Development of an algorithm for automatic elaboration, representation and dissemination of landslide monitoring data

Aleksandra Wrzesniak and Daniele Giordan

Istituto di Ricerca per la Protezione Idrogeologica, Consiglio Nazionale delle Ricerche, Turin, Italy

ABSTRACT

Despite the support of technological improvements in hazard monitoring and management, the aspect of dissemination of scientific data is still underestimated. Hazard monitoring systems are usually organized in complex networks, composed of automatized procedures in order to capture, pre-process, elaborate, transfer the monitoring result data and to generate warnings. However, a well-organized communication strategy leads to success in hazard management, especially concerning emergency conditions. In this paper, we present an approach for monitoring results dissemination in the form of single-page informative bulletin, composed of synthetic information dedicated to non-expert receivers. We developed an automatic methodology for fast and efficient data analysis and proper elaboration and dissemination, and we integrated all these elements into an algorithm for automatic bulletin generation. Our purpose was to construct a configurable tool that could be easily adapted to the hazard conditions under study. Afterwards, we applied the developed algorithm to landslide monitoring data-set. We validated the proposed approach by verifying the consistency of the model. Our methodology shows how to integrate a variety of information relative to landslide evolution, and it can be a convenient support for the management of natural hazards especially during critical situations.

1. Introduction

The recent technological development has made available a large number of possibilities in the field of hazard monitoring and management. It allowed for the development of automatic systems intended to facilitate the acquisition of information and the generation of warnings. This resulted in a variety of applications in different environments (natural or human-made), especially in the field of geohazards monitoring. In the literature, one can find applications in different contexts with the aim to control the evolution of landslides (Bobrowsky et al. 2015; Franz et al. 2016), rockfalls (Janeras et al. 2016), volcanoes (Calvari et al. 2016) and glaciers (Godone and Godone 2012), among many others. However, the aspect of dissemination of such monitoring data is still underestimated, especially if they are related to emergency scenarios (Giordan et al. 2015).

Hazards management is a multidisciplinary process, because it requires collaboration across many different organizations and specialists. The aim of such management is to reduce human, economic and environmental losses, and the application of early warning systems (EWSs) often provides an important support.

Many recommendations about EWSs design can be found in the literature. For example, the EWSs can be communication systems linking a variety of organizational actors to each other and
then to the public (Sorensen and Mileti 1988; Mileti and Sorensen 1990; Sorensen 2000; Xu and Zlatanova 2007). Therefore, a properly designed EWS can link science, technology, levels of government and public.

Furthermore, according to studies conducted by the United Nations, each EWS must be human-centred and should be composed of elements related to (1) risk knowledge, (2) monitoring and warning, (3) warning dissemination and communication, (4) response capability (UNISDR 2006, 2015). It has been noticed that each sub-system is continuously considered as an individual component, causing EWSs to be often unsuccessful.

Also, Garcia and Fearnley (2012) analysed the concept of EWS, and highlighted the weak aspects thereof, validated by real case studies. These studies have emphasized the need of strong links between the different sub-systems for efficient EWSs. The key to link these elements is to produce usable science, which focuses on practical aspects: being useful for societal or individual well-being, being helpful for decision-makers, producing understandable results for the public (Edwards et al. 2012; Garcia and Fearnley 2012; Gaillard and Mercer 2013; Giordan et al. 2015; Aitsi-Selmi et al. 2016).

Usually, monitoring systems integrate the EWS, because they provide reliable and accurate displacement and deformation measurements, which may be representative of the evolution of the geo-hazardous phenomena. Hence, they can be adopted for the definition of alert thresholds and for early warning purposes (Lacasse and Nadim 2009; Intrieri et al. 2013; Thiebes et al. 2014; Atzeni et al. 2015; Macciotta et al. 2016).

We have applied such systems in several contexts to manage various types of hazards, often to support the National Civil Protection Department during several Italian emergencies: L’Aquila earthquake (Manconi et al. 2012), Costa Concordia wreck (Manconi et al. 2013a), Montaguto and Mont de La Saxe landslides (respectively, Giordan et al. 2013; Manconi and Giordan 2015). Such experience in hazard monitoring and management has underlined the need of a communication strategy, which is strictly correlated with a proper representation of the scientific data (Giordan et al. 2015). This is a critical element in hazard governance, especially concerning emergency conditions and the generation of early warnings.

Hazards management, due to its complexity, must consider the risk communication during all stages of hazard governance: for early warning, for emergency and for pre/post emergency conditions. The communication which focuses on the imminent threat of a hazardous event is referred to as a warning and it is meant to produce an appropriate emergency response. On the contrary, the communication focusing on the long-term is considered as hazard awareness programme, intended to produce long-term hazard adjustments Van Westen et al. (2011).

In this context, in order to fulfil the presented requirements, we propose the development of a human-centred communication concept, adoptable for any condition of hazard management, suitable for non-expert receivers and helpful for communication between all people involved in the hazard management (population, politicians, decision-makers, experts, etc.).

In this paper, we present an approach for monitoring results dissemination in the form of single-page informative bulletin, composed of synthetic information about landslide status. Further, we present the development of an automatic methodology for fast and efficient data analysis, proper elaboration and dissemination, and we integrate all these elements into an algorithm for automatic bulletin generation. We apply the algorithm to Mont de La Saxe rockslide (hereinafter La Saxe) monitoring data-set to study the consistency of the model. The purpose is to construct a configurable tool that can be easily adapted to the hazard conditions under study and that can be adapted to different stages of hazard evolution.

