average per day and per person, for a total population of 7.2 million inhabitants.

**Social aspects, results and feedback**

Hong Kong's early warning system is the oldest system in place. It is now considered a global reference, from a technology perspective and from the perspective of the support it provides to preparations for the ability to respond.

In particular, the SWIRLS system received international recognition during the 2008 Olympic Games in Beijing and the 2010 Universal Exhibition in Shanghai.

These excellent results were made possible by the innovations instigated by the GEO and HKO, and by all the means used to educate the population.

The GEO and HKO regularly verify and revise their criteria for issuing and cancelling warning alerts to take into account technological limitations and changes in the behaviour of the unstable slopes (e.g. the models). Neither the revision methodology nor the statistics are accessible on-line. However, it seems that the false alarms are today mainly caused by issues linked to the radar measurements (effect of topography, precipitations out of the scanning area of the radar, etc.). They can also be caused by uncertainties in rain zone progression forecasts.

Every year, several hundred ground movements induced by rainfall or extreme climatic events are recorded. In 2017, 157 landslides were noted, in the context of a slightly higher (+7%) annual precipitation compared to previous years.

Finally, we stress that the number of fatalities has been greatly reduced since the introduction of the warning system (Figure 14) and the deployment of the LPM programme.

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[18] See www.hko.gov.hk/myobservatory_e.htm

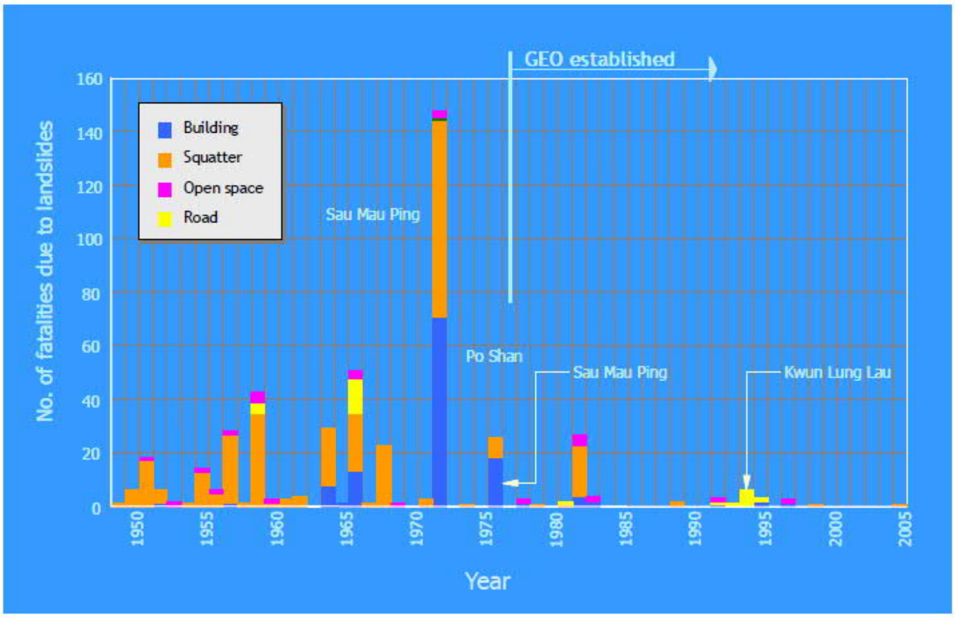


*Figure 14: histogram of the number of fatalities due to slope instabilities from 1950 to 2005 (Cheung et al, 2006). The early warning system was introduced following the last catastrophic event in Sau Mau Ping in 1976.*

## 4.4 Regional scale systems: the case of Norway

**Context**

In 1989, Norway introduced a national warning system for floods, managed by the public operator NVE[19], under the auspices of the Ministry of Oil and Energy. This system was used as a basis for the construction of a national warning system, between 2009 and 2012, for landslides induced by rainfall and snowmelt. It was declared operational at national scale in October 2013.

This national warning system for landslides is managed by the NVE in collaboration with other state services: the Norwegian Meteorological Institute[20], the bodies in charge of managing road infrastructures[21] and rail infrastructures[22].

There are very strong synergies between the services concerned (Krøgli et al., 2018) since managing the system for landslides requires hydrogeological and meteorological data and forecasts that are also produced and used to prevent the risk of flooding.

Finally, we should note that the national warning system for landslides integrated 4 local systems: those of Åknes, Mannen, Hegguraksla and Jettan. The Åknes system is no doubt the best known of the four. These systems were at prototype stage before being integrated in the national warning system.

