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Discussions

Technical Note: An operational landslide early warning system at regional scale based on space–time variable rainfall thresholds

S. Segoni, A. Battistini, G. Rossi, A. Rosi, D. Lagomarsino, F. Catani, S. Moretti, and N. Casagli

Department of Earth Sciences, University of Firenze, Florence, Italy

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Correspondence to: S. Segoni (samuele.segoni@unifi.it)

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Abstract

We set up an early warning system for rainfall-induced landslides in Tuscany (23 000 km^2). The system is based on a set of state-of-the-art intensity-duration rainfall thresholds (Segoni et al., 2014b), makes use of LAMI rainfall forecasts and real-time rainfall data provided by an automated network of more than 300 rain-gauges.

The system was implemented in a WebGIS to ease the operational use in civil protection procedures: it is simple and intuitive to consult and it provides different outputs. Switching among different views, the system is able to focus both on monitoring of real time data and on forecasting at different lead times up to 48 h. Moreover, the system can switch between a very straightforward view where a synoptic scenario of the hazard can be shown all over the region and a more in-depth view were the rainfall path of rain-gauges can be displayed and constantly compared with rainfall thresholds.

To better account for the high spatial variability of the physical features, which affects the relationship between rainfall and landslides, the region is subdivided into 25 alert zones, each provided with a specific threshold. The warning system reflects this subdivision: using a network of 332 rain gauges, it allows monitoring each alert zone separately and warnings can be issued independently from an alert zone to another.

An important feature of the warning system is the use of thresholds that may vary in time adapting at the conditions of the rainfall path recorded by the rain-gauges. Depending on when the starting time of the rainfall event is set, the comparison with the threshold may produce different outcomes. Therefore, a recursive algorithm was developed to check and compare with the thresholds all possible starting times, highlighting the worst scenario and showing in the WebGIS interface at what time and how much the rainfall path has exceeded or will exceed the most critical threshold.

Besides forecasting and monitoring the hazard scenario over the whole region with hazard levels differentiated for 25 distinct alert zones, the system can be used to gather, analyze, visualize, explore, interpret and store rainfall data, thus representing a potential support to both decision makers and scientists.

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1 Introduction

Landslide early warning systems (EWS) are important tools for the scientific community, even if their potential is not always fully understood by the broad society, including governments and decision makers (Baum and Godt, 2010; Intrieri et al., 2013). In landslide related hazards, many examples of site-specific EWS have been reported (Michoud et al., 2013 and references therein), but when the area to be monitored is large (e.g. tens of thousands of squared kilometers – regional scale henceforth) and the location of landslide occurrence cannot be known in advance, EWSs are not so well established and the description of new case studies is needed.

Regional scale landslide warning systems pay particular attention on rainfall as the main triggering factor; however, the use of physically based models is still at an experimental level (Mercogliano et al., 2013) and in most cases empirical rainfall thresholds are used (Keefer et al., 1987; Aleotti, 2004; Hong et al., 2005; Tiranti and Rabuffetti, 2010; Baum and Godt, 2010; Capparelli and Tiranti, 2010; Cannon et al., 2011; Floris et al., 2012; Jakob et al., 2012; Staley et al., 2013; Lagomarsino et al., 2013; Tiranti et al., 2014).

A broad literature exists on landslide rainfall thresholds (Guzzetti et al., 2007 and references therein) and intensity–duration (*I*–*D*) thresholds are the most popular (Caine, 1980; Guzzetti et al., 2008, and references therein). However, some authors (Rosi et al., 2012) highlighted that a comparison between rainfall paths and thresholds may produce different results depending on where the starting point of the critical rainfall event is set. This introduces a temporal variable that in traditional studies on intensity–duration rainfall thresholds is not addressed or is solved with expert judgment, with the drawback that EWSs cannot consistently reproduce human choices. This issue is not present in EWSs based on rainfall parameters as measured over a given duration (Chleborad, 2003; Cardinali et al., 2006; Cannon et al., 2008, 2011; Martelloni et al., 2012; Zhuang et al., 2014).

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In this work we describe the setting up of a regional landslide EWS in Tuscany (23 000 km^2), Italy, and we discuss the main practical issues encountered.