2. General description of the bulletin

An appropriate communication of monitoring results is necessary for efficient management of natural hazards. As presented in Giordan et al. (2015), in the field of slope instability, these type of results
must be disseminated to a large number of people who have different needs and understanding capabilities. For this reason, all people directly involved in management have been categorized into three background group-types: ROLE-1, ROLE-2 and ROLE-3. ROLE-1 includes authorities (e.g. mayor, aldermen, politicians), who often do not have adequate technical background. However, they are at the terminal of the decision process and they need a clear overview of the situation in order to provide public safety. ROLE-2 is dedicated to engineers, geologists and technicians with specialized knowledge and experience. Their tasks are mainly related to technical analysis and to support ROLE-1 in their decisions. ROLE-3 is mainly composed of engineers and geologists, highly-specialized in hazard monitoring and EWSs. Their goals are to develop and to run monitoring networks, to analyse and to validate the data and the results especially to facilitate hazard management for other involved groups. All these people contribute to the emergency management; so, the dissemination process must have a multilevel structure. In fact, in Giordan et al. (2015), we can find a specific approach consisting of representing the same data-set in the form suitable for each group (ROLE-1, ROLE-2 and ROLE-3) and establishing an adequate access permission to these results. However, the real terminal receiver of complex monitoring systems’ results is the population at risk.

A proper dissemination strategy of the monitoring results is fundamental, considering either emergency condition or educating the population at risk because only a well-prepared and risk-conscious population will respond efficiently to the warning. Additionally, the management of hazard monitoring systems often incorporates EWSs and as mentioned in the introduction, the EWSs should be human-centred and should serve as the communication system linking a variety of organizational actors to each other and then to the public. To face this problem, the content of the proposed single-page document (easy to read, easy to interpret, easy to disseminate) is independent of the reader knowledge basics and so it is adequate for all members. In this context, the bulletin is mainly dedicated to ROLE-1 members, who can decide to distribute it to the population. Therefore, the present bulletin has been designed by means of infographic techniques.

An infographic is a way to represent complex data or information in a graphic format in order to quickly deliver the data and make it at a glance easily understandable by the audience (Smiciklas 2012). Infographics are used to quickly communicate a message, to simplify the presentation of large amounts of data, to see data patterns and relationships and to monitor changes in variables over time. The use of infographic techniques represents a good solution to integrate a variety of information relative to landslide evolution. Therefore, we have decided to communicate the monitoring results in the form of an informative bulletin, and according to the infographic approach, the bulletin layout consists of graphic visual representation of monitoring data.

The principal elements considered in this bulletin are: (1) description of the unstable area (definition of landslide limit and sectors, and nearby elements at risk); (2) assessment of landslide activity level in the considered time interval; (3) definition of movement trend based on registered displacement in the considered time interval with respect to the previous one.

The identification of the landslide limit and the kinematic domains (sectors) is a well-known procedure in the field of landslide characterization and monitoring. This is usually performed using geomorphological investigations and monitoring results analyses (Giordan et al. 2013; Crosta et al. 2014). Usually, large landslides have several kinematic domains, which can be distinguished by selecting the zones with similar internal behaviour. The definition of these domains is important for a correct evaluation of the level of risk and the comprehension of landslide evolution and activity.

The activity level is another element considered in this bulletin. According to the landslide status classification proposed by Cruden and Varnes (1996), the currently moving landslides are classified as active phenomena. However, in the field of landslide monitoring, stating that a landslide is ‘active’ is insufficient for a correct definition of the landslide status. In this bulletin, we propose three different levels of activity that can be useful for non-expert people to understand a possible evolution of the landslide. According to the concept introduced in Giordan et al. (2015), these levels are defined as follows: Low activity level means that the landslide is considered to be active with low displacement trend; however, local activation and/or rock falls cannot be excluded. In the case of moderate
activity level, the displacement is locally high and elevated attention is required due to possible occurrence of moderate to large size activations. Finally, high activity level is related to high values and to possible acceleration of the displacement; thus, a careful landslide evaluation is strongly recommended. The macroscopic behaviour of the slide (e.g. the activation of rock falls and/or other limited gravitational processes) is the only element that is perceived by the population who live nearby an unstable slope. A correct perception of these signs is important for a better awareness of the level of risk.

Velocity thresholds, whose definition is a critical aspect in landslide monitoring, indicate the boundaries of activity levels. According to Crosta and Agliardi (2003), velocity thresholds should be evaluated on the single case considering several aspects as the landslide geometry, lithology and registered displacement velocity.

The last element considered in this bulletin is the movement trend of different kinematic domains (sectors). Providing exclusively the displacement velocity measured in a particular sector of the slide is not representative enough, because it is important to inform the stakeholders if the displacement rate is increasing, decreasing or is stable. A prolonged increasing phase may be, in fact, the beginning of a critical period that could also consist of partial or total collapse of the unstable area.

The bulletin combines all the presented elements, whose purpose is not risk evaluation, but the clear representation of landslide evolution based on acquired monitoring data-set. Afterwards, ROLE-1 members have to consider, according to predefined Civil Protection procedures, the interdiction or the evacuation of the area at risk.