**Components of the early warning system**

The system integrates real-time measurements from over 70 piezometers and 400 weather stations deployed over the area, depending on accessibility. These measurements are used as input for the short-term (66 hours) and long-term (+ 9 days) weather forecasting models.

These weather forecasting data are then used to establish hydrogeological forecasts at national scale, based on a 1 km x 1 km mesh by simulating, for example, snow melt, run-off, or frost. Depending on the models used (Beldring et al., 2003; Colleuille et al., 2010) and the available calibration data, interpretations are made to determine e.g. aquifer recharge/drainage, water infiltration in the ground, the depth of accumulated snow, etc.

[19] NVE: Norwegian Water resources and Energy

[20] MET: Norwegian meteorological Institute

[21] NPRA: Norwegian public road administration

[22] Bane NOR: Norwegian national rail administration

The meteorological and hydrogeological forecasting data are then cross-checked with a database of 65000 instabilities, created in 2001 and including all types of landslides .

Finally, the thresholds and warning levels are based on models that predict instability occurrences built using historical data (cf. below).

**Thresholds and warning levels**

The alert thresholds are not based on rain intensity-duration, as is often the case (cf. section 3.3.1). Instead they are derived from statistical studies carried out by combining historical hydrometeorological and instability data (Colleuille et al., 2010 and Krøgli et al., 2018). Two parameters are thus highlighted when defining the warning criteria (Devoli et al., 2018):

- the relative water discharge, expressed as a percentage of the annual water discharge over the reference period 1981-2010, which is derived from simulating snow melt and interpolated precipitations;
- the degree of groundwater level which describes the ratio between the current groundwater level and the maximum one during the same reference period.

The alert thresholds are set statistically by the NVE (Figure 15), at national and regional scales (2 main regions, the East and the West of Norway) in order to take into account the regional differences in climate and topography (Boje et al., 2017). Maps of the likelihood of instabilities occurring are also published daily.

All this information is used to communicate with the population using 4 warning levels (low, moderate, high, very high) which are associated with a colour code (respectively green, yellow, orange, red, see Devoli et al., 2014).

**Organisation and management of the alerts**

The system is based on variable warning zones. They can cover a small number of municipalities or several administrative regions, depending on the hydrometeorological conditions and forecasts.

The warning alert is issued by the NVE, following the information chain described in Figure 16. It is relayed by different channels to the local and regional administrations, the media, etc. The website http://www.varsom.no/en/ is also widely used to communicate with and to inform the public.

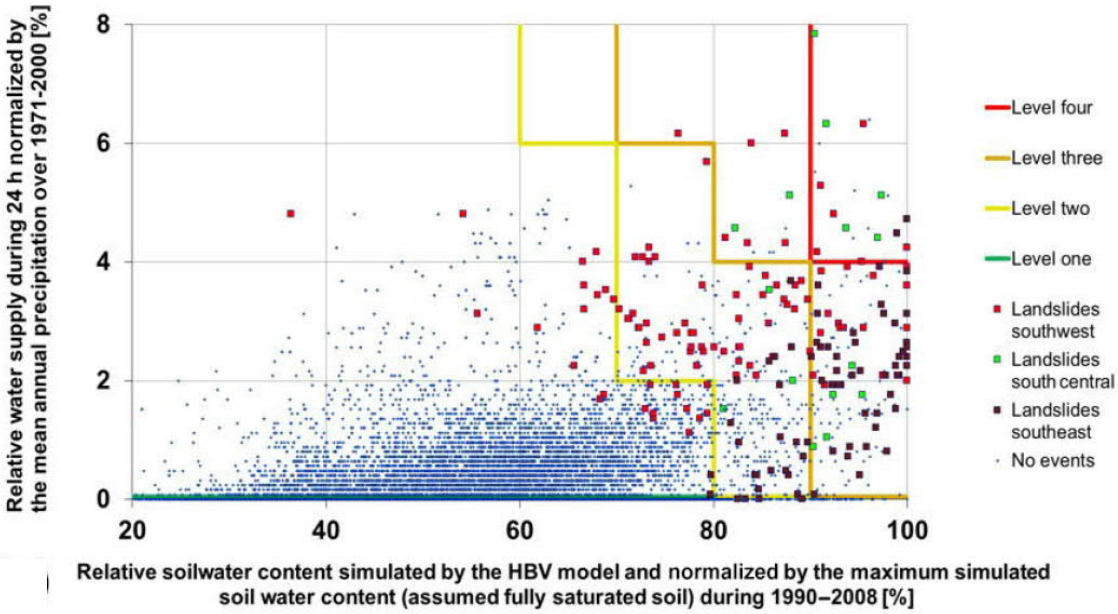


*Figure 15: the four alert thresholds are represented by the green, yellow, orange and red lines. The blue dots are days without instabilities and the coloured dots are the days when an instability occurred, depending on the geographical sector (Devoli et al., 2018).*

