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Dynamic structure and data sets of a GIS database for geological risk analysis in the Azores volcanic islands

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Abstract. Geological hazards in the Azores archipelago include earthquakes, volcanic eruptions, degassing phenomena and landslides, being the cause of thousands of deaths and severe damage and loss. To reduce the impact of future events it is necessary to improve the emergency response and reinforce land-use planning, and this has given rise to the development of AZORIS, a GIS database for risk analysis in the Azores. At present this computer-based system comprises nine main dynamic data sets where elemental, monitoring and historical data are grouped in layers of first and second order. The logical structure of the database was conceived in order to facilitate interactivity between data sets and to guarantee the evolution of the system, as determined by the input and the generation of new and more detailed information. Archive organization was designed taking into account regional and local aspects of geological hazard. In order to ensure consistency of the database and the quality of the data within it, an internal process of validation was included.

1 Introduction

The Azores archipelago is located in the Atlantic Ocean and is formed by nine volcanic islands. Its complex geological setting is dominated by the existence of a mantle plume where the American, Eurasian and African plates meet (White et al., 1976; Searle, 1980). In the last five hundred years thirty destructive earthquakes have occurred in the region and at least twenty-eight volcanic eruptions have been reported. Landslides take place every year triggered either by seismic events or very intense rainfall episodes (Valadão et al., 2002) and volcanic gases are permanently being released in several inhabited areas (Baxter et al., 1999). Over the years landslides have been responsible for thousands of deaths and a huge amount of damages and losses (Gaspar et al., 1998).

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In order to minimize the impact of future events it is necessary to define and implement strategies for both land-use and emergency planning having in mind that risk increases with urban expansion. However, risk analysis is a complex subject due to the nature and variety of data and processes that need to be taken into account (Cruz-Reyna, 1996), and there is not a definitive way to deal with it. Moreover, people and authorities often find it difficult to understand risk uncertainty and do not expect to be restricted because of something that is probabilistic. To face this reality the Centre of Volcanology and Geological Risk Assessment of the Azores University decided to build a Geographic Information System (GIS) database to compile all the data required for risk assessment and management in the Azores. GIS are computer-based systems with a high potential to archive, manipulate, analyse and display georeferenced data (Aronoff, 1989) and are becoming a major tool for geological hazard analysis and risk mitigation (Coppock, 1995). Several papers have recently been published concerning the use of GIS tools for the study of geological (Salvi et al., 1999), seismological (Ganas and Papoulia, 2000), volcanological (Kauahikaua et al., 1995; Pareschi et al., 2000; Pareschi, 2002) and landslides data (Carrara et al., 1991; Carrara et al., 1995; Carrara et al., 1999; Jibson et al., 2000; Van Westen et al., 1999). When available, hazard and vulnerability data can easily be represented in a GIS and a great diversity of risk maps can then be produced following the implementation of specific predicting models.

A major difficulty for those dealing with GIS is to obtain high quality and validated georeferenced data (Carrara et al., 1995). This situation is particularly evident in the scope of risk analysis due to the diversity of data that need to be considered. Moreover, the acquisition, storage and maintenance of all this information following a high criterion of quality are critical to guarantee the accuracy and consistency of the GIS database through time. In this work we present the structure and the data sets of AZORIS, a GIS database for geological risk analysis in the Azores based on the ArcGIS® software from ESRI and installed over a Windows 2000® platform from Microsoft.