The graphic layout of the present bulletin has been created with a special focus on communication aspects. Since this bulletin is dedicated to non-expert people (ROLE-1 and population), it has been designed with low expectations about the readers’ knowledge basis; thus, the monitoring data have been presented in a clear, illustrative and quickly interpretable manner. Also, experts (ROLE-2 and ROLE-3) may take the opportunity to consult the bulletin in order to get a quick preliminary overview of the situation. Certainly, experts have access to the data-set in order to perform a broader evaluation of the landslide status.

An example of such a bulletin, for La Saxe landslide, is presented in Figure 1. It has been generated based on the real monitoring data-set relative to the month of November 2014. The data-set is referred to a monitoring network based on a Robotized Total Station (RTS) and a set of optical prisms installed at the unstable slope area. The RTS measurements have been governed by ADVANCE, an ADVanced dIsplaCement monitoring system for Early warning (Allasia et al. 2013).

In the following, the layout of the bulletin is described. The central part of the page is dedicated to the photographic representation of the monitored area and its surroundings. The monitored area is contoured by the limits of its sectors, represented with dashed lines. A different colour is assigned to each sector. The perspective view of the area of interest is an optimal representative solution: in fact, it is an easily recognizable view for the population involved (i.e. every person present in the risky zone) and it can include the infrastructures (civil houses, public buildings or transportation structures) located in the hazard neighbourhood. Furthermore, the surface deformation map of current displacement status is presented in gradual colour scale and overprinted on the perspective view of the slide. Additionally, the displacement is expressed by means of three-dimensional (3D) arrows associated with the prisms’ location, showing the real direction of motion. The magnitude of such arrows is normalized so that they are visible on the picture of the monitored area (Allasia et al. 2013). Such a combined representation gives, at a glance, information about different variables like distribution, direction and magnitude of the displacement. It permits for an immediate, clear and easily interpretable overview, unlike classical time-series plots (Manconi et al. 2013b).

The movement trend is analysed separately for each possible landslide sector: this is obtained by comparing the value registered in the considered lapse of time with respect to the previous one. This trend information is displayed by means of simple icons representing a tachometer, and it may be defined as: decelerate, constant or accelerate. The only numerical value available for the reader is the
Figure 1. Example of monthly bulletin (November 2014) automatically generated by the algorithm for La Saxe landslide. The used data-set is relative to RTS measurements. The document is mainly composed (1) in its central part of perspective view of La Saxe slide with overprinted surface deformation map of the line of sight (LOS) displacement and three-dimensional arrows (based on displacement measured in three directions) showing the real direction of movement; (2) of movement trend definition (decelerate, constant or accelerate) with the displacement values measured in the analysed periods for each sector of the landslide; (3) of general activity level definition (low, moderate or high) with a brief description of each level.

The monitoring network is divided, for simplicity, in three sectors corresponding to the Civil Protection plan. *maximum values measured in each sector.
maximum displacement of current and previous period (used to define a trend); the current ones are highlighted in order to obtain an intuitive separation of the presented data. In order to simplify the reading of the bulletin, the values are rounded-off to a convenient number of decimals.

Finally, the landslide general activity level for the considered period is presented. This information is disseminated in the form of an eye-catching logo coloured according to the detected activity level (see upper-right corner of Figure 1). The activity level may result as low, moderate or high. As a logo tonality, a gradual colour change (traffic light-type) increasing together with the activity level (low = green, moderate = orange, high = red) has been employed. A short description with the expected evolution of each level is presented in the bottom part of the bulletin.

We supported the National Civil Protection Agency during the two most-critical La Saxe activations: in March 2013 and in March 2014 (respectively Manconi and Giordan 2015, 2016). During these emergency periods, the municipality of Courmayeur organized several public assemblies to explain to the population the evolution of the landslide using the representations provided by the bulletin. As this bulletin-type document has obtained positive feedback from the population, and acceptance from the Geological Survey of Aosta Valley, the National Civil Protection Agency and municipal authorities, the bulletin has been periodically issued (initially weekly and then monthly).

3. Structure of the algorithm

All bulletins issued since 2014 have been realized by an adequate expert who had the responsibility to prepare the bulletin layout and to state the landslide activity level and trend, according to the available monitoring data-set and his own experience. Certainly, this experience-based approach shows evident issues concerning the repeatability of the process, because of the lack of a defined procedure. Additionally, the need of an analysis performed by an expert is time-consuming and it does not match with the potential application within the EWS. In order to overcome these limitations, we propose an automation of the process by developing an algorithm for bulletin generation.

This algorithm has been implemented in Matlab® environment. It has been designed in order to be compatible with any point measurements data-set (produced by RTS, global positioning system (GPS) or GB-SAR, a Ground-Based Synthetic Aperture Radar) and processed by the ADVICE system. A simplified version of ©3DA (Three-Dimensional Displacement Analysis) was implemented inside the algorithm for automatic bulletin generation. For more details about ©3DA, the reader may refer to Allasia et al. (2013).

Our algorithm not only plots the monitoring data and generates the bulletin layout, but also evaluates landslide general activity level and movement trend, thanks to the definition and implementation of the criteria to determine these landslide characteristics.

The criteria to define tendency and activity have been implemented based on target measurement data-set. In general, this type of data-set is composed of time-series that, depending on the monitoring scenario and instrumentation used, can be either the displacement in three directions and/or the line-of-sight displacement (LOS).