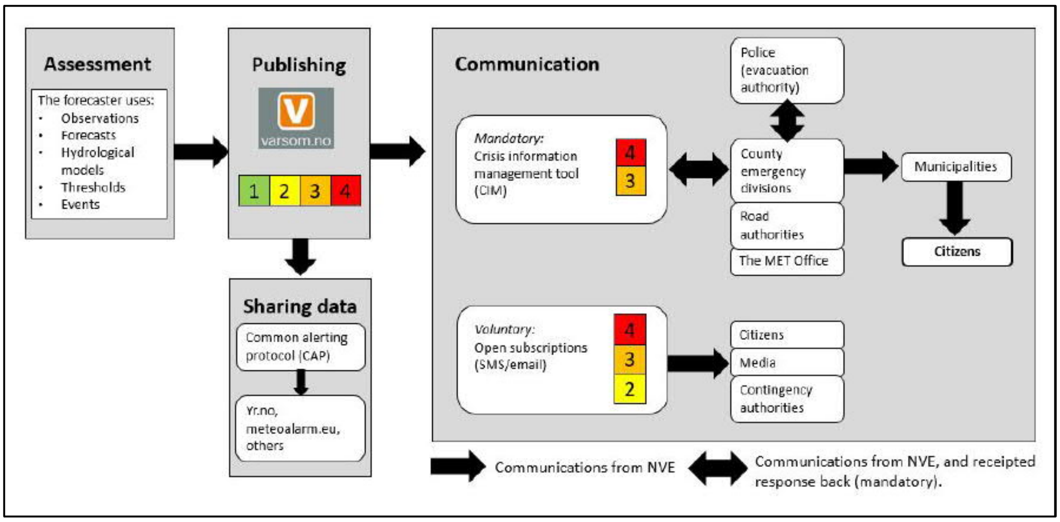


*Figure 16: the warning information chain in Norway (Krøgli et al., 2018).*

**Social aspects, results and feedback**

In order to provide clear information to the population, the warning alerts for slope instabilities use the same baselines (the same colour code and descriptions) as used for floods and avalanches. All this information is relayed through the same information channels.

The notion of response capability for this warning system is barely addressed in the literature, but the literature does tell us that from the point of view of Norwegian regulation, it is the responsibility of the municipalities to design and implement the measures and emergency plans. The NVE[19] says that there remains a good deal of work on this subject since the system has only been operational at national scale for only a few years. To do this, the NVE is conducting surveys with the direct users (the mayors, local authorities, etc.) in order to draft information campaigns that meet the expectations of the public and the municipalities.

The NVE has recently produced some new research on the issues of feedback and warning system effectiveness (Krøgli et al., 2018; Devoli et al., 2018). One of the studies assesses the system's effectiveness by looking at whether the warning alerts it issued over the 2013-2017 period were pertinent and assigned with the appropriate warning level. It shows that the rate of false alarms was at most 5% and the rate of missed alarms (not issued) was at most 2.2%. During sustained rain or snowmelt episodes, these rates are slightly worse, at 14.5% and 5.8% respectively.

These studies show that the system's effectiveness and the very definition of the warning thresholds is still tightly linked to observations on the ground and the reported number of events (instabilities) , which supply the national instability database. These observations are clearly likely to bias, some of which were difficult to quantify since they are based for most part on volunteer input, since the witnesses are invited to input information on a dedicated site [23].

# 5 Summary & Discussion

## 5.1 Technological prospects

From a scientific and technical point of view, deploying an early warning system requires a high degree of knowledge and expertise and should be conducted with rigour and method. As seen above, a good deal of innovation tends to be required to address the ground conditions and operational constraints. Some innovations only apply to one site and cannot be transposed to other case studies, while others could conceivably be applied more widely.

This is the case for example for the integrated multi-parameter monitoring solutions, which collect

[23] http://www.regobs.no/

physical data from a large number and variety of sensors spread across the area. These have been made possible by recent technological developments in many domains (miniaturization of components, low-energy consumption, internet, 4G, georeferencing tools, data mining, etc.). Digital data management and treatment methods, and complex phenomenon modelling methods have also greatly progressed over the last decades and now make it possible to issue warning alerts with a good degree of efficacy.