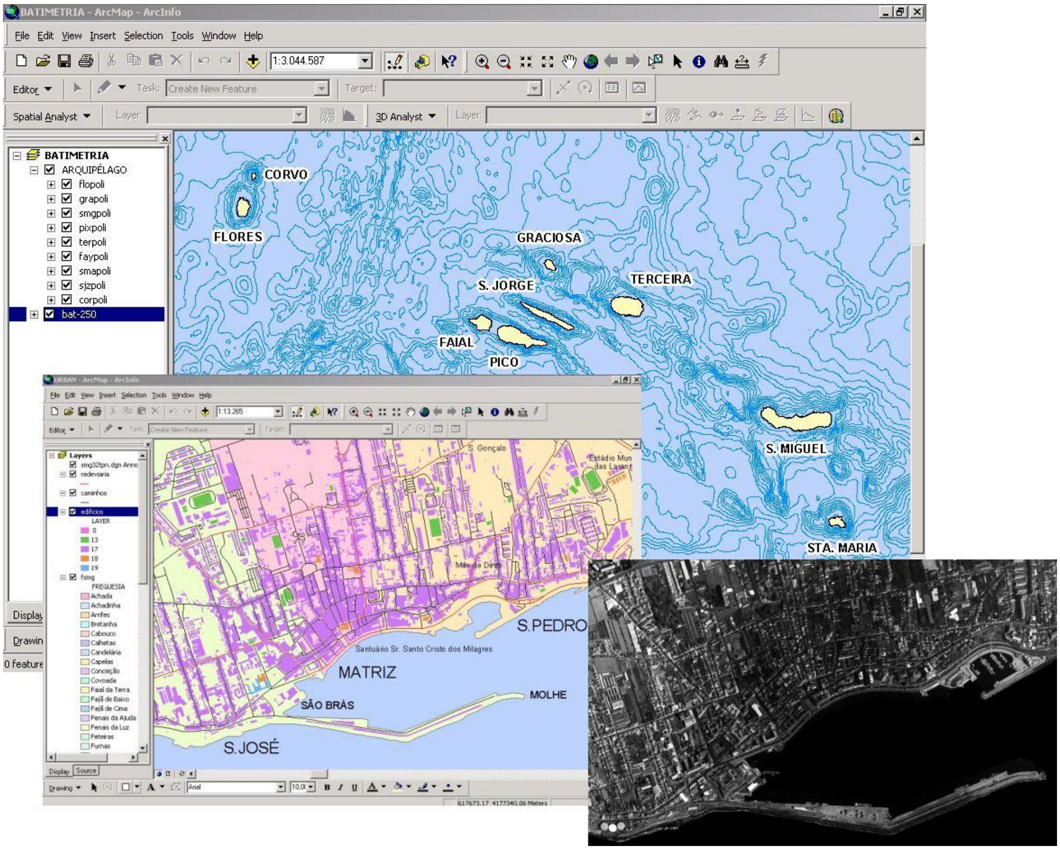

Fig. 1. AZORIS database includes geographical and socio-economic data for the Azores archipelago and municipalities.

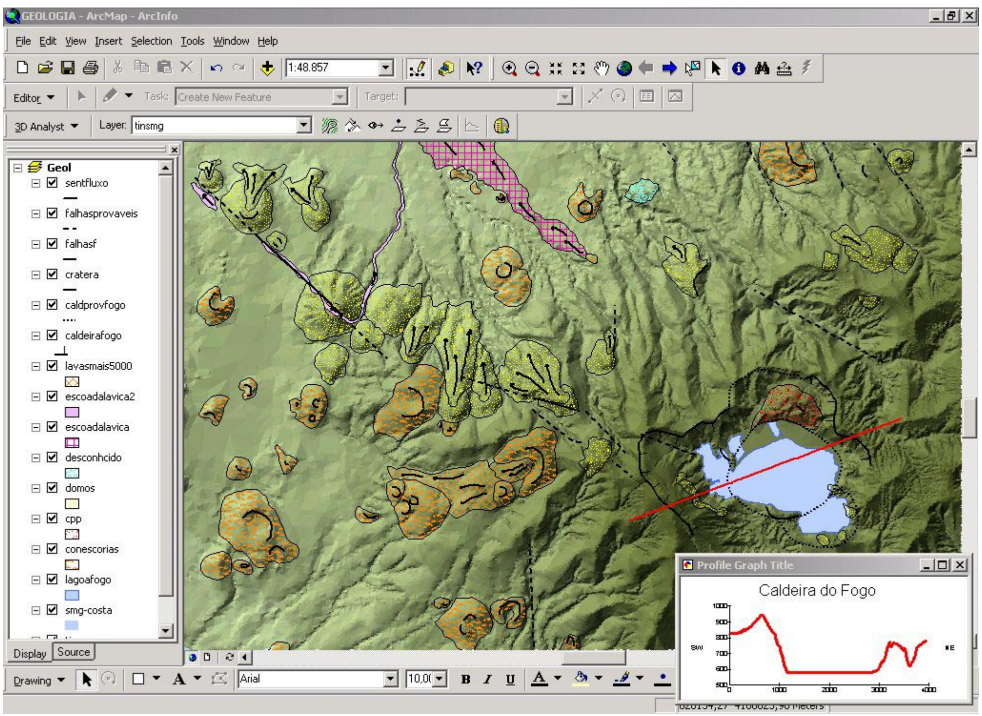

Fig. 2. Example of a display with layers from the geological and geomorphologic data sets.