The EWS was based on a set of recently published *I–D* rainfall thresholds (Segoni et al., 2014b), that were defined using a recently proposed approach and methodology of analysis (Segoni et al., 2014a). The EWS combines LAMI (Limited Area Model Italy) weather forecasts and real-time rainfall measured by an automated network of 332 rain-gauges.

The EWS handles an issue associated to the spatial variability of the rainfall-landslide empirical relation and the temporal issue explained above. The former was managed considering a warning level analysis differentiated for each of the 25 alert zones; the latter was solved implementing a moving window that shifts the threshold in the time axis until the worst scenario is found.

The EWS was implemented in a WebGIS system with advanced functions but with an intuitive graphical interface. It provides a useful tool for assisting decision makers in assessing the warning level over the whole Tuscany region and at specific locations. The EWS and its WebGIS interface have been tested for two years with satisfactory results and are currently operated by the Tuscany Civil Protection Authority.

2 Material and methods

2.1 Physical setting

Tuscany (23 000 km^2) is an Italian region characterized by a heterogenic physical setting, including mountains up to an elevation of 2000 m, plains and wide hilly areas (Fig. 1).

The main reliefs are distributed in the northern and eastern parts of the region, and they belong to the Northern Apennine, a NW–NE elongated orogenic belt formed since Upper Cretaceous by the stacking of Ligurian Units over Tuscan – Umbrian Units and over Metamorphic Tuscan Units by the intercalation of Sub – Ligures Units (Bortolotti, 1992; Vai and Martini, 2001). Apennines flyschoid ridges are alternated with intermontane basins, which are basically grabens or semi-grabens filled up with granular and cohesive terrains. Other main reliefs are made up of metamorphic rocks, to the north-west, and volcanic rocks, to the south. The hills that characterize large part of the Tuscan landscape are constituted by cohesive or granular deposits.

Landslide processes have pervasively shaped the Tuscan landscape and still are an active geomorphic process in the whole region, especially in the northern steep mountainsides made up of flysch or schists.

Tuscan rainfall regime is typically Mediterranean: the main peak of precipitation is in autumn, whereas summer is the driest season. The rainfall amount varies largely depending on the main reliefs. The maximum values of mean annual precipitation (about 2000 mm year^{-1}) are found in the north-west and are favored by high mountains located near the warm Mediterranean Sea. The minimum values of mean annual precipitation are found in the southern plains and are lower than 600 mm year^{-1} (Rosi et al., 2012).

2.2 State-of-the-art rainfall thresholds

The different physical settings that are present in Tuscany correspond to different empirical relationships between rainfall and landslides. Segoni et al. (2014b) demonstrated that the effectiveness of a warning system could be enhanced subdividing the region into 25 independent Alert Zones (AZ) (Fig. 1), each characterized by a specific intensity-duration rainfall threshold. The warning system follows this approach and uses the mosaic of I–D thresholds proposed by Segoni et al. (2014b) and reported in Table 1.

The thresholds are defined considering a power law function in the form (Caine, 1980)

$$I = a\,D^{-b} \tag{1}$$

where I and D are rainfall intensity and duration, respectively, and a and b are empirical parameters.

A complete insight on the methodology used to define the threshold can be found in Segoni et al. (2014a), here we summarize two original features of the rainfall analysis performed for the threshold identification. These features need to be properly accounted for in this work, to obtain a consistent automatic interpretation of the rainfall paths by the early warning system.

First, each threshold is characterized by an additional parameter, namely "no rain gap" (NRG), which represents the amount of time without rainfall that is needed to consider two rainfall events as separate.

Secondly, the thresholds are based on an empirical correlation between landslides and the most severe rainfall conditions (in terms of both I and D) measured by the rain gauges located in the same alert zone. The most severe rainfall is defined comparing the return periods of the rainfall events recorded by the rain gauges and those of each rainstorm episode of shorter duration but higher intensity which may be contained within the main rainfall events. This procedure is very important in case of complex rainfall events characterized by a series of peaks of short duration and great intensity alternated with mild rainfalls or dry periods shorter than NRG.

These two peculiar features may be useful to standardize and automate the rainfall analysis, but they need to be consistently replicated in the early warning system to ensure a conceptual continuity from the theoretical analysis and the actual operational use of the thresholds.

2.3 Architecture of the early warning system

The architecture of the warning system is summarized in Fig. 2.

