Int J Disaster Risk Sci (2018) 9:129–142
https://doi.org/10.1007/s13753-018-0160-2

www.ijdrs.com
www.springer.com/13753

ARTICLE

SIRENE: A Spatial Data Infrastructure to Enhance Communities' Resilience to Disaster-Related Emergency

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Published online: 22 February 2018

Abstract Planning in advance to prepare for and respond to a natural hazard-induced disaster-related emergency is a key action that allows decision makers to mitigate unexpected impacts and potential damage. To further this aim, a collaborative, modular, and information and communications technology-based Spatial Data Infrastructure (SDI) called SIRENE—*Sistema Informativo per la Preparazione e la Risposta alle Emergenze (Information System for Emergency Preparedness and Response)* is designed and implemented to access and share, over the Internet, relevant multisource and distributed geospatial data to support decision makers in reducing disaster risks. SIRENE flexibly searches and retrieves strategic information from local and/or remote repositories to cope with different emergency phases. The system collects, queries, and analyzes geographic information provided voluntarily by observers directly in the field (volunteered geographic information (VGI) reports) to identify potentially critical environmental conditions. SIRENE can visualize and cross-validate institutional and research-based data against VGI reports, as well as provide disaster managers with a decision support system able to suggest the mode and timing of intervention, before and in the aftermath of different types of emergencies, on the basis of the available information and in agreement with the laws in force at the national and regional levels. Testing installations of SIRENE have been deployed in 18 hilly or mountain municipalities (12 located in the Italian Central Alps of northern Italy, and six in the Umbria region of central Italy), which have been affected by natural hazard-induced disasters over the past years (landslides, debris flows, floods, and wildfire) and experienced significant social and economic losses.

Keywords Data retrieval · Decision support system · Disaster management · Italy · Spatial data infrastructure · Susceptibility/hazard and risk maps · Volunteered geographic information

1 Introduction

Nowadays there is a recognized need for designing and developing ICT (information and communications technology)-based strategies and tools to support decision makers in preparedness and response to disaster-related emergencies. The Council of the European Union (1999, 2005) recommends, in its Community Action Programme Decisions in the field of Civil Protection, to "take account of scientific research and technological development," "improve techniques and methods of response," and "increase public information, education and awareness," so as to help citizens who live in at risk areas to protect themselves more effectively.

The *Hyogo Framework for Action 2005–2015* (UNISDR 2005, p. 9) promoted initiatives expected to improve early warning systems based on the direct involvement of the population and "the use, application and affordability of recent information, communication and space-based technologies and related services, as well as earth observations, to support disaster risk reduction." The *Sendai Framework*

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for Disaster Risk Redaction 2015–2030 (UNISDR 2015, p. 15) promotes a "real time access to reliable data, the use of space and in situ information, including geographic information systems (GIS), and use information and communications technology innovations to enhance measurement tools and the collection, analysis and dissemination of data."

Within the above mentioned international frameworks, we designed and implemented an interoperable ICT-based spatial data infrastructure (SDI) and related Web services called SIRENE—*Sistema Informativo per la Preparazione e la Risposta alle Emergenze (Information System for Emergency Preparedness and Response)* to support local disaster managers to anticipate, cope with, resist against, and recover from the impacts of natural hazard-induced disasters (debris flows, landslides, floods, and wildfire, among others). The initial definition of the SDI requirements revealed a limited knowledge on the part of the locally appointed disaster managers about the mode and timing of intervention. Improving their decision-making tasks was identified as the primary aim of the SDI. This goal was accomplished by incorporating five principles: (1) plan in advance preventive and mitigation measures to reduce the effects of unexpected and adverse events; (2) anticipate, as far as possible, the demand for disaster relief operations; (3) enhance the knowledge of local managers on procedures and methods of intervention in order to have a positive control in the aftermath of the disaster (preparedness); (4) organize and manage resources and responsibilities to deal with the emergency; and (5) increase the level of data sharing and communication during the disaster (response).

The SIRENE SDI comprises the following modules/services:

- A local repository in which to store and manage heterogeneous, multisource, and geographically localized information: metadated, authoritative, and research-based susceptibility/hazard and risk maps; volunteered geographic information provided by observers directly in the field (Goodchild 2007); and data useful to cope with a disaster (strategic structures and infrastructures, resources, and so on);
- A GIS installation to visualize and interact with both local and remote geospatial data;
- A VGI module to create, assemble, and disseminate VGI reports concerning the critical environmental conditions that could require monitoring or rapid intervention;
- An engine to flexibly search and retrieve data from the repository;
- A cross-validation service to analyze the extracted institutional and research-based susceptibility/hazard and risk maps against VGI reports;
- A decision support system to suggest, for different types of natural hazards, the proper emergency management procedures (in agreement with the regulatory framework in force at the national and regional levels), the instructions of execution, the people in charge of performing each action, and the legal documents to be issued at each emergency phase; and
- A communication system (e-mail, Short Message Service (SMS), Skype) to enable data sharing and dissemination.

From the citizens' side, SIRENE may improve risk awareness by its efforts to (1) increase citizen's understanding of the risks and their components (hazard sources, vulnerable elements, potential consequences of impacts, and so on); (2) monitor and track identified risks; and (3) evaluate risk process effectiveness. People who may be threatened by a disaster may learn in advance what to expect and how to react, and increase their personal culture of safety as a result. This induced proactive participatory mechanism can complement the disaster managers' effort to save lives, reduce property damage, and sustain a community's essential functions.

Although some of the SIRENE SDI services have already been proposed in the literature, the novelty consists in the services integration as a whole. As recognized by the Civil Protection Services, where testing installations are in use, this is one of the main pros in using SIRENE. Specifically, disaster managers have at their disposal, in a timely and efficient manner:

- All the modules/services in a single infrastructure to cope with different types of risk; and
- The opportunity to adopt and deploy homogeneous and standardized emergency preparedness and response procedures all over the municipalities that are affected by the disaster.

The main aim of this article is to describe SIRENE's design and implementation. A review of related research publications and projects is initially presented. An overview of the SDI architecture and the different modules and services then are described. A hypothetical use case of the SIRENE SDI follows. Discussion and ongoing activities conclude the article.

2 Literature Review

The scientific literature relevant to our SDI ranges from volunteered geographic information (VGI) collection and exploitation to multisource spatial data infrastructures (SDIs) and decision support systems (DSS) for disaster-related emergency management.

Craglia et al. (2012, p. 389) provide useful insights into the value of social network data for policy and science reports. The authors extend "the paradigm of spatial data infrastructures by advocating an interactive and dynamic framework based on near-to-real time information from sensors and citizens" and analyze the extent to which it is possible to extract information (messages and photos) that are posted daily through social networks such as Twitter and Flickr. The results show that the proposed system can efficiently retrieve useful and timely information from the large volumes of VGI being exchanged daily. SIRENE exploits only structured information provided by different types of observers by means of the VGI portal. Ongoing activities are related to the inclusion, among the monitored sources, of the information that could be extracted from social networks. In fact, the big data created in the context of social networks are valuable, not only for detecting critical events but mainly and more importantly, for analyzing and studying the crowd habits and mode of reactions during the occurrence of critical events.

A systematic literature review of collaborative approaches based on VGI exploitation in hazard analysis is presented by Klonner et al. (2016). The authors conclude that the use of VGI in preparedness and mitigation brings with it many opportunities, but also contend that there are still several challenges that remain. These difficulties include the need for integrated research, given that most of the analyses are revealed to be discipline-centric with a lack of interdisciplinary approaches. SIRENE starts from this suggestion and considers VGI as a complementary source of information in the SDI framework.