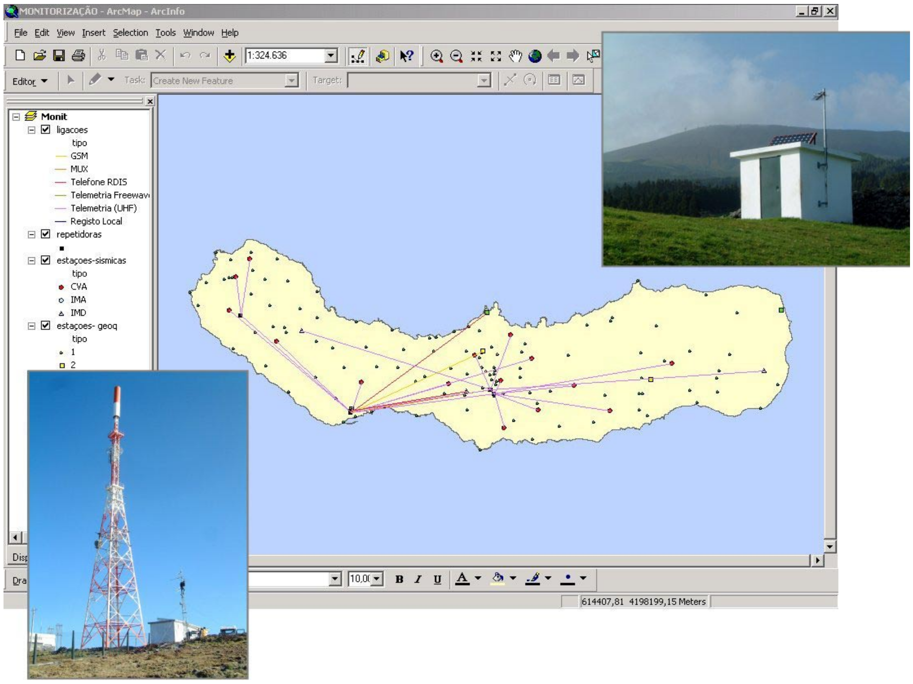

Fig. 3. Information related with the different monitoring systems as well as the data acquired are gathered in AZORIS.

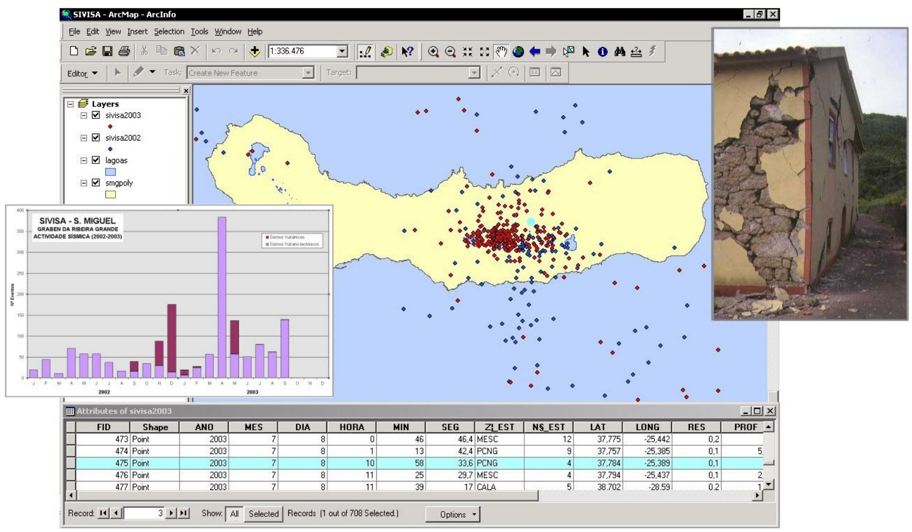

Fig. 4. Example of the spatial and temporal analyses of seismological data within AZORIS.

2 Data sets definition

The AZORIS database is composed of several thematic data sets defined according to the type of information. Each data set comprises several layers, which in turn can include numerous data. Due to the constant input of new and more detailed information the system was built in such a way that data can become a layer and, thus, develop into a data set without changing the physical or logical structure of the database. At this stage the available data is grouped in nine sets comprising basic, monitoring and historical information:

- Geographical and socio-economic
- Civil protection
- Geological and geomorphologic
- Landslides
- Volcanological
- Seismological
- Geodetic