In Figure 2, the general algorithm flow-chart is presented. Four sections can be identified: the ©3DA-type one is highlighted in blue, the trend/activity one is highlighted in yellow and their common parts are highlighted in green. Inputs and output are displayed in grey colour.

©3DA-type subroutine produces two- and three-dimensional magnitude maps of a physical quantity (declared in the configuration file) by interpolating the monitoring data over a given region of interest (ROI). Moreover, it provides 3D vectors at the initial measurement points to indicate the magnitude, intensity and direction of displacement (measured at this particular point). These results are referenced and projected either on photograph or on digital terrain model (DTM) of the ROI.

The outputs of the second section are the general activity level, the trend definition for each sector and the maximum displacements registered in each sector.
Furthermore, all collected outputs pass to the bulletin-generating subroutine, which associates the obtained result with corresponding icons and related descriptive text, and generates the final bulletin layout (see Figure 1).

3.1. 3D representation of surface deformation

The first step to generate a ©3DA-type output is the definition of the input for surface interpolation subroutine (D’Errico 2006). Figure 3 illustrates the possible components for surface interpolation.
input, i.e. measuring points location e.g. prism, landslide limit and/or another boundary condition e.g. structural discontinuities, external boundary and grid density of the ROI. The displacement values at the measuring point locations are assigned based on the extracted monitoring data. On the contrary, a zero value displacement may be imposed at the landslide limit and external boundaries coordinates, in order to avoid non-realistic interpolation out of the landslide zone and to provide a more accurate result. The landslide limit is identified thanks to preliminary geomorphological investigations and monitoring data analysis, in order to ensure the absence of displacement out of the defined boundaries.

Once the interpolation procedure is complete, the elevation data (necessary for the surface plot in 3D space) are passed to the algorithm from the DTM input file, and the surface plot is performed.

In order to plot the displacement vectors, which indicate the real direction of motion, the monitoring network must be referenced to a convenient geographic system (e.g. UTM-WGS84). For this reason, if necessary, the algorithm rotates the components of the displacement to the north.

Once all the described steps have been completed and camera viewing parameters (e.g. camera position coordinates, tilting during the shot, viewing angle) have been imposed, the collective plot is created.

### 3.2. Sectors trend definition

For each sector of a landslide, the algorithm defines a displacement trend by analysing two consecutive time slots. The first step consists of finding, for each sector, the maximum displacement value for the current period and the one for the previous period. Then, the difference between these two displacements is computed. Finally, the trend is defined according to the approach shown in Figure 4. The

Figure 3. Schematic representation of the components of the input for surface interpolation: measuring point locations, e.g. prisms, external boundary and grid density of ROI, landslide limit and/or another boundary condition.

Figure 4. Trend conditions scheme. Three trend types can be distinguished based on the difference between the maximum displacements of the consecutive time slots. The trend type is defined separately for each landslide sector. The boundary values are identified as a percentage of maximum displacement \(\%\text{MAX}_p\) of the previous period with respect to the analysing one.
boundary values defining the three regions are identified as a percentage of the maximum displacement of the previous period (\(\%\text{MAX}_p\)). For a difference resulting between \(+\%\text{MAX}_p\) and \(-\%\text{MAX}_p\), the trend is defined as \textit{CONSTANT}, otherwise it is defined as \textit{DECELERATE} or \textit{ACCELERATE}.

### 3.3. General activity definition

The algorithm provides an indication about the general activity level by analysing the entire landslide average velocity. The velocity representative of each sector is calculated as the ratio between the maximum displacement in that sector and the current time slot. The entire landslide average velocity is the simple arithmetic mean between the calculated sector velocities.

In Figure 5, the activity level definition approach is presented. Two velocity values \(V_1\) and \(V_2\) are imposed in order to identify the boundaries of the three activity levels. These two velocities must be declared in the input file by the operator, as they are purposely defined according to a preliminary evaluation of the landslide characteristics. For a landslide average velocity between \(V_1\) and \(V_2\), the activity is defined as \textit{MODERATE}, otherwise it is defined as \textit{LOW} or \textit{HIGH}.

Furthermore, a border zone is established in order to perform a reasonable choice of the activity level when the average velocity falls in the proximity of a boundary. We assume such case as questionable, and further assumptions for this particular case are implemented.

The activity level definition flow-chart is presented in Figure 6. To specify the activity level when the average velocity falls in the border zone, the velocity changes with respect to the previous period are analysed. A positive velocity derivative determines an increase of activity level (e.g. from low to moderate or from moderate to high), otherwise a decrease of activity level is imposed (e.g. from high to moderate or from moderate to low). A zero velocity derivative validates the solution of the previous step of the algorithm.

The width of each border zone is equal to a percentage (\(\%B_Z\)) of the difference between \(V_2\) and \(V_1\).

### 3.4. Configuration parameters

This algorithm is built into a standalone application. The standalone executable runs without using MATLAB® software. This means that a local and/or remote computer used for surveying the phenomenon does not need to have MATLAB® software installed on board; thus, this standalone executable can be easily distributed and used. All settings related to bulletin generation can be easily modified via the configuration file.

The purpose is to develop a universal bulletin-generator tool based on configurable parameters. In fact, the standalone application hides the source code, but the user can configure its inputs and parameters in order to adapt the application to the conditions of the hazard under study.
The input files necessary for automatic bulletin generation are presented at the top of Figure 2. They are mainly related to the monitoring network characteristics, to the geometry of the landslide, to the ©3DA-type graphical representation, to the trend and activity evaluation and to the bulletin periodicity; all of these files are passed to the algorithm through the configuration file.