Developments have also been made in artificial intelligence algorithms which opens new prospects for warning forecasting. This domain is currently growing fast and positive results have already been achieved in flood forecasting, where the processes and the dynamics at work have been understood for a long time. We can imagine that progress is also possible in the case of complex, large-size or large-scale instabilities, provided large quantities of data can be collected and combined, but this issue is still puzzling the experts. Indeed, significant means would be required to handle such large quantities of data, both on-site to collect the data over the long term, and in the laboratory to archive, manage and process them. Thus implementing such learning techniques also requires an increased involvement of data scientists, alongside experts in the phenomena at play and other stakeholders, which will doubtless further complicate the management of the warning systems. The issue of transposing these approaches from site to site also raises questions.

Finally, another priority that is not currently being debated in the scientific community concerns improving the weather forecasts to better quantify and anticipate water inflows. In 2018, the first ever satellite dedicated to measuring global winds, the European Aeolus satellite, was launched. This should lead to significant progress in weather forecasting within the next ten years.

## 5.2 Effectiveness and stakeholders

In the examples presented above, the warning alerts are almost always issued as the result of a human decision made by an expert or a non-expert decision maker, such as the Prefect in France, for example (see Table 1).

This scenario is suitable for local systems and it is then the responsibility of the experts to help decision-makers make the right decision. However, the regional systems are all systematically based on experts to make the decision, and they are also responsible for relaying appropriate information to the different stakeholders.

Until now, warning system effectiveness has mainly been assessed and analysed from a technical point of view. Neither response capability nor population involvement are accounted for in such assessments.

Population involvement can take different forms, including reporting events witnessed through the internet portals accessible to all, such as in Norway, to contribute to the ground movement database. Nevertheless these witness reports, which are of course subjective since they are produced by non-specialists and do not undergo an exhaustive survey, contribute to improving the forecasting models and thus ultimately to improving the effectiveness of the systems.

Additionally, warning simulation exercises are very rarely included in the alert preparation of warning systems for landslides, or at least, there is no mention of this in the literature. Feedback from other domains (the Richter exercise for example) however shows that running warning simulation exercises can help to maintain a high level of information in the affected populations and encourages their involvement. It also makes it possible to use the lessons learned to propose and design means of improvement aimed at reducing the vulnerability of populations.

## 5.3 Synergy and coexistence between systems

Synergy between the warning systems is overall poorly developed. This observation is valid for the regions where local and regional systems coexist, such as Italy for example. There are many difficulties encountered. They relate first to the distribution of responsibilities between the various stakeholders and the interactions between the managers of the systems. The systems are often constructed independently of one another, without considering their interoperability, and using technologies and tools that do not facilitate collaboration. The coexistence of multiple systems at different scales with different operators and actors also tends to confuse the populations concerned. The communication campaigns for the populations are not always collaborative, neither in their format nor their content. The distribution of the roles and responsibilities is not always well understood, and in a context where the main actors do not communicate, the situation cannot improve. Worse still, there is often a lack of synergy between the actors, which discredits the whole operational and decisional chain.

Exceptions do exist however, and the approaches taken by Hong Kong and Norway are good examples. In these two cases, the distribution of roles and responsibilities was defined with a good deal of coherence and means; they take an overall approach that promotes coordination between the services and sharing of the means of prevention and warning. This strategy also makes it possible to conceive a more general system that includes multiple hazards or multiple risks (for example by integrating the raw issues - floods, avalanches and landslides). This approach also has the advantage of promoting greater participation of the affected populations.

Administrative and operational divisions within the region can however make it difficult to deploy such an approach. In Germany for example, the federal structure makes it harder to coordinate the different public and private services involved in preventing and managing major risks.

Finally, the lack of effort to disseminate and share knowledge in this domain is regrettable. The experts and the management and warning centres often lack funding and support to widely promote their work to their peers. This explains, for example, the omission of the Séchilienne warning system in the international review of local systems (see section 3.1). More generally, this lack of synergy is present in all the components of a warning system: from taking measurements to feedback from at-risk situations. However, things are beginning to change. A joint study carried out by the Norwegian system and that of Piedmont in Italy (Devoli et al., 2018) following the Vb cyclone in May 2013, which affected both Italy and Norway, is illustrative of this change.