The research proposed by Schade et al. (2010) suggests that up to 6 billion human sensors are potentially available to monitor the state of the environment, validate global models with local knowledge, and provide information that only humans can capture. The authors argue that Sensor Web Enablement[1] (SWE) standards can be applied to develop metadata from VGI reports, thus converting VGI into a timely, cost-effective, and valuable source of information for a SDI. Schade et al. describe a workflow for VGI integration into SDI and how VGI sensing and event detection techniques can support a crisis information system. This is close to our approach of deploying VGI maps that use the standard Open Geospatial Consortium (OGC) services in order to analyze the contemporary maps with information from other sources. In our approach we deploy VGI by Web Map Service[2] (WMS) and Web Feature Service[3] (WFS) standard services. The rational for not using SWE standard is that in our case observers are asked to report observations described qualitatively by categories, free text, and pictures and not by quantitative measurements, as in the case of VGI created by means of sensors.

Hertfort et al. (2016) analyze the different kinds of geographic information generated by crowdsourcing as a new data source to complement official information. Specifically, they distinguish three types of crowdsourcing with increasing complexity and demand in terms of experience or skills: classification, digitization, and conflation. They develop a geographical information crowdsourcing and use it to further point out the potential of the different types of crowdsourcing for disaster management and humanitarian aid. In our approach, VGI is mainly used to point out critical conditions affecting real world objects (classification) or to identify areas that could require monitoring or rapid intervention (digitization). Conflation is carried out later, during the VGI analysis phase, to identify areas with a sufficient density of VGI reports to become a priority for intervention.

Horita et al. (2015) stress the utility of VGI to complement sensor data. These authors use and evaluate the impact of VGI reports to improve the coverage of monitored areas in flood risk management. In order to be able to cross-analyze VGI with sensor data, created and managed within distinct VGI platforms and information systems, Horita and colleagues outline the need to adopt interoperable services. This meshed service is achieved by adopting the Sensor Observation Service (SOS) from the OGC standards, which defines the interfaces for both data receiving and sharing. The SOS also stores the received data in a sensor database. This SOS supports the integration of distinct data formats as well as the interoperability of diverse data sources. Data collected in an SOS are then converted to the geospatial service standard WFS, which enables the researcher to ask questions about geographical features on the Internet. Horita et al. (2015) provide two means to query VGI and sensor data: the former for specifying spatial conditions, the latter for specifying temporal conditions. In SIRENE, we rely on the WFS service for VGI querying with spatial and content conditions. We also apply a spatial/temporal density-based clustering algorithm (Arcaini et al. 2016) to identify and validate VGI reporting of critical situations.

1 http://www.opengeospatial.org/ogc/markets-technologies/swe.

2 http://www.opengeospatial.org/standards/wms.

3 http://www.opengeospatial.org/standards/wfs.

Camponovo and Freundschuh (2014) have analyzed VGI reports created by volunteers via the Ushahidi[4] Web platform (2015) in response to the earthquake that occurred in Haiti on 12 January 2010. Volunteers translated messages (text, e-mail, and voice) submitted by the victims of the earthquake and categorized each message into a primary and secondary category, expressing distinct emergency needs. Camponovo and Freundschuh's analysis illustrated that the VGI categories and subcategories mostly failed to convey the main idea of the victims' message. Notwithstanding these results, the authors recognized the utility of VGI for emergency rescue was considerable and they outlined the need for novel methods to cope with the imprecision and uncertainty embedded in VGI. Haklay (2013) offers a different point of view: he points out that imprecision and uncertainties are integral parts of any VGI collection and he states that novel methods to represent and to deal with those problems are needed. A VGI creation and management facility is incorporated into SIRENE SDI. This element provides a flexible discovery service that can identify VGI reports able to answer vague queries and to rank the VGI reports. This feature helps to cope with VGI imprecision and uncertainty.

As for a multisource SDI for disaster risk management, Miyazaki et al. (2015) offer a comprehensive survey of many worldwide initiatives for disaster risk management. They highlight the important role played by exploitation of satellite data products, ground-based observation measurements, and crowdsourcing data created by volunteers with tools such as Ushahidi (2015) and Sahana (Sahana Software Foundation 2015).

A comprehensive overview that achieves state-of-the-art status in geoprocessing Web architecture and technologies, combined with examination of the most current developments in recent years, is undertaken by Zhao et al. (2012). These authors state that light-weight protocols, crowdsourcing capability, and the potential to process real-time geospatial data sources provided by sensors enables distributed, interoperable, and collaborative processing of geospatial data for information and knowledge discovery.

Manfré et al. (2012) discuss the role of spatial data sharing in the context of the establishment of SDIs to deal with natural hazard-induced disasters. They maintain this can best be done by reinforcing participation from organizations and governments that improves preventive and emergency plans and that increases the potential involvement of citizens in the risk and disaster management process by providing VGI reports. These ideas are also at the basis of SIRENE, since the SDI provides access to multisource geospatial data and VGI.

The AGORA Project (2016) "aimed at advancing knowledge on the use of crowdsourcing and social media for supporting decision-making in disaster risk management." This project fosters the use of VGI as a source of useful information to "improve the resilience of cities against disasters and extreme events." SIRENE complements AGORA features by providing a flexible discovery service that uses susceptibility/hazard and risk maps consistent with current query conditions, a cross-validation service to compare VGI reports against the susceptibility/hazard and risk maps, and a DSS able to guide the disaster managers in emergency preparedness and response. SIRENE is an improvement of the original SDI presented by Bordogna et al. (2016) that integrates multisource heterogeneous geospatial data sets and time series information (for example, multitemporal satellite data and VGI) in a fully interoperable framework. The main differences rely on the following: (1) the susceptibility/hazard and risk maps management within an SDI, potentially distributed in several nodes on the Internet (to support scalability); the maps are derived by processing multisource geo-information by distinct models whose use depends on the type of risk, the authoritative and research-based data available, and the geo-referenced observations collected in situ by observers (VGI); (2) the DSS workflow automation to support disaster managers in disaster preparedness and response; and (3) the query and retrieval engine, which can ease the analysis of the geospatial data sets by providing complex intelligent spatiotemporal querying and answering facilities.

For decision support of environmental domains, a review is proposed by Sokolova et al. (2011) in areas of complex system analysis and decision making by means of intelligent tools, including agent-based systems. The article also compares existing agent-oriented methodologies and frameworks for decision support. Although multiple efforts, created for theoretic research and practical implementation of information systems, resulted in many successful applications, many successful efforts still lack a systemic view and cannot offer a coordinated and controlled approach that links methods together into a coherent methodology. Such partially successful DSSs focus excessively on a specific aspect of environmental management in contrast with the comprehensive nature of the SIRENE DSS, which is a workflow support tool for all the emergency management phases needed for all kinds of risk.

The Decision Support Systems Characteristics and Best Practices report drafted within the DECIDE project (DECIDE 2015) reviews the literature on the state-of-the-art of DSSs for disaster management (DM). Advances and theory are investigated based on a project's theoretical foundation, commonly used models, and usage of geographical information systems (GIS). Finally, a review of

[4] https://www.ushahidi.com/.

eight DSS for DM research and operational projects is performed, which also includes a comparative analysis of their functionalities. The review indicates that DM, especially in the phases of preparedness and response, includes complex decision processes. In such a context, situational awareness, forecasted conditions, efficient communications, and comprehensive visualization in a DSS for DM are valuable to decision makers. In designing the SIRENE SDI, such ideas are kept in mind by introducing modules that enhance specific aspects such as situational awareness and forecasted conditions (VGI reports and a flexible discovery service of susceptibility/hazard and risk maps), efficient communication by local stand-alone platforms to manage disaster-related emergencies at the local level, comprehensive visualization by means of the adoption of OGC Web services for maps, and VGI sharing and visualization on the Web.