As explained in Sections 3.2 and 3.3, trend and activity definition are based on configurable parameters. The algorithm is able to process up to five sectors; the user shall organize the targets position data into separate input files. In order to configure the trend and activity definition conditions, the user shall also impose $\%\text{MAX}_p$, the velocity $V_1$ and $V_2$ and the border zone width coefficient $\%B_Z$.

Bulletin periodicity can be configured as 1 month, 1 week, 24 h or 12 h. The algorithm automatically recalculates all necessary data to select the periods of interest (i.e. previous and current).

Concerning the ©3DA-type output, the user can impose interpolation parameters and visualization parameters related to surface and vector plots, as well as input files such as DTM, monitoring network, base map and boundary conditions.

The user may choose the variable to be analysed and presented in the bulletin: LOS, planimetrical displacement or 3D displacement.

4. Algorithm application

Since 2012, we have supported the Geological Survey of Aosta Valley for the management of La Saxe rockslide. However, the year 2014 represents the period of maximum displacement from the beginning of monitoring activities, as described in Manconi and Giordan (2015).

In this section, we present the application of the algorithm to the La Saxe landslide evolution of 2014. In the first part of this section, La Saxe landslide is briefly described, and we analyse its evolution based on the relevant monitoring data. In the second part of this section, we apply the algorithm to the same data-set and then we present and discuss the results.
4.1. Mont de La Saxe rockslide description

La Saxe is a large and complex slope instability located in the region of the Aosta Valley in northern Italy. It involves an unstable volume of ca. $8 \times 10^6$ m$^3$ (Crosta et al. 2014, 2015) and it hazards a part of the Courmayeur municipality, i.e. Entreves and La Palud villages. Moreover, it threatens the access road to the Mont Blanc Tunnel, an important connection for trans-Alpine transport. Due to these characteristics, continuous and automatic monitoring of surface displacement has started in 2009.

The monitoring system for superficial displacement measurements consists of the following instrumentation: (1) RTS surveying optical targets positioned inside the rockslide as well as outside of it; (2) GB-SAR; (3) GPS receivers for automatic continuous measurements and (4) GPS benchmarks for periodic, manually operated measurements (Crosta et al. 2014). This monitoring allowed to observe that spring snow-melt progressively accelerates the surface displacement, which may locally reach up to several decimetres or even metres per day. Over the years, these acceleration phases have caused partial failures of the landslide body, with volumes ranging from minor rockfalls up to relatively larger mass wasting ($>1 \times 10^4$ m$^3$).

Analysis of monitoring data allowed to distinguish the activity-type distribution of La Saxe rockslide. Due to the fact that this landslide does not behave as a unique mass and that different kinematic zones have been localized, the whole body of the landslide has been divided into three sectors – A, B and C (as shown in Figure 1).

In the following, the annual landslide behaviour is briefly described. After the winter period, characterized by limited movement, the first significant activity was noticed at the end of March. At this time, prisms representing sector C have augmented their movement rate. The significant values of cumulative displacement (LOS) in the first trimester ranged from 1.80 to 2.60 m, with a notable velocity increment at the end of March. This acceleration was considered as a consequence of the registered increase of temperature and of La Saxe known sensitivity to the seasonal snow-melt.

The displacement rate of prisms in other sectors was neglected.

This seasonal acceleration, mainly localized in sector C, continued to evolve in the following period. The most significant displacement, registered in April, had a maximum of 62.7 m. This acceleration phase has resulted in a large number of minor rockfalls and in two main failure events: 17 and 21 April, with respectively ca. $5 \times 10^3$ m$^3$ and ca. $3 \times 10^4$ m$^3$ of released material (Manconi and Giordan 2015). The highest velocity of the unstable mass has reached 60 cm/h. In the following months, May and June, the maximum displacements registered were respectively 22.2 and 14.6 m.

In this period of strong activity of the frontal part (sector C), the activity of the other two sectors (A and B) was notable but regular. The total three-month displacements registered in sector B ranged from 60 to 100 cm, and for sector A the maximum reached approximately 60 cm.

The third trimester showed a general and progressive decrease of the displacements rate. Such decrease was mostly evident in sector C, with a total measured displacement of approximately 10 m. Sectors A and B showed a similar decreasing trend, with a three-month maximum displacement of approximately 41 cm (sector B) and 23 cm (sector A).

The fourth trimester confirmed the general decreasing trend of the previous one. This behaviour was observable in all the three sectors. The three-month maximum displacement measured for sectors A, B and C was respectively 25 cm, 39 cm and 6.3 m. However, this trend was not monotonic, as a significant increase of the displacement could be observed in November in all the three sectors. This may have been a consequence of the elevated autumnal precipitation, especially during October and November.

4.2. Results and discussion

As outlined in subsection 4.1, the data collected in 2014 are heterogeneous because of the existence of different kinematic zones and of various behaviour during the year (activation, partial failures,
slowdown). Beside this, La Saxe is one of the most hazardous landslides in northern Italy, extensively investigated and monitored, and in consequence, the availability of monitoring data is large (Crosta et al. 2015). In this context, the selected case study is appropriate to develop the algorithm and to test the consistency of the proposed methodology, because it represents a worst-case scenario, and therefore a severe test bench for the algorithm.