The Tuscany Region is equipped with an automated network consisting of 332 rain-gauges. These instruments measure rainfall at hourly time steps and each measure is sent in real time to the Regional Functional Center, which is in charge to maintain the network and to collect and store in a secure FTP (File Transfer Protocol) server all the measured data. Rainfall data are memorized in a Comma Separated Value (CSV) file containing, for each rain-gauge, the hourly rainfall intensity measured in mm h^{-1}. The

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file is constantly updated at hourly time steps. The FTP server hosts and constantly updates another CSV file containing information such as name, geographical coordinates and elevation of each active rain-gauge belonging to the network.

A real-time warning system service is implemented using PHP scripting (http://www.php.net/): every 30 min the script sets a connection to the FTP site, checks the presence of updated CSV files and downloads them then store the data in a local DBMS (Data Base Management System).

This is a MySQL database (http://www.mysql.com) where the information provided by the CSV file is replicated. The database contains also some keys to set a bidirectional relationship between Alert Zones and rain-gauges. In addition, a table stores for each Alert Zone all the parameters needed to define the threshold equation (α and β) and to allow a correct interpretation of the rainfall paths (no rain gap).

Immediately after each update, the rainfall paths are updated as well and the new values of cumulative rainfall recorded by each rain-gauge are compared with the appropriate thresholds.

An alert zone is alerted if at least one of its rain-gauges exceeds the threshold.

Even if rainfall thresholds are expressed in terms of intensity (mm h^{-1}) and duration (h), the warning system operates in terms of rainfall amounts (mm) and duration (h), to ease the interpretation of the time-evolution of the rainfall event by the civil protection personnel (Fig. 3). The consistency between threshold analysis and threshold implementation in the EWS is maintained using a simple algebraic conversion from rainfall intensity (I) to rainfall amount (C):
considering that $C = ID$,
the generic form of the rainfall threshold formula (Eq. 1) can be rewritten as

$$C = Da\, D^{-b} = a\, D^{1-b}. \quad (2)$$

In this form, the thresholds can be visualized in a linear graphic and directly compared to the rainfall path recorded by the rain-gauges to immediately visualize the rainfall amount fallen and the additional rainfall amount needed to exceeded the threshold (Fig. 3).

Whenever a rain-gauge does not measure any rain for an amount of time equal to the no rain gap value that characterizes its alert zone, the rainfall event is considered concluded. A new rainfall path will be built and analyzed independently starting from the next recorded precipitation. The data in the database are deleted to reduce the amount of used resources, but the system stores a steady stream of rain information on DB and CSV files. Rainfall events with cumulative values greater than 20 mm are characterized by a set of parameters (Fig. 4) which are stored as well, for future reference:

- ID_rg: unique ID of the rain-gauge (used as a link to other data);
- t_start: time when the rainfall event starts;
- t_end: time when the rainfall event ends;
- status: alert issued or not;
- cumulRain: final value of cumulative rainfall (mm);
- maxSovrCum: maximum value exceeding the threshold (or minimum distance from it if the threshold was not exceeded) (mm);
- t_maxSovrCum: time of occurrence of maxSovrCum;
- t_over_thres: time when the threshold was first exceeded;
- rainMax: maximum rainfall intensity (mm h^{-1});
- t_rainMax: time of occurrence of rainMax.

It could be possible that the whole rainfall event "t_start-t_end" does not represent the most hazardous condition. This is the case, for example, of complex pluviometric paths where very intense rain-bursts are averaged, over long durations, with less

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intense precipitations. This possibility is taken into account in the methodology used in threshold definition (Segoni et al., 2014a) and a consistent approach is needed for the early warning system. We therefore implemented a recursive procedure in which a script computes all possible cumulative rainfalls considering as starting time each time-step between t_start and the current time, then it compares the cumulative curves with the corresponding thresholds. From a visual point of view, this procedure is depicted in Fig. 5 and consists on a shifting of the beginning of the rainfall event until the worst scenario is found (highest value of maxSovrCum). In other words, the combination that exceeds the threshold by the largest amount (or that is below it by the shortest distance) is selected and shown in the WebGIS interface introduced in the following section of the manuscript.

The system, as described so far, allows nowcasting and monitoring activities. The early warning system is fully accomplished considering also the impact of rainfall forecasts on the thresholds.