Shan et al. (2012) propose an emergency response decision support system (ERDSS) as an important tool for authorities to enhance their emergency response capabilities. ERDSS is mainly used to make emergency early warning contingency plans, coordinate and command emergency response activities, manage resources, and provide related knowledge. An effective ERDSS is one of the key factors that determine whether emergency management will be successful. Shan and his fellow authors provide an in-depth literature review of existing research about emergency response, e-government, information technology (IT) service management, and decision support systems is provided. Such proposal, although focused on the emergency response control and planning, fails to offer a discovery service of susceptibility/hazard and risk maps whose efficacy can be great during the emergency preparedness and response phase.

Horita et al. (2015) propose a conceptual data model based on OGC interoperable standards and a framework that integrates voluntary (VGI) and conventional data from wireless sensor networks (WSN) with a spatial decision support system (SDSS) to assist the decision makers in flood risk management. This research is relevant to SIRENE because it also integrates VGI into the SDI and includes a DSS to support disaster managers in the execution of emergency procedures and protocols, in compliance with the regulations in force at the regional and national levels.

SIRENE takes great advantage of the studies analyzed in this section. Our emergency preparedness and response information system moves a step forward by integrating different modules and services in support of disaster management decision-process operations.

3 Overview of the SIRENE SDI Architecture

From a software engineering point of view, the main characteristics of SIRENE implementation are the cost minimization of both hardware and software components gained by: (1) its freely distributable licence (with no royalties required); (2) its self-explanatory user interface and user interaction: (3) its comprehensive functionalities that exploit both authoritative/research-based and freely provided geographic information; (4) its stand-alone set up without external dependencies except for the common libraries provided by the operating system); (5) its rapid prototyping (functional requirements and logic details may change within the prototyping loop) and easiness to update; and (6) its network failure resilience, since its use is possible even in the event of Internet failure).

From a conceptual point of view (Fig. 1), SIRENE consists of several distributed modules and services, customized to the protocols, policies, and needs of local disaster managers, and connected via the Internet to a central server, which is located at the Civil Protection Service. The Web-based services provides: query and retrieval facilities of both susceptibility/hazard and risk maps and VGI reports; and cross-validation functions to check VGI against susceptibility/hazard and risk maps. The Internet connection allows information (maps and DSS rules) to be transferred from/to the central server and shared with other potential end users (neighboring municipalities, local and regional administrative agencies, and so on).

Nevertheless, each municipality hosts a local minimal self-contained kernel installation of the Web services that includes a data repository (Preparedness and Response Geo-Database), a GIS application, a VGI portal (Ushahidi), and the DSS with its execution engine. This enables decision makers to manage local data and carry out preparedness and response procedures even if the Internet connection is not working. In effect, each component of the SDI has to be intended as a basic "brick," designed and developed so that it can be installed and run as a stand-alone component, one independently from another. This makes possible a customized deployment of the digital environment in each municipality based on local policies and needs.

An overview of the SIRENE SDI architecture is provided in the following subsections: each module or service is described from an end user's point of view.

3.1 Preparedness and Response Geo-Database

The rationale of the Preparedness and Response Geo-Database is to make available institutional and noninstitutional (mainly research based) information to a

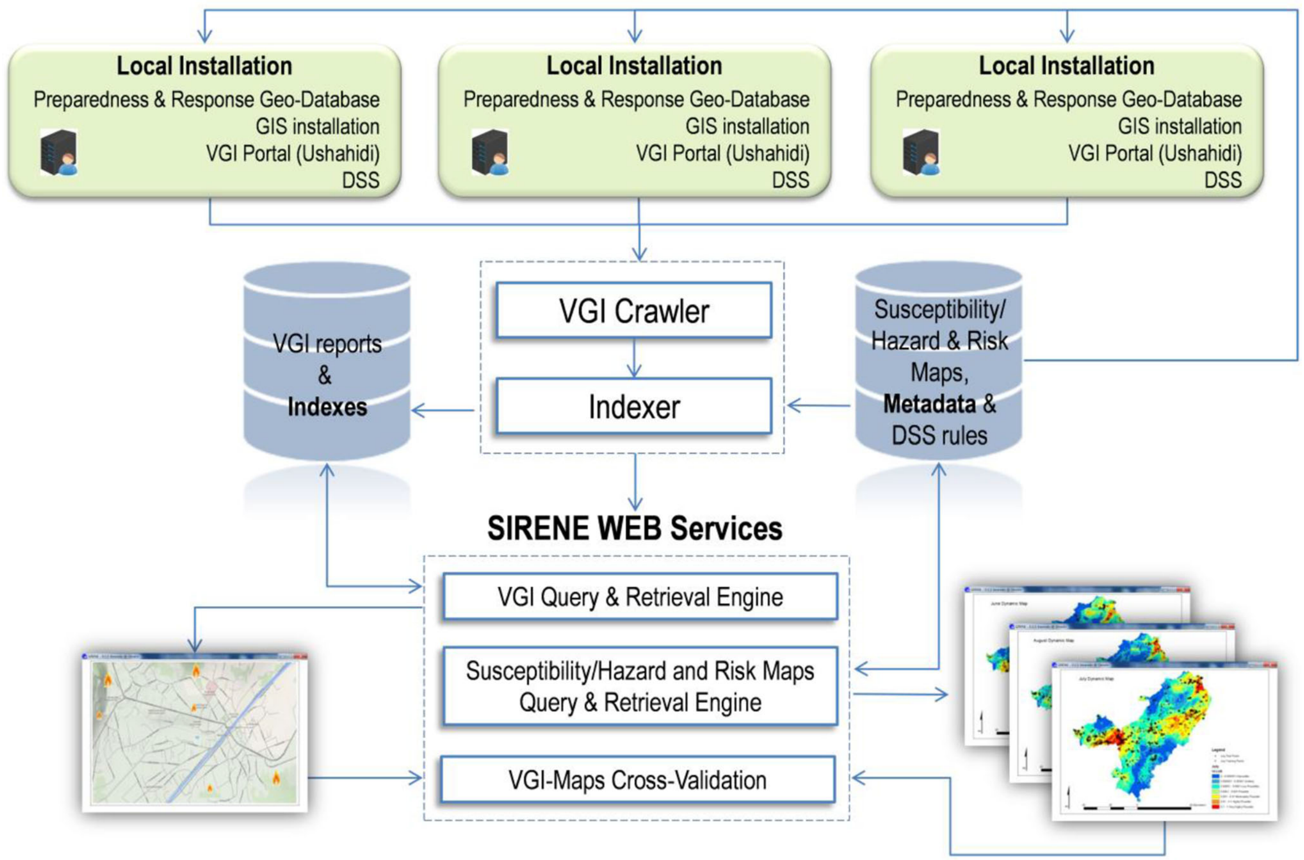


Fig. 1 Conceptual scheme of the distributed modules/services composing SIRENE. A minimal kernel installation of the Web services is hosted locally to allow disaster managers to cope with an emergency even when the Internet connection is not working. It includes: a data repository (Preparedness and Response Geo-Database), a GIS application, a VGI portal (Ushahidi 2015), and the DSS with its execution engine. The Web services provide: query and retrieval facilities for both metadated susceptibility/hazard and risk maps and indexed VGI reports together with cross-validation functions to check VGI against susceptibility/hazard and risk maps

multidisciplinary group of potential end users (scientists, experts, and technicians).

Institutional information focuses on four data sources: (1) susceptibility/hazard and risk maps certified by authorities as reference information to be used in disaster management for different types of natural events (Fig. 2a for landslides); (2) a list of strategic structures, infrastructures, and resources; (3) the people appointed to cope with an emergency; and (4) other thematic maps that may support the decision-making process.

Noninstitutional information primarily refers to susceptibility/hazard and risk maps generated off-line by applying different modeling techniques for different types of natural events (Fig. 2b, c for debris flows). Although these models are compliant with uncertain information management, such as Bayesian, soft computing, and evolutionary computation modeling, the resulting maps are not ratified as "institutional" by the authorities and only can be used as supplemental information that is complementary to the institutional maps.