As explained previously, the trend is specified based on the percentile displacement difference between the analysed period and the previous one (see Figure 4), and for this landslide, a gauge of 10% was chosen. Furthermore, the activity level is defined according to the average value of maximum velocities of each sector. For La Saxe landslide, these velocity thresholds have been established based on the thresholds defined by the Geological Survey of Aosta Valley region. The interval between 1 and 2 mm/h describes a moderate activity, and in consequence, the values out of this interval determine respectively low and high activity. The border zone was defined as 1% of the intermediate interval.

We applied our algorithm to the RTS measures of the entire 2014, processed by the ADVICE system. We evaluated the performance of the proposed methodology by producing 12 monthly bulletins and by verifying the consistency of this model, especially the accuracy of the criteria to define the landslide general activity level. Table 1 summarizes the main results for each month in terms of trend type (decelerate, constant or accelerate) for each sector (A, B and C) and general activity level (low, moderate or high). Furthermore, the maximum values measured for each sector during both previous and current period are provided.

The evolution of general activity levels identified by the algorithm follows the overall landslide behaviour described in subsection 4.1. A simplified representation of this evolution is shown in Figure 7. The resulting activity level is coherent with the activity level defined by the experience-based approach.

At the turn of March and April, abrupt landslide movements have been registered; hence, an immediate transition from low to high activity has been obtained. Certainly, the moderate activity was omitted due to the choice of time-sampling window, i.e. for this case study – one month.

On the contrary, the decelerating phase was characterized by the gradual reduction of the displacement rate (see Section 4.1). The activity evolution illustrates this phase (period July–October) accurately and it describes a passage from high activity to moderate one and then to low one. Moreover, the data indicated slight acceleration of all sectors in November, and the algorithm correctly defined the activity as moderate (see bulletin example in Figure 1).

The results (trend and activity) are complementary and they must be always evaluated together. In fact, after the abrupt event in April, the activity level during the period May–July is defined as high because of the elevated displacement values, even if the trend is defined as decelerating for all sectors. This proves that a decelerating trend does not necessarily imply a moderate or low activity.

These bulletin examples, with a relatively large sampling time (one month), are meant to be used for informative purpose, and not for emergency situations. Anyway, thanks to the structure of this algorithm (see Section 3.4), it is possible to reduce the time-window in order to adapt it for emergency purposes (to issue the bulletin more frequently) as an additional support for the population at risk, decision-makers and experts.

Besides, the automation of the process permits to integrate the bulletin generator within the EWS, by requesting the generation of the bulletin and by attaching it to the warning message when the threshold is exceeded. In fact, in Intrieri et al. (2012), the authors introduce three warning levels for the application of EWS: ordinary level, attention level and alarm level. For each warning level, they propose to issue bulletin-type document with different frequencies: respectively month, 24 and 12 h.

An important feature of the bulletin generator algorithm is the configurability. In fact, natural hazards are heterogeneous; they are characterized by different evolution schemes and they may need different monitoring techniques. The algorithm is able to process every monitoring data-set which provides point measurements, e.g. target displacement measured by RTS, GPS or GB-SAR.
Table 1. Summary of the monthly bulletins main results for La Saxe landslide for the period January–December 2014. The bulletins were generated considering the LOS measurements data-set obtained by RTS. The resultant trend is reported for each sector together with the maximum values relative to the considering periods. The general landslide activity level is stated for each month. The activity thresholds are 1 mm/h (between low and moderate) and 2 mm/h (between moderate and high).

|     | Sec.A | Sec.B  | Sec.C | Act. |
|-----|-------|--------|-------|------|
| Jan. | DECELERATE | 10.2/8.4 | DECELERATE | 73.6/50.4 | Low |
| Feb. | DECELERATE | 8.4/5.3 | DECELERATE | 50.4/33.3 | Low |
| Mar. | ACCELERATE | 5.3/8.1 | ACCELERATE | 33.3/176.8 | Low |
| Apr. | ACCELERATE | 8.1/29.7 | ACCELERATE | 176.8/6268 | High |
| May  | DECELERATE | 29.7/18.1 | DECELERATE | 6268/2224 | High |
| Jun. | DECELERATE | 18.1/13.1 | DECELERATE | 2224/1461 | High |
| Jul. | DECELERATE | 13.1/9.6 | DECELERATE | 1461/527.9 | High |
| Aug. | DECELERATE | 9.6/7.8 | DECELERATE | 527.9/277.8 | Mod. |
| Sep. | DECELERATE | 7.8/5.6 | DECELERATE | 277.8/175 | Low |
| Oct. | DECELERATE | 5.6/5.8 | DECELERATE | 175/154.3 | Low |
| Nov. | ACCELERATE | 5.8/11.1 | ACCELERATE | 154.3/259.1 | Mod. |
| Dec. | DECELERATE | 11.1/8.3 | DECELERATE | 259.1/214.5 | Mod. |
The possibility to configure input data and algorithm parameters is a fundamental aspect, as it guarantees flexibility and quick application of the developed tool for various scenarios, especially during emergencies when the time is limited. Therefore, this tool might have potential applications not only for landslide monitoring but also in other contexts, such as monitoring of other geohazards and of complex infrastructures, for example open-pit mines, buildings, dams.