According to the regional laws and the civil protection procedures, the Regional Functional Center is in charge of providing rainfall forecasts, with 6, 12, 24 and 48 h lead times, which are estimated using the LAMI (Limited Area Model Italy) meteorological model (Cacciamani et al., 2002). LAMI forecasts are commonly used in hydrological and hydrogeological modelling (Taramasso et al., 2005).

Since LAMI data are spatially distributed (with a horizontal resolution of 7 km), they are automatically sampled at each pluviometer location. These values are saved in a CSV file stored in the FTP server. When the connection is set to the FTP server, a script transfers these values to the warning system. Rainfall forecast values are then summed to the real time measurements and the cumulative rainfall amount is estimated for four different future scenarios (6, 12, 24 and 48 h in advance). This allows evaluating a few days in advance whether the threshold will be exceeded or not, according to rainfall forecasts.

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2.4 WebGIS interface

A WebGIS was developed with the purpose of providing the civil protection personnel with a straightforward tool for both the forecasting and the real time monitoring of the temporal evolution of the hazard associated with rainfall induced landslides.

The WebGIS continuously connects to the database (60 s refresh time) and, in its basic view, displays the status of all the rain-gauges of the network using different colors depending on the value of cumulative rainfall (Fig. 6):

- Inactive (no data available because of malfunctioning or temporary communication breakdown)
- No rain (no rain recorded in the last X hours, where X represents the no rain gap of the alert zone)
- Ordinary (rainfall below the threshold)
- Alert (rainfall above the threshold)

If needed, the WebGIS allows a more in-depth control on rain-gauges. With a hyper textual link, each rain-gauge can be accessed and its rainfall path is displayed and compared with the threshold (Fig. 6). The system allows the operator to consider both the real-time scenario, e.g. for monitoring purposes (Fig. 6), and the forecasted scenario at different lead times (in this case rainfall forecasts are joined to the real time measurements) (Fig. 7). In the background an algorithm shifts the initial time of the rainfall until the worst scenario (in terms of maxSovrCum) is identified; this is also the only scenario shown by the WebGIS (Fig. 7).

3 Results and discussion

The system went through a 2 years long test phase and continuous feedbacks from the civil protection personnel allowed adapting the visual interface to the operational needs

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experienced during the managing of emergency phases. To date, the use of the EWS is integrated in the official civil protection procedures.

Based on the experiences reported during the main critical events, the performance of the system was evaluated positively by the Civil Protection Agency.

For example, Fig. 8 shows the specific case of the December 2013 rainfall event that struck north-west Tuscany. According to official Civil Protection reports, the event triggered an unspecified number of landslides in the alert zone A3, and indeed two rain-gauges just exceeded the alert threshold. In addition to the spatial accuracy, in this case the timing of the alert was in good agreement with the ground truth as well: according to reports, all landslides happened between 28 and 29 December and this is approximately the time when the threshold was exceeded.

Figure 6 shows another study case where the system provided satisfactory outcomes: the March 2013 event was characterized by a very prolonged low-intensity rainfall without extremely intense peaks. Such circumstance is usually unfavorable to I–D thresholds, which are considered to be particularly appropriate for short and intense rainfalls. Nonetheless, the warning system outputs resulted in accordance with the official Civil Protection reports. We believe that this result could be partially due to the use of space-variable no rain gaps, which in some circumstances can be very long (up to 36 h), thus allowing to account properly for the rainfalls with low intensity and long duration.

Even if the civil protection procedure consists of issuing a warning if a single pluviometer exceeds the thresholds, the possibility of zooming and to investigate the behavior of a dense rain-gauge network can allow the identification of areas where the rainfall is particularly severe and the heaviest effects to the ground (landsliding) could be expected. To improve this capability, an ongoing research is experimenting the coupling of EWSs based on rainfall thresholds with landslide susceptibility maps (Segoni et al., 2014c) and with physically based slope stability models (Mercogliano et al., 2013; Rossi et al., 2013).

4 Conclusions

We set up an early warning and monitoring system for rainfall induced landslides in Tuscany (23 000 km^2). The system is based on a set of intensity-duration rainfall thresholds, makes use of LAMI rainfall forecasts and real-time rainfall data supplied by an automated network of more than 300 rain-gauges.

The EWS was implemented in a WebGIS to ease the operational use in civil protection procedures: it is intuitive and simple to consult and it provides different outputs. Switching among different views, the system is able to focus both on monitoring of real time data and on forecasting scenarios at different lead times. Moreover, the system can switch between a very straightforward view where a synoptic scenario of the hazard can be shown all over the study area and a more in-depth view, where the rainfall path of rain-gauges can be displayed and constantly compared with rainfall thresholds.