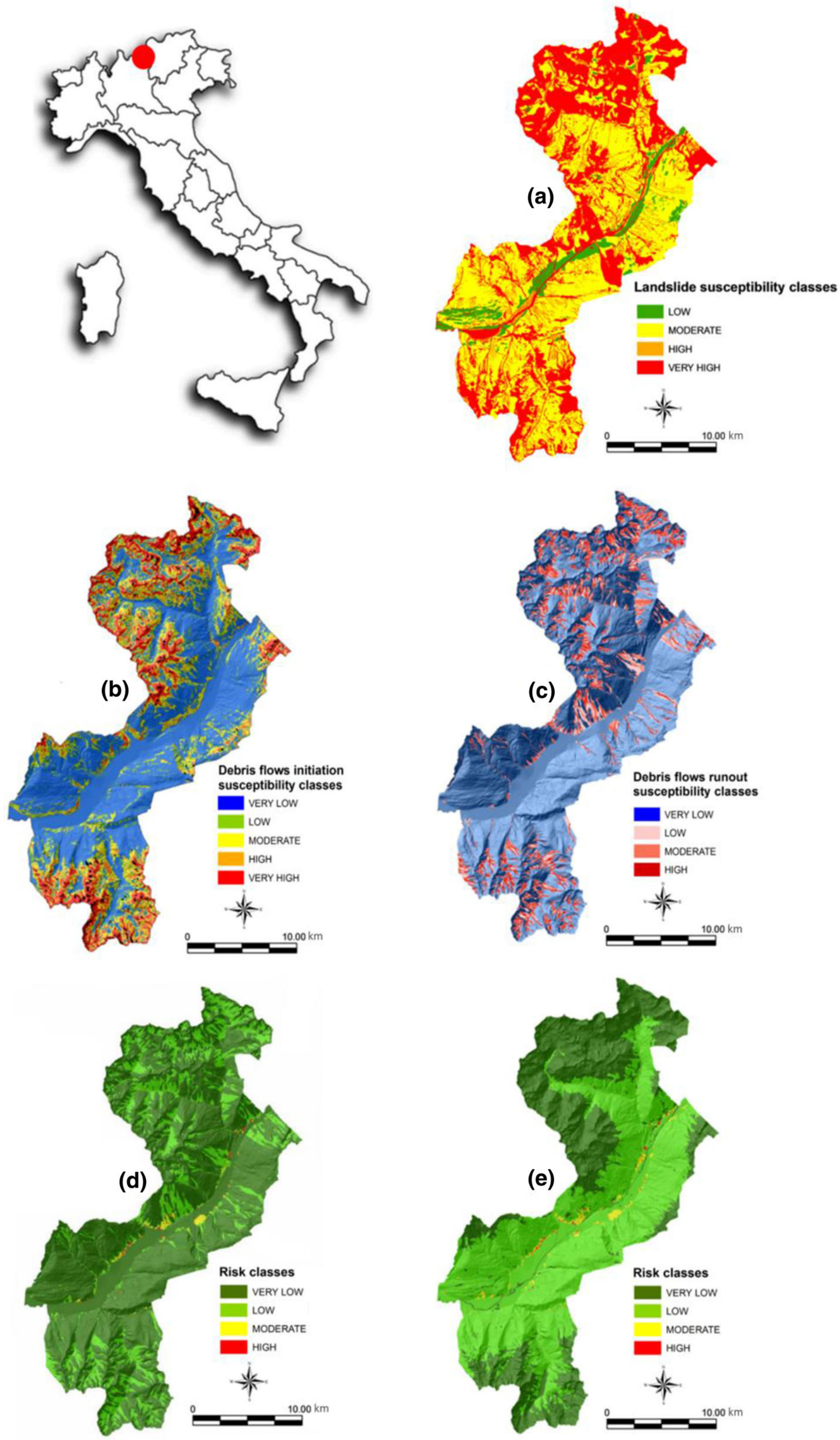
The geo-database is locally managed by an open-source database management system (DBMS) (PostgreSQL/PostGIS[5]) connected to an open-source desktop GIS (QGIS[6]—GIS installation in Fig. 1). It is populated off-line, and maintained and updated by each municipality with local information. Through the SDI synchronization protocol, each local geo-database is periodically accessed by a Web crawler of the central SDI component in order to copy its content to the central geo-database (managed by the Civil Protection Service). In this way, an updated backup copy is always available and can be shared among many potential end users (neighboring municipalities, local and regional administrative agencies, and so on).

Institutional and noninstitutional maps are indexed by an off-line procedure through their metadata, managed by a metadata catalogue service. Metadata allow decision makers to query flexibly and retrieve susceptibility/hazard and risk maps (via the query engine) on the basis of

[5] http://postgis.net/.

[6] https://www.qgis.org/en/site/.

Fig. 2 Examples of hydrogeological susceptibility/hazard and risks maps of the Consortium of Mountain Municipalities (Italian Central Alps). These maps are stored in the Preparedness and Response Geo-Database: **a** institutional qualitative index-based landslide susceptibility map; **b** noninstitutional debris flow initiation susceptibility map; **c** noninstitutional debris flows runout susceptibility map; **d** institutional qualitative index-based landslide and debris flow risk map; **e** noninstitutional semiquantitative debris flow risk map



relevant user-defined criteria (mainly referring to static geo-environmental variables and/or the dynamic meteorological-climatic parameters).

Institutional and noninstitutional maps are then compared with the spatial distribution of vulnerable elements. The institutional approach classifies the study area into four qualitative risk classes (from very low to high, Fig. 2d) by means of a bidimensional matrix (hazard against exposure/impact); the noninstitutional approach classifies the study area into four semiquantitative risk classes (Fig. 2e) and also provides exposure data, expressed in monetary terms and the expected degree of loss (risk) by applying three different vulnerability values (Blahut et al. 2014).

The geo-database also provides disaster managers with authoritative and geocoded information about strategic structures, infrastructures, resources, and personal contacts (related to authorities, technicians, and volunteers) with the intention to prepare for and cope with a disaster-related emergency.

A graphic user interface is designed and implemented to make data entry easier for people who are not expert in Structured Query Language (SQL). Control mechanisms are also implemented to constrain and regulate data entry by checking errors, data completeness, and consistency.

3.2 Susceptibility/Hazard and Risk Maps Query and Retrieval Engine

Given that modeling susceptibility/hazard and risk maps is a computationally time-consuming activity, a large number of institutional and noninstitutional maps are prepared and stored in advance for each study area, each of which is synthesized by thematic, modeling, geographic, and temporal metadata. This module (Susceptibility/Hazard and Risk Maps Query and Retrieval Engine in Fig. 1) makes use of the SDI catalogue service to manage, query, and retrieve the metadata. It is based on the Open Geospatial Consortium (OGC) Catalogue Service for the Web (CSW) standard that describes common interfaces with which to access metadata information. This Web service provides the decision maker with a high level, flexible query language to search, retrieve, and display the most plausible institutional and noninstitutional maps (by exploring their metadata content). Plausible maps in this context are considered to be those maps that have been generated or modeled with parameter values that best fit an area's current geo-environmental and meteorological-climatic conditions, ranked according to the degree of fulfillment of the above-mentioned conditions.

3.2.1 Storing the Metadata in a Catalogue Service

Metadata are encoded in Extensible Markup Language (XML), a format compliant with current regulations in force at the European level for geo-data interoperability (INSPIRE 2007). These metadata are an extension of the standard INSPIRE metadata schema, which guaranties full compliance with OGC CSW as far as the discovery facility is based on spatial, temporal, and thematic representation. The metadata fields, which describe the spatial content of the hazard/susceptibility and risk maps, are embedded within the content field of the standard metadata format, since they enable a content-based discovery of the maps as described below.