The applied methodology for realizing the presented bulletins allows to integrate information about the multiple characteristics of the landslide phenomena (e.g. movement value, trend, activity) in an efficient, illustrative and clear way by means of several typologies of representation. In fact, the bulletin presents the results with an appropriate graphical representation, e.g. 3D displacement into an arrow, displacement trend into a simple tachometer icon, landslide activity level into a coloured eye-catching logo. Such a combined data visualization facilitates risk assessment for the bulletin reader. A fundamental confirmation about bulletin usability was provided by the Geological Survey of Aosta Valley, the National Civil Protection Agency and municipal authorities, as we obtained their positive feedback and acceptance to periodically issue the bulletin.

5. Conclusions

Hazards governance is a complex task due to its multidisciplinary nature and variety of actors involved. Although technological improvements are observed, the aspect of dissemination of the scientific data is underestimated. A proper dissemination strategy of monitoring results is fundamental, either considering emergency conditions or educating population so that response to warnings is efficient. However, despite the fact that the technological advancement enables a quick dissemination of warnings, often times the message may not be clear for the final receivers. The concept of single-page bulletin was governed by the need to enhance the effectiveness of communication between all people involved (population, politicians, decision-makers, experts, etc.), to increase the general awareness of the population about the risk status and to support decision-makers. To achieve this goal, we focused not only on bulletin contents but also on how these contents are represented. This development is based on multidisciplinary approach due to the variety of aspects to be considered: communication features, infographic techniques, monitoring data analysis and interpretation and adequate algorithm design.

The presented bulletin illustrates the monitoring results and describes landslide general activity and movement trend. We have constructed it in such a way that receivers can easily consult monitoring data and information on the evolution of the hazardous phenomena.

In order to exploit the full potential of the bulletin, the automation was a crucial aspect. We applied the developed algorithm to the RTS monitoring data-set of Mont de La Saxe landslide, and we validated it by verifying the consistency between the model, the real evolution of the landslide.
and the results of the experience-based approach. In particular, we successfully verified the coherence of the results obtained by the algorithm with those obtained by the experience-based approach. The algorithm for automatic bulletin generation allowed a rapid and effective analysis of numerical data-set and their translation into infographics.

A further improvement of the presented work concerns the integration of the algorithm with the ADVANCE system (Allasia et al. 2013), which runs in automatic mode, in order to operate in near-real time and to set up bulletin generation either continuous with a desired frequency or within the EWS.

Acknowledgments

The authors would like to thank D. Bertolo and P. Thuegaz of the Geological Survey of Aosta Valley (RVDA) for providing the necessary data for the validation of the method.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Daniele Giordan http://orcid.org/0000-0003-0136-2436

References

Aitsi-Selmi A, Blanchard K, Murray V. 2016. Ensuring science is useful, usable and used in global disaster risk reduction and sustainable development: a view through the Sendai framework lens. Palgrave Commun. 2:16016.

Allasia P, Manconi A, Giordan D, Baldo M, Lollino G. 2013. Advice: a new approach for near-real-time monitoring of surface displacements in landslide hazard scenarios. Sensors. 13(7): 8285–8302.

Atzeni C, Barla M, Pieraccini M, Antolini F. 2015. Early warning monitoring of natural and engineered slopes with ground-based synthetic-aperture radar. Rock Mech Rock Eng. 48(1): 235–246.

Bobrowsky P, Sladen W, Huntley D, Qing Z, Bunce C, Edwards T, Hendry M, Martin D, Choi E. 2015. Multi-parameter monitoring of a slow moving landslide: Ripley slide, British Columbia, Canada. In: Lollino G, Giordan D, Crosta GB, Corominas J, Azzam R, Wasowski J, Sciarra N, editors. Engineering geology for society and territory. Vol. 2. Cham: Springer; p. 155–158.

Calvari S, Intrieri E, Di Traglia F, Bonacorso A, Casagli N, Cristaldi A. 2016. Monitoring crater-wall collapse at active volcanoes: a study of the 12 January 2013 event at Stromboli. Bull Volcanol. 78(5): 1–16.

Crosta G, Agliardi F. 2003. Failure forecast for large rock slides by surface displacement measurements. Can Geotech J. 40(1): 176–191.

Crosta G, Di Prisco C, Frattini P, Frigerio G, Castellanza R, Agliardi F. 2014. Chasing a complete understanding of the triggering mechanisms of a large rapidly evolving rockslide. Landslides. 11(5): 747–764.

Crosta GB, Lollino G, Paolo F, Giordan D, Andrea T, Carlo R, Davide B. 2015. Rockslide monitoring through multi-temporal lidar dem and tls data analysis. In: Lollino G, Giordan D, Crosta GB, Corominas J, Azzam R, Wasowski J, Sciarra N, editors. Engineering geology for society and territory. Vol. 2. Cham: Springer; p. 613–617.

Cruden DM, Varnes DJ. 1996. Landslide types and processes. In: Turner AK, Shuster RL, editors. Landslides investigation and mitigation. Transportation Research Board, Special Report 247. Washington (DC): National Academy Press; p. 36–75.

D’Errico J. 2006. Surface fitting using gridfit. MATLAB® Central File Exchange. [accessed 2006 May 18]. http://www.mathworks.com/matlabcentral/fileexchange/8998.