One of the main peculiar features of the warning system is the use of space–time variable thresholds, which overcome two issues commonly encountered when passing form the definition of intensity-duration thresholds to their actual implementation in early warning systems for civil protection purposes. The first one is a time related issue: depending on when the starting point of the critical rainfall event is set, the comparison between rainfall path and threshold may produce different results. In our approach this temporal variable is handled by a script that recursively considers all possible starting points and selects for the EWS the worst scenario. The second one is a space related issue: to better account for the high variability of the physical features encountered in the test site, rather than a single regional rainfall threshold, we used a mosaic of local intensity–duration thresholds.

After a two years test period, the early warning system is presently operated by the Tuscany Regional Civil Protection Agency.

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Table 1. Threshold equation and no rain gap used in the early warning system for each alert zone.

Alert zone	Threshold	No rain gap (h)
A1	$I = 61.4D^{-0.78}$	18
A2	$I = 34.0D^{-0.86}$	18
A3	$I = 52.4D^{-0.73}$	24
A4	$I = 101.5D^{-0.99}$	18
B1	$I = 33.8D^{-0.81}$	20
B2	$I = 22.5D^{-0.65}$	24
B3	$I = 22.5D^{-0.65}$	24
B4	$I = 49.9D^{-0.73}$	24
B5	$I = 405.9D^{-1.29}$	24
C1	$I = 49.2D^{-0.77}$	24
C2	$I = 49.2D^{-0.77}$	24
C3	$I = 49.2D^{-0.77}$	24
C4	$I = 49.2D^{-0.77}$	24
D1	$I = 40.5D^{-0.90}$	24
D2	$I = 31.6.5D^{-0.76}$	12
D3	$I = 40.5D^{-0.90}$	24
D4	$I = 33.5D^{-0.74}$	15
E1	$I = 20.0D^{-0.66}$	12
E2	$I = 29.6D^{-0.75}$	12
E3	$I = 20.9D^{-0.75}$	10
E4	$I = 15.0D^{-0.69}$	32
F1	$I = 37.2D^{-0.88}$	24
F2	$I = 50.7D^{-0.78}$	36
F3	$I = 50.7D^{-0.78}$	36
F4	$I = 37.2D^{-0.88}$	24

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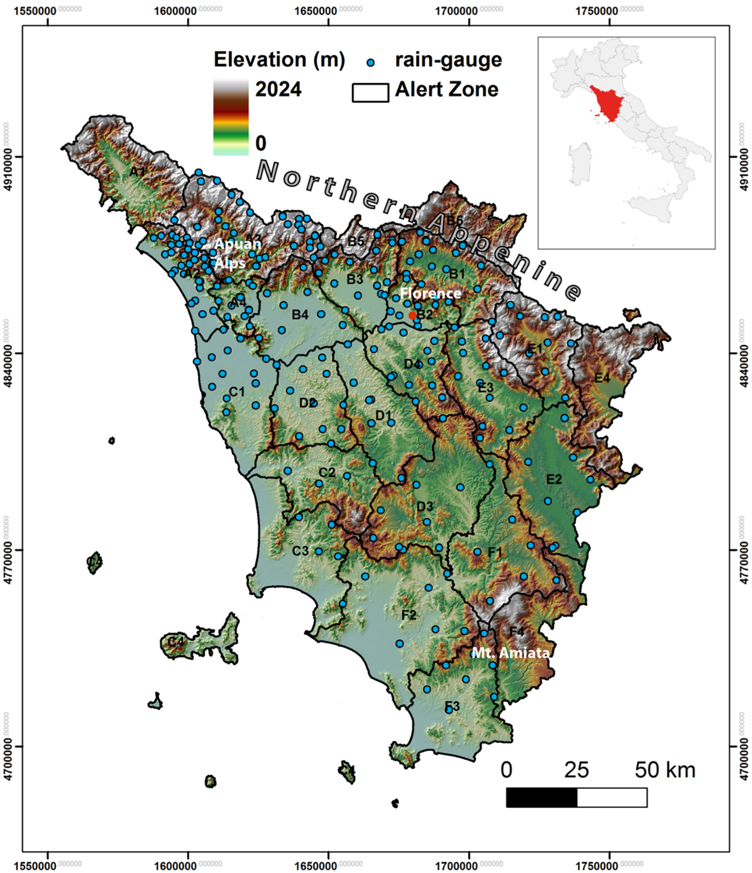

Figure 1. Study area (Tuscany).