3.2.2 Searching Susceptibility/Hazard and Risk Maps

In order to retrieve susceptibility/hazard and risk maps that are most plausible with respect to current environmental and meteorological-climatic conditions, the metadata first are indexed. Each query must be flexible enough in order to allow the end user to specify vague selection conditions, which can containing linguistic terms that have vague meaning, such as "high temperature in the last week" (in case of wildfire) or "high precipitation in the last three days" (in case of floods). This is done by modeling flexible queries in the framework of fuzzy databases (Bordogna and Psaila 2004; Galindo 2008). When precise information concerning triggering or predisposing parameters is available, classic queries with crisp conditions can be formulated as a special type of flexible queries.

(1) Direct query by constraining the parameters values

A flexible direct query can specify soft conditions for the values of some parameters. For example, the end user can specify a query by the following soft conditions:

- *Select SM = "wildfire susceptibility map"*

  Where

- *high pn = temperature* during *TP = last month* *AND*
- *very high pn = temperature* during *TP = last week* *AND*
- *very high pn = wind* during *TP = yesterday* *AND*
- *None pn = rainfall* during *TP = last month*

in which *SM* stands for "spatial map theme," *pn* stands for "parameter name," and *TP* for "time parameter."

The end user formulates this query when interested in retrieving the most plausible wildfire susceptibility maps given the current conditions described by the linguistic values of the parameters. Such soft conditions constrain the values of the correspondent parameter to some ongoing recent meteorological-climatic conditions, which are expressed by the linguistic values "high" for "temperature" during the "last month," or "very high" for "temperature" during the "last week," and so on.

This query is evaluated by accessing the metadata indexes to compute the ranking score of each indexed map. The SM maps associated with the ranking scores greater than zero can be listed in decreasing order to the user.

(2) Direct query by constraining the parameters trends

The end user specifies a soft condition concerning the trend of some parameters based either on recent or forecasted values:

An example of such query can be:

- *Select SM = "wildfire susceptibility map"*
  Where
- *High_increasing pn = temperature* during *TP = last month*
  AND
- *High_increasing pn = wind* during *TP = yesterday*
  AND
- *High_decreasing pn = rainfall* during *TP = last month*

The evaluation is performed as in the previous case. The SM maps associated with the positive ranking scores are listed to the end user in decreasing order.

(3) Inverse query

Inverse queries are useful when a decision maker needs to know the lower/upper bounds of some environmental and/or meteorological-climatic parameters (*pn*) that may trigger a given susceptibility/hazard or risk level. In this case the result of a query is a summary of the parameter maps that generated the top ranked map that best satisfies the query condition.

An example of query could be the following:

- *Select pn1 = "temperature", pn2 = "wind"*
  Where
- *SM = "wildfire susceptibility map" is high*

in which "high" is a soft condition on the susceptibility values of wildfire maps. This query is evaluated by accessing the SM maps content index, by identifying the SM map that best matches the soft constraint "high" and in retrieving the parameters "temperature" and "wind" that are encoded into the metadata of the SM map.

(4) Results

The result of a flexible query must be an informative answer. Besides retrieving the most plausible susceptibility/hazard or risk maps, two virtual maps, which represent the most likely optimistic and pessimistic scenarios that may occur, are generated, together with the variability of susceptibility/hazard or risk levels in each pixel. To provide this additional information, a map fusion operation is performed. Specifically, given *m* maps retrieved by a query, they are merged in order to obtain the most pessimistic/optimistic scenario. For the optimistic scenario, the value of a pixel can be computed as the minimum susceptibility/hazard or risk level in all maps. In fact, in the optimistic map the best case is expected to happen, that is, the lowest level within each pixel is selected. Conversely, for the pessimistic scenario, the value of a pixel is computed as the maximum value, the highest susceptibility/hazard or risk level in each pixel.

3.3 Volunteered Geographic Information (VGI) and Query and Retrieval Engine

This module (VGI Portal (Ushahidi) in Fig. 1) exploits the geographic information freely reported by different types of observers (citizens, volunteers, technicians, and authorities), before or in the early stages of an emergency. In order to define the authorship of the VGI reports, four different types of observers are considered: (1) citizens are the general public; (2) volunteers are the civil protection volunteers who have received an adequate training in civil protection matters and so they can contribute to the disaster risk preparedness and response of an area; (3) technicians are local employees whose technical background can be effectively exploited during a disaster emergency; and (4) authorities are local representatives or delegates who have the power or right to give orders and make decisions.

VGI providers use a customized version of the free tool Ushahidi to create locally and submit their observations (VGI reports), which consist of text, date, and time categories, and possibly also images and videos (more details in Arcaini et al. 2013). These observers connect to the local VGI portal, managed by the local control room operator, who authenticates their identity on the administration registry. This procedure discourages spam reports. Observers are categorized according to their status as authorities, technicians, volunteers, and citizens who may be unregistered or registered observers.

Each municipality hosts a local installation of Ushahidi. The local acquisition of VGI was chosen to allow the operator to confirm the reliability of VGI reports by: (1) cross-checking the authorship of the VGI authors with their personal information (status); and (2) comparing the VGI reports with the contents of the other incoming VGI reports. In effect, one of the primary problems in the use of VGI is estimating the quality of the information, which depends on several factors, such as the reputation of the source, and the truthfulness and accuracy of the content (Devillers and Jeansoulind 2006; Goodchild and Li 2012). A method for estimating report quality is based on a comparison between the textual content of the VGI reports close to each other both in space and time. A high density of records that point out the same observation in a given region at the same time reinforces the truthfulness of their content and thus increases the level of attention to and possible intervention in the reporting area. After applying these filters, the operator can demand a supplementary in situ monitoring activity or can make the VGI reports directly visible both locally and remotely to other municipalities.

Each local, independent Ushahidi database is periodically visited by the central VGI crawler of the SIRENE SDI and the new VGI reports are indexed and managed by the central VGI catalog service to enable their availability to other municipalities. Finally, a mapping and a cross-validation component (Arcaini et al. 2013) allows users to visualize VGI reports by matching a query from all municipalities. The operator can extract and visualize on a map where all reports concerning a particular hazard category (for example, "smoke" in Fig. 3) are located in a given time interval. The operator can also visualize, by distinct colors and symbols, different levels of the same hazard (high flames, medium flames, low flames, smoke, fire off) and the category of observers who are submitting the reports. A cross-validation service also can be used to compare the preselected susceptibility/hazard and risk maps against the VGI maps in order to analyze their spatial correlations and, eventually, highlight their consistencies and/or conflicts. As a consequence, by exploiting VGI reports, each map can be updated and made into a dynamic support for disaster managers.

3.4 Decision Support System (DSS)

The DSS module (Fig. 1) is the core of the SDI that supports decision makers in disaster-related emergency management. Four emergency phases are prescribed by the Italian National and Regional laws: null, normal, moderate, and high. For each of these, a list of expected/mandatory activities is provided. The DSS does not take any direct decision on the actions to execute. The role of the DSS is passive, since it suggests the expected or compulsory actions for different types of events (in agreement with the regulatory framework in force at the national and regional levels, for different types of natural hazards) together with the instructions of execution, the people in charge of performing each action, and the legal documents to be issued at each emergency phase.

The emergency management procedures (DSS rules in Fig. 1) are formalized by using Petri Nets (Murata 1989) and executed by the DSS engine installed locally (Fig. 4). A Petri Net is a formal mathematical modeling language used to describe stepwise processes that include choice, iteration, and concurrent execution. Finally, the DSS engine and related Graphic User Interface (GUI) take the user to the guided execution of an emergency procedure.