## 5.4 French feedback: overview and proposals

Feedback in France is limited to local warning systems deployed in the context of major natural risks. There are few cases in the country. The best documented is that of Séchilienne, presented in section 4.1, for which significant means were deployed between 1986 and 2016. The information available in the literature and on-line is mainly technical and organisational, while the performance and effectiveness of the Séchilienne system is never fully addressed. It is limited to considering that the system has fulfilled its function since it has made it possible to manage the risk over several decades, the time during which the different measures to reduce vulnerability were put in place.

There is also a regrettable lack of summary documentation, although the site has undergone 3 marked periods in terms of its evolution (cf. section 4.1). Equally, the effectiveness of preparative measures for the affected populations has never really been considered, apart from during the Riskydrogeo[24] and ANR SLAMS[25] projects.

We should remember that warning systems for unstable slopes and ground movements are specific in that, as opposed to earthquake, flood or storm risks, they are recurrent in the same area. These systems are diffuse and lack visibility since they are very localised, and some have a duration limited to a few years.

One area of progress in natural ground movement risk management strategies using monitoring and warning alerts thus consists of setting up a centralised system to capitalise the data and feedback from observation and instrumental monitoring projects carried out over time across the area, on behalf of local authorities, town planners and other supervisory managers. Such a system could be designed, initially, by a work group made up of experts in the scientific and technical network, before being widened to actors in the regional administration, academic world, consultancy firms and natural landslide risk managers.

A guiding thread could be to develop a capacity to follow, select, centralise, and openly share the reference cases for local warning systems on natural ground movement risks at national, European, and even international scale. These projects often attract little visibility. This capacity should include any relevant documentary and instrumental data as well as the most informative possible technological, scientific and human-organisational feedback on the projects completed.

We should remember here that an intelligent, documented access to banking of monitoring and warning systems by the scientific community and bodies of experts has already been organised in a structural manner for earthquake risks at the European and international scale.

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[24] see http://www.risknat.org/projets/riskydrogeo/riskydrogeo.html

[25] see https://anr.fr/fileadmin/user_upload/documents/aap/2009/finance/risknat-financement-2009.pdf

This subject could be discussed in work groups on “monitoring strategies for ground movements” steered by the DGPR[4] where the aim is to set a doctrine that spells out the criteria used to introduce (and implement) site monitoring and to define the legal responsibilities of the State services at each administrative scale (regional, departmental) and of the regional authorities. The work started in 2019, as part of the national C2ROP[26] project, on classifying rockfalls monitoring systems covering up to 1000 $m^3$ is another interesting opportunity to improve the systems.

# 6 Conclusions

Technically and scientifically, the conditions to deploy early warning systems for slope instabilities induced by rainfall have been well understood, as illustrated by the different examples presented in this report. These systems can be local, and thus cover one large-scale complex slope, or regional to cover several types of instabilities. Although the means and methods differ according to the scale of the project, these systems are always managed through an organisational and decisional algorithm based on expertise. This algorithm describes all the information on the number of warning levels, how to activate them and the follow-up actions to be taken within a defined timeframe.

There are many, doubtless promising technological routes to take to further improve the data acquisition, processing, and management, and to improve the forecasts. Their operational implementation will result in increasingly technical systems and will necessarily require a growing involvement of data scientists. The effort to integrate and to improve acceptance of the often complex new technologies by the users and stakeholders of warning systems should thus be redoubled, starting immediately. Indeed, many systems, including some recently deployed in the US for example, are still based on a top-down approach where the affected population is involved at the very end of the process, simply as recipients of the information. Yet, to be effective, the early warning systems should be developed around a genuine risk culture and be carried by strong political will. They should also be sustainably anchored in the civil society.

Indeed, all the actors involved in managing the warning systems would benefit from greater interactions with their peers. At all levels, there is too little cooperation between the warning system managers. The feedback culture is too underdeveloped, since it is extremely beneficial, as demonstrated in the industrial domain, for example. This is all the more so since case of catastrophic large-scale movements only occur relatively rarely compared to other recurrent phenomena.

Because of this, common standards and baselines do not exist to deploy and to manage warning systems yet, nor to measure their effectiveness. Synergy between the different warning systems covering the same area or bordering each other, potentially covering other geological or hydro-climatic hazards, is also often still entirely neglected. But practices are changing with the collective rise in awareness of the challenges presented by adaptation to climate change, and with the availability of new instrumental data. In the next few years, most countries are likely to possess large-scale multi-risk warning systems with uniform regulation, at least at the European scale. Equally, an intelligent, documented banking of monitoring and warning systems by the scientific community and bodies of experts should quickly start to be organised at international scale.

# 7 Acknowledgments

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[26] https://www.c2rop.fr/

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