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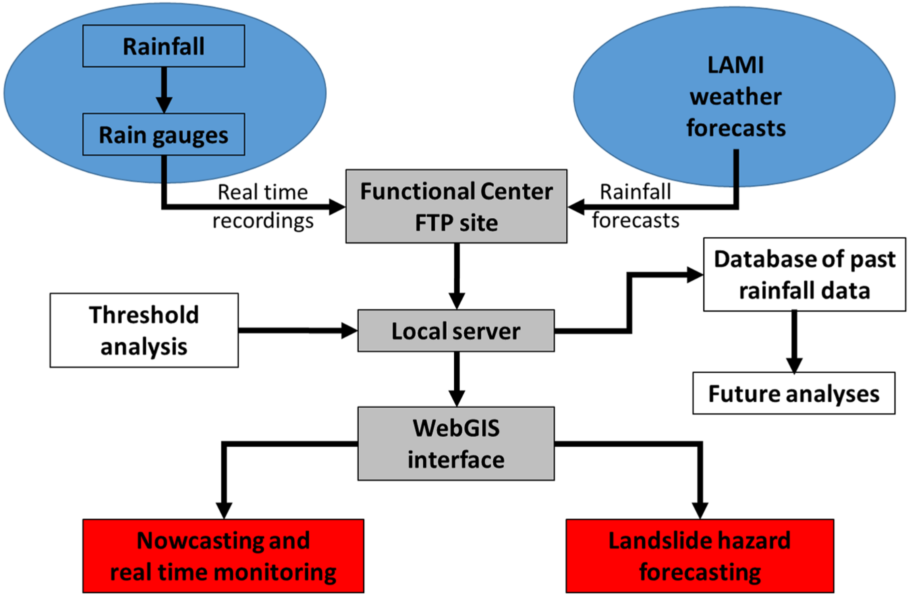

Figure 2. Architecture of the early warning system.

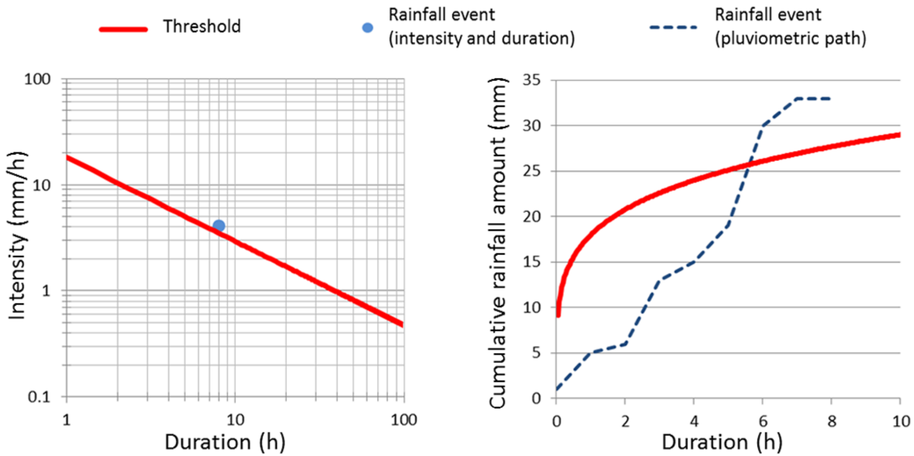

Figure 3. In the left panel, a typical log-log *I*–*D* diagram that allows the comparison between a power-law threshold and a rainfall event expressed in terms of its peak intensity and duration; in the right panel, the same threshold and the same rainfall event are expressed in terms of duration and cumulative rainfall amount, allowing a constant monitoring of the evolution of the rainfall path and to assess visually when the threshold is overcome.