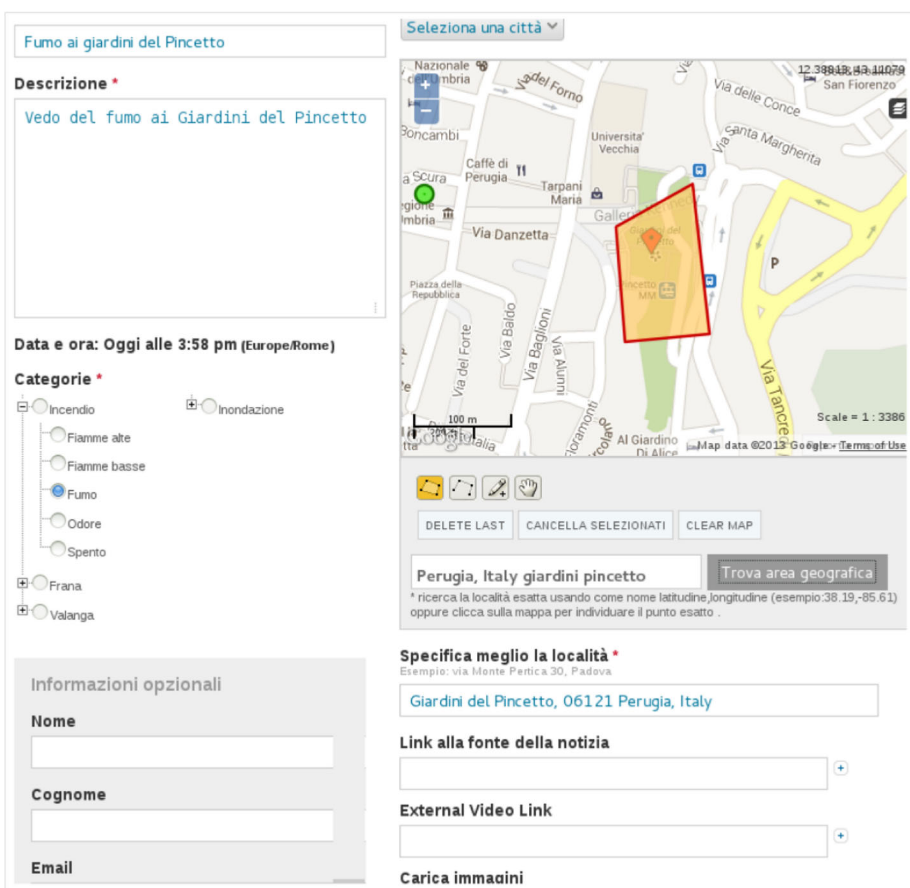


Fig. 3 Authorities, technicians, volunteers, and (registered/unregistered) citizens can provide geo-localized information by filling out a simple form on their mobile device. In this case, a potential danger (smoke) at a public park is provided

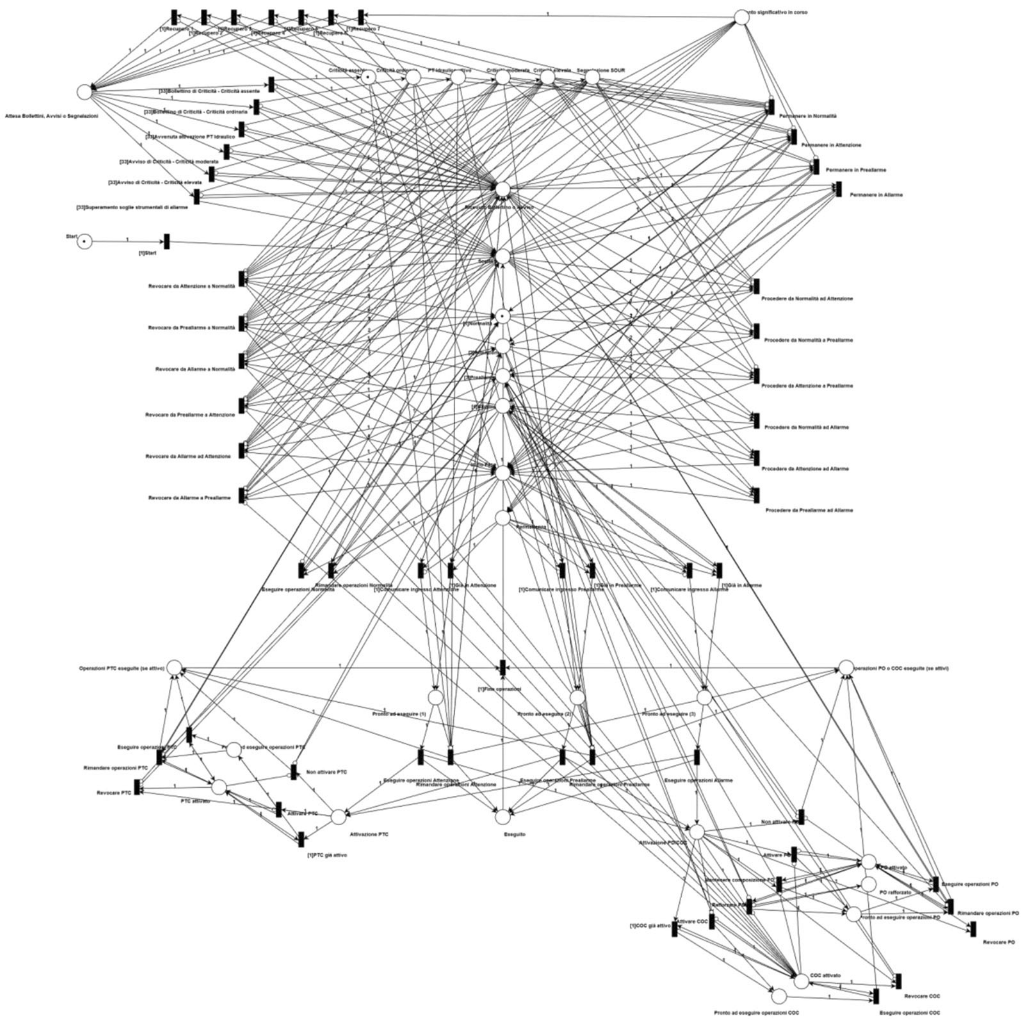


Fig. 4 A Petri Net that formalizes the emergency management procedure for hydrogeological risks. It is designed according to the national and regional legislative framework in charge for this type of risk

When accessing SIRENE, the disaster manager is allowed to (Fig. 5):

1. Select the proper management procedure (workflow) among those that are listed (as explained in the Use Case) in relation to the hazard type, graphically visualize and interactively execute it;
2. follow the instructions of execution of each procedural step;
3. access the local geo-database and extract institutional and noninstitutional data;
4. access and issue the documents linked to each procedural step;
5. deliver the current state of emergency management to the Civil Protection Service, through the Internet connection;
6. access institutional regional/national weather forecast websites through Web services;
7. access institutional regional/national volunteers' management websites through Web services; and
8. guarantee communication and information sharing by communication tools (Skype, SMS, and e-mails).

At any time, the workflow can be forced to move forward, although the ongoing action may not yet be completely accomplished. This is important when an event becomes extreme and no time is available to start and conclude each step before getting to the proper emergency phase. A log file registers all the executed actions, the operator in charge and the time and date of each action. This log file plays a crucial role: in the training phase, to measure the response capacity to different hazard types and, if needed, to check and modify the formalized procedures; to carry out back analysis (identify lessons learned from past events or simulations); and to control, verify, and validate the consistency of each procedural step.