Edwards SJ, Fearnley CJ, Lowe CJ, Wilkinson E. 2012. Disaster risk reduction for natural hazards: putting research into practice. Environ Hazards. 11(2): 172–176.

Franz M, Carrea D, Abellán A, Derron MH, Jaboyedoff M. 2016. Use of targets to track 3D displacements in highly vegetated areas affected by landslides. Landslides. 13(4): 821–831.

Gaillard JC, Mercer J. 2013. From knowledge to action: bridging gaps in disaster risk reduction. Prog Hum Geogr. 37(1): 93–114.

García C, Fearnley CJ. 2012. Evaluating critical links in early warning systems for natural hazards. Envirom. Hazards. 11(2): 123–137.
Giordan D, Allasia P, Manconi A, Baldo M, Santangelo M, Cardinale M, Corazza A, Albanese V, Lollino G, Guzzetti F. 2013. Morphological and kinematic evolution of a large earthflow: the Montaguto landslide, southern Italy. Geomorphology. 187: 61–79.

Giordan D, Manconi A, Allasia P, Bertolo D. 2015. Brief communication: on the rapid and efficient monitoring results dissemination in landslide emergency scenarios: the Mont de La Saxe case study. Nat Hazards Earth Syst Sci. 15(9): 2009–2017.

Godone D, Godone F. 2012. The support of geomatics in glacier monitoring: the contribution of terrestrial laser scanner. Rijeka: INTECH Open Access Publisher.

Intrieri E, Gigli G, Casagli N, Nadim F. 2013. Brief communication”landslide early warning system: toolbox and general concepts”. Nat Hazards Earth Syst Sci. 13(1): 85–90.

Intrieri E, Gigli G, Mugnai F, Fanti R, Casagli N. 2012. Design and implementation of a landslide early warning system. Eng Geol. 147: 124–136.

Janeras M, Jara J, Royán M, Vilaplana J, Aguasca A, Fábregas X, Gili J, Buxó P. 2016. Multi-technique approach to rockfall monitoring in the Montserrat massif (Catalonia, NE Spain). Eng Geology. 219(9): 4–20.

Lacasse S, Nadim F. 2009. Landslide risk assessment and mitigation strategy. In: Landslides–disaster risk reduction. Berlin, Heidelberg: Springer; p. 31–61.

Macciotta R, Hendry M, Martin CD. 2016. Developing an early warning system for a very slow landslide based on displacement monitoring. Nat Hazards. 81(2): 887–907.

Manconi A, Allasia P, Giordan D, Baldo M, Lollino G. 2013a. Monitoring the stability of infrastructures in an emergency scenario: the “Costa Concordia” vessel wreck. In: Wu F, Qi S, editors. Global View Eng Geol Environ. London: Taylor & Francis Group; p. 587–591.

Manconi A, Allasia P, Giordan D, Baldo M, Lollino G, Corazza A, Albanese V. 2013b. Landslide 3D surface deformation model obtained via RTS measurements. In: Margottini C, Canuti P, Sassa K, editors. Landslide Science and Practice. Berlin, Heidelberg: Springer; p. 431–436.

Manconi A, Giordan D. 2015. Landslide early warning based on failure forecast models: the example of the mt. de La Saxe rockslide, northern Italy. Nat Hazards Earth Syst Sci. 15(7): 1639–1644.

Manconi A, Giordan D. 2016. Landslide failure forecast in near-real-time. Geomat Nat Hazards Risk. 7(2): 639–648.

Manconi A, Giordan D, Allasia P, Baldo M, Lollino G. 2012. Surface displacements following the mw 6.3 L’Aquila earthquake: one year of continuous monitoring via robotized total station. Ital J Geosci. 131(3): 403–409.

Mileti DS, Sorensen JH. 1990. Communication of emergency public warnings. Landslides. 1(6): 52–70.

Smiciklas M. 2012. The power of infographics: using pictures to communicate and connect with your audiences. Indianapolis (IN): Que Publishing.

Sorensen JH. 2000. Hazard warning systems: review of 20 years of progress. Nat Hazards Rev. 1(2): 119–125.

Sorensen JH, Mileti DS. 1988. Warning and evacuation: answering some basic questions. Indust Crisis Q. 2(3-4): 195–209.

Thiebes B, Bell R, Glade T, Jäger S, Mayer J, Anderson M, Holcombe L. 2014. Integration of a limit-equilibrium model into a landslide early warning system. Landslides. 11(5): 859–875.

[UNISDR] United Nations Office for Disaster Risk Reduction. 2006. Global survey of early warning systems. Geneva: UNISDR.

[UNISDR] United Nations Office for Disaster Risk Reduction. 2015. The Sendai framework for disaster risk reduction 2015–2030. Geneva: UNISDR.

Van Westen CJ, Alkem D, Damen MCJ, Kerle N, Kingma NC. 2011. Multi-hazard risk assessment. Distance education course. Guide book version 2011. United Nations University-ITC School on Disaster Geoinformation Management. [accessed 2017 Mar 9]. ftp://ftp.itsc.nl/pub/westen/Multi_hazard_risk_course/Guidebook/Guidebook%20MHRA.pdf.

Xu W, Zlatanova S. 2007. Ontologies for disaster management response. In: Li J, Zlatanova S, Fabbri AG, editors. Geomatics solutions for disaster management. Lecture Notes in Geoinformation and Cartography. Berlin, Heidelberg: Springer; p. 185–200.