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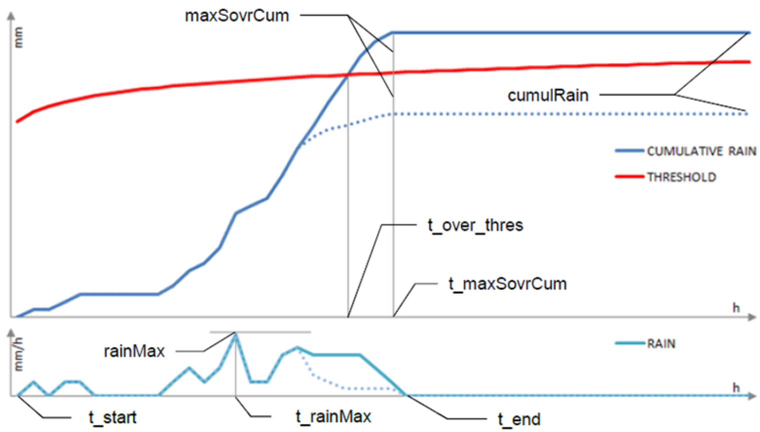

Figure 4. Parameters used to characterize each rainfall event and that are stored in the database; to visualize all the possible cases, two examples of rainfall events are represented: the dotted line refers to a rainfall event that does not exceeds the thresholds, while the solid line represents a rainfall event that exceeds the thresholds.

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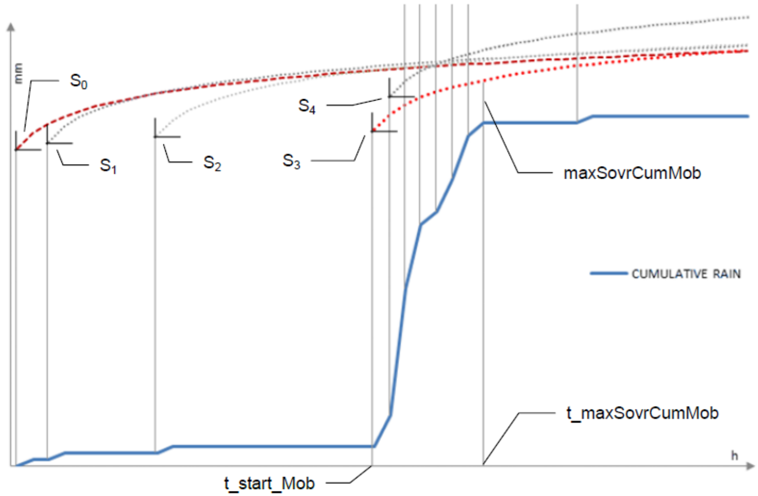

Figure 5. Example of the functioning of the algorithm that shifts the initial time of the rainfall until the worst scenario is identified; S1 to S4 are four examples of shifted starting time.

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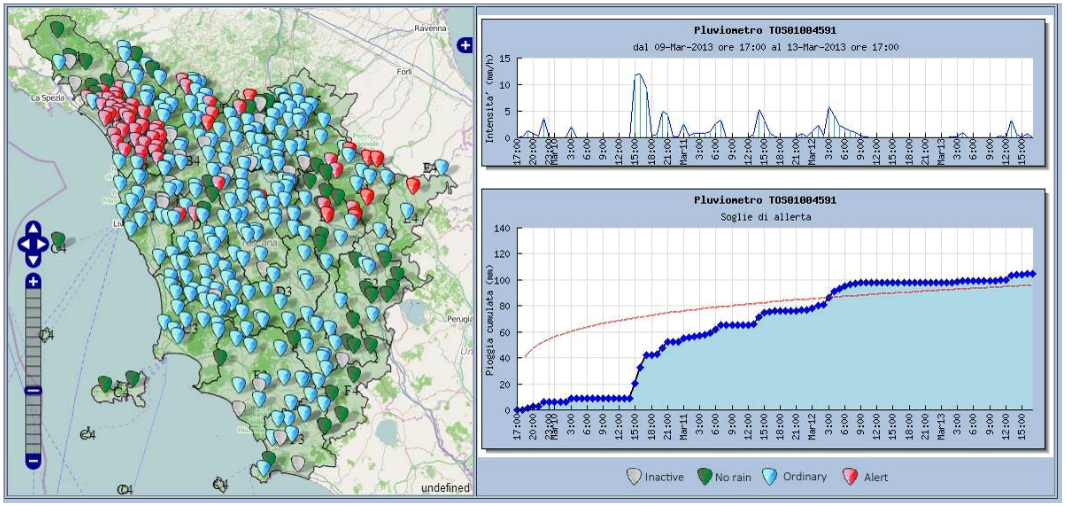

Figure 6. WebGIS interface of the warning system; on the left, an overview of the regional rain-gauge network is provided; for each rain-gauge, the rainfall path can be visualized and compared to the threshold (on the right).