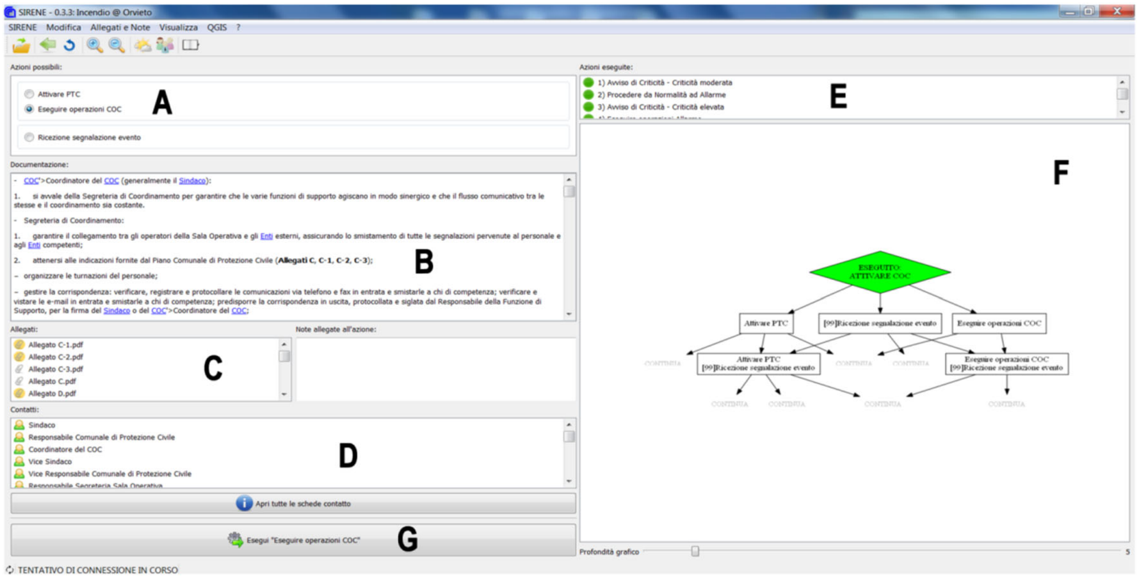


Fig. 5 SIRENE DSS module—an overview of the entire GUI. Capital letters identify each major part of the module. A: the list of selectable actions in a given emergency phase; B: the instructions of execution concerning the chosen action; C: the list of legal documents related to the ongoing action; D: the list of people in charge to give their contribution in executing the chosen action; E: the list of actions already carried out; F: the graphic window showing the ongoing action (in green) and the expected ones; G: execution button of the ongoing action. The module's tool bar contains buttons and drop-down lists to access the log file, the weather forecast websites, the volunteers' management websites, among others

4 SIRENE SDI Use Case

In this section we describe the steps that a decision maker can perform when managing a hypothetical disaster-related emergency by means of SIRENE SDI. After receiving a meteorological bulletin that details severe weather forecast for the following hours in an area vulnerable to flood hazard, the decision maker launches SIRENE and starts a new session selecting the procedure formalized for Hydraulic Risk. When the Moderate Emergency Phase is adopted by the Regional Office of Civil Protection, SIRENE leads the decision maker throughout the flow of procedural steps defined in compliance with the Italian legislative framework and guides him/her in planning the earliest countermeasures to be put into practice to deal with the predicted phenomena.

The decision maker proceeds choosing the proper action and, jointly, the DSS shows the instructions of execution. For each operational step the decision maker visualizes information and contacts (fixed and mobile phone numbers or e-mails) of either authorities or responsible parties who must be alerted (that is, the Operative Municipal Responsible, the Volunteers Responsible, the Municipal Police Commander, and all other members of the Local Crisis Unit), and generates the documentation to be issued (for example, for the activation of volunteers). Through the geo-database, the decision maker verifies the location and availability of strategic structures and logistic resources.

At the same time, the DSS allows the decision maker to stay up-to-date with evolving meteorological conditions through direct access to the Regional Civil Protection website. A worsening of meteorological conditions initiates a statement of the High Emergency Phase by the Regional Meteorological Office of Civil Protection. This warning triggers SIRENE to push the decision maker to elevate the local emergency phase to a regional scale response. The DSS suggests the decision maker prearranging the activation of local coordination centers for emergency management (the Local Crisis Unit) and, eventually, provides supporting material and documentation to be approved and submitted. The decision maker is exhorted to carry on and adjust monitoring actions that focus attention on the potential to exceed instrumental thresholds (that is, rainfall or river water depth thresholds) that activate risk scenarios in the most critical points.

By accessing the geo-database through the Query and Retrieval Engine, the decision maker retrieves previously stored institutional and noninstitutional susceptibility/hazard and risk maps in order to evaluate the extent of the areas potentially affected by the expected flood event. By overlapping the expected scenarios with the VGI provided by different types of observers directly in the field (Cross-Validation Module), the decision maker is able to update the hazard scenario and to verify the number and location of the exposed elements in order to plan a possible evacuation. The communication capabilities implanted in

SIRENE allow the decision maker to alert the strategic structures available to shelter people who could be displaced during an evacuation, as well as alert the responsible parties appointed to perform the evacuation procedure. The decision maker keeps a positive control on monitoring all such actions and resources deployment.

When a critical hazard condition arises and threatens to become extreme, the decision maker can raise the local emergency phase. The decision maker is called to activate the Local Crisis Unit and to intensify countermeasures to manage rescue activities, evacuation, and population assistance. The decision maker carefully examines each operational step suggested by the DSS, which makes available execution instruction for every responsible person involved in local coordination centers for emergency management. The action protocol can be stopped uniquely by the senior decision maker with the revocation of the emergency phase previously activated. The DSS guarantees the decision maker a positive control on the return to the Normal Emergency Phase as well as on the proper management of human and logistic resources.

5 Discussions and Ongoing Activities

Risk managers need up-to-date, authoritative, research-based, and geo-localized information in order to improve their ability to prepare and deal with critical ongoing or expected events, under specific static and dynamic environmental conditions. This allows monitoring and mitigation options and emergency interventions to be planned effectively in advance and deployed on time.

The main challenge of SIRENE is to provide disaster managers with a modular, collaborative ICT-based SDI aimed at preparing for and coping with disaster-related emergencies. Although some modules and services of the infrastructure have already been proposed in the literature, others are relatively new as is their integration into a coherent emergency information, decision, and action framework.

SIRENE SDI provides different modules and services that can be used to manage both the preparedness and the response phases of an emergency. During the former, the Preparedness and Response Geo-Database can be continuously updated. The VGI portal can be used to collect freely provided data on most at risk areas that potentially need monitoring and/or mitigation actions. The Query and Retrieval Engine can be used to extract and collate data to know in advance what to expect and how to visualize potential hazardous events within a Web GIS. The DSS can be used under normal conditions to check the workflow consistency of the model and train disaster managers and responders. During an emergency response, the cross-validation functions can be used to check VGI evidence against existing susceptibility/hazard and risk maps and, if needed, refine them. The integration of authoritative and research-based data with freely provided volunteer information makes the maps' updating procedure more reliable and very effective. The DSS also makes emergency management more controlled and completely compliant with the relevant laws at the national and regional levels. The communication system (Skype, SMS, and e-mails) supports easy and quick data sharing and dissemination.

No similar SDI is currently available in Italy. Although advantages have been recognized by the Civil Protection Services, where a test version has been running for over a year, the main disadvantage is that multirisk procedure, intended to manage jointly different types of concurrent or subsequent correlated events (for example, a landslide that dams a river), have not yet been designed and implemented. Today, each event is managed separately and independently one from another. In the next release of SIRENE, we will address this weakness by providing new mechanisms to improve multirisk procedures and share related information.

SIRENE has not yet been used to manage an actual disaster officially; nevertheless the Civil Protection Services of the study areas in northern Italy and Umbria have tested the SDI and provided feedback to support its upgrading and redesign of the graphic user interface (GUI). Initially, the study areas contribution was mainly restricted to the definition of system requirements and then to error identification both in the system's architecture and its workflow contents. Nowadays many volunteers, technicians, and authorities (no citizens at this stage of the development) are using SIRENE in order to provide feedback concerning SIRENE's usability, efficiency, reliability, and, above all, the correctness and completeness of its workflows contents.