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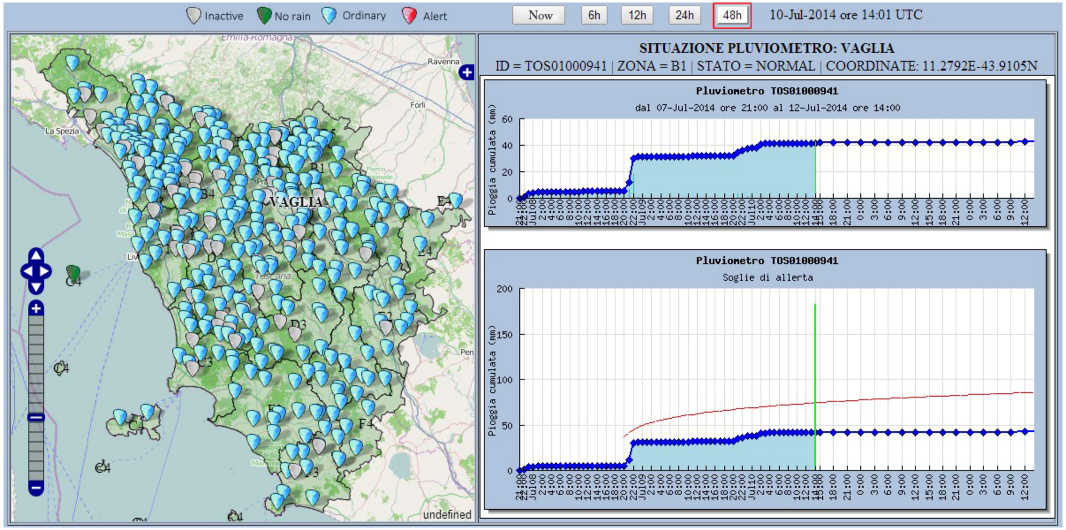

Figure 7. Screenshot of the WebGIS interface in the forecasting mode (48 h lead time); the green line represents the current time and separates real time data (to the left) and rainfall forecasts (to the right); please note that in this case the worst scenario is obtained considering a t_start other than the beginning of the rainfall event.

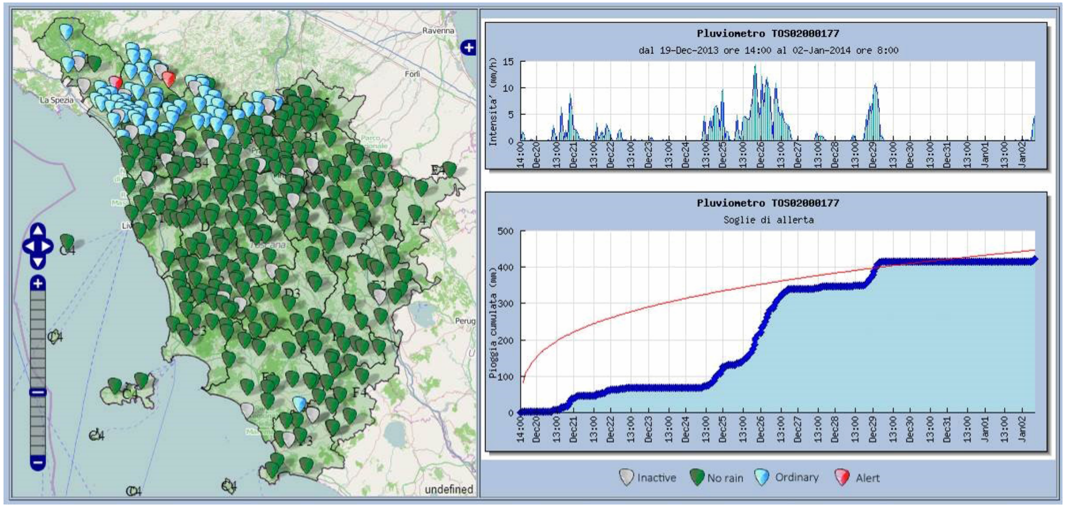

Figure 8. Evolution of the rainfall event that struck on Northern Tuscany on December 2013.

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