Other workflows will be designed and implemented by Petri Nets for chemical and industrial accidents, heat waves, and dam collapse. So far only the workflows for the management of disaster-related emergencies caused by floods, wildfires, landslides, and debris-flows have been designed and implemented by Petri Nets. Because these hazards are the main risks in the study areas, which disaster managers have faced in the past and are expected to cope with in the future, they represent the first priority in the design of comprehensive management workflows.

Acknowledgements This work has been carried out within the project: SIMULATOR—*Sistema Integrato ModULAre per la gesTione e prevenziOne dei Rischi*—Integrated Modular System for Risk Prevention and Management, financed by the Lombardy regional government, Italy. The authors would like to thank the anonymous reviewer for the valuable comments aimed to improve the manuscript.

References

AGORA Project. 2016. A geospatial open collaborative architecture for building resilience against disasters and extreme events. http://www.agora.icmc.usp.br/site/agora/. Accessed 17 Dec 2017.

Arcaini, P., G. Bordogna, and S. Sterlacchini. 2013. Flexible querying of volunteered geographic information for risk management. In *Proceedings of the 8th Conference of the European Society for Fuzzy Logic and Technology (EUSFLAT-13)*, ed. J. Montero, G., Pasi, and D. Ciucci, 281–288. Paris: Atlantis Press.

Arcaini, P., G. Bordogna, D. Ienco, and S. Sterlacchini. 2016. User-driven geo-temporal density-based exploration of periodic and not periodic events reported in social networks. *Information Sciences* 340–341: 122–123.

Blahut, J., T. Glade, and S. Sterlacchini. 2014. Debris flows risk analysis and direct loss estimation: The case study of Valtellina di Tirano, Italy. *Journal of Mountain Science* 11(2): 288–307.

Bordogna, G., and G. Psaila. 2004. Fuzzy-spatial SQL. In *Flexible query answering systems*, ed. H. Christiansen, M.S. Hacid, T. Andreasen, and H.L. Larsen, 307–319. Berlin: Springer.

Bordogna, G., T. Kliment, L. Frigerio, P.A. Brivio, A. Crema, D. Stroppiana, M. Boschetti, and S. Sterlacchini. 2016. A spatial data infrastructure integrating multisource heterogeneous geospatial data and time series: A study case in agriculture. *ISPRS International Journal of Geo-Information* 5(5): Article 73.

Camponovo, M.E., and S.M. Freundschuh. 2014. Assessing uncertainty in VGI for emergency response. *Cartography and Geographic Information Science* 41(5): 440–455.

Craglia, M., F. Ostermann, and L. Spinsanti. 2012. Digital Earth from vision to practice: Making sense of citizen-generated content. *International Journal of Digital Earth* 5(5): 398–416.

DECIDE (Decision Support System For Disaster Emergency Management). 2015. Decision support systems characteristics and best practices report. http://www.decide-project.eu/. Accessed 17 Dec 2017.

Devillers, R., and R. Jeansoulind. 2006. *Fundamentals of spatial data quality*. London: ISTE.

European Union. 1999. Council decision of 9 December 1999 establishing a community action programme in the field of civil protection, 1999/847/EC OJ L327/53. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX: 31999D0847&from = EN. Accessed 17 Dec 2017.

European Union. 2005. Council decision of 20 December 2004 amending decision 1999/847/EC as regards the extension of the community action programme in the field of civil protection, 2005/12/EC OJ L6/7. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX: 32005D0012&from = EN. Accessed 17 Dec 2017.

Galindo, J. 2008. *Handbook of research on fuzzy information processing in databases*. Hershey, PA: IGI Global.

Goodchild, M.F. 2007. Citizens as sensors: The world of volunteered geography. *GeoJournal* 69(4): 211–221.

Goodchild, M.F., and L. Li. 2012. Assuring the quality of volunteered geographic information. *Spatial Statistics* 1: 110–120.

Haklay, M. 2013. Citizen science and VGI: Overview and typology of participation. In *Crowdsourcing geographic knowledge: Volunteered geographic information (VGI) theory and practice*, ed. D.Z. Sui, S. Elwood, and M.F. Goodchild, 105–125. New York: Springer.

Herfort, B., M. Eckle, and J.P. de Albuquerque. 2016. Being specific about geographic information crowdsourcing: A typology and analysis of the Missing Maps project in South Kivu. In *Proceedings of the 13th International Conference on Information Systems for Crisis Response and Management*, Rio de Janeiro, Brazil, 22–25 May 2016, ed. A.H. Tapia, P. Antunes, V.A. Bañuls, K. Moore, and J. Porto de Albuquerque. Information Systems for Crisis Response and Management (ISCRAM) Digital Library.

Horita, F.E.A., J.P. de Albuquerque, L.C. Degrossi, E.M. Mendiondo, and J. Ueyama. 2015. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. *Computers & Geosciences* 80: 84–94.

Klonner, C., S. Marx, T. Usón, J.P. de Albuquerque, and B. Höfle. 2016. Volunteered geographic information in natural hazard analysis: A systematic literature review of current approaches with a focus on preparedness and mitigation. *ISPRS International Journal of Geo-Information* 5: Article 103.

INSPIRE (Infrastructure for Spatial Information in the European Community). 2007. Directive 2007/2/EC of the European Parliament and of the Council of 14 March establishing an infrastructure for spatial information in the European Community (INSPIRE). *Official Journal of the European Union*, 2007, L 108/1, 50.

Manfré, L.A., E. Hirata, J.B. Silva, E.J. Shinohara, M.A. Giannotti, A.P.C. Larocca, and J.A. Quintanilha. 2012. An analysis of geospatial technologies for risk and natural disaster management. *ISPRS International Journal of Geo-Information* 1(2): 166–185.

Miyazaki, H., M. Nagai, and R. Shibasaki. 2015. Reviews of geospatial information technology and collaborative data delivery for disaster risk management. *ISPRS International Journal of Geo-Information* 4(4): 1936–1964.

Murata, T. 1989. Petri nets: Properties, analysis and applications. In *Proceedings of the IEEE* 77(4): 541–580.

Sahana Software Foundation. 2015. Open source disaster management software. http://sahanafoundation.org/. Accessed 14 Nov 2016.

Schade, S., G. Luraschi, B. De Longueville, S. Cox, and L. Díaz. 2010. Citizens as sensors for crisis events: Sensor Web enablement for volunteered geographic information. In *Proceedings of WebMGS 2010—1st International Workshop on Pervasive Web Mapping, Geoprocessing and Services*, ed. M.A. Brovelli, S. Dragicevic, S. Li, and B. Veenendaal. ISPRS—International Society for Photogrammetry and Remote Sensing.

Shan, S., L. Wang, L. Li, and Y. Chen. 2012. An emergency response decision support system framework for application in e-government. *Information Technology and Management* 13(4): 411–427.

Sokolova, M., A. Fernández-Caballero, and F. Gómez. 2011. A review on frameworks for decision support systems for environmental domains. *Revista EIDOS* 4: 74–83.

UNISDR (United Nations International Strategy for Disaster Reduction). 2005. *Hyogo framework for action 2005–2015*. https://www.unisdr.org/we/coordinate/hfa. Accessed 24 Nov 2017.

UNISDR (United Nations International Strategy for Disaster Reduction). 2015. *Sendai framework for disaster risk reduction 2015–2030*. http://www.unisdr.org/we/coordinate/sendai-framework. Accessed 17 Dec 2017.

Ushahidi. 2015. Web site. http://www.ushahidi.com/. Accessed 17 Dec 2017.

Zhao, P., T. Foerster, and P. Yue. 2012. The geoprocessing web. *Computers & Geosciences* 47: 3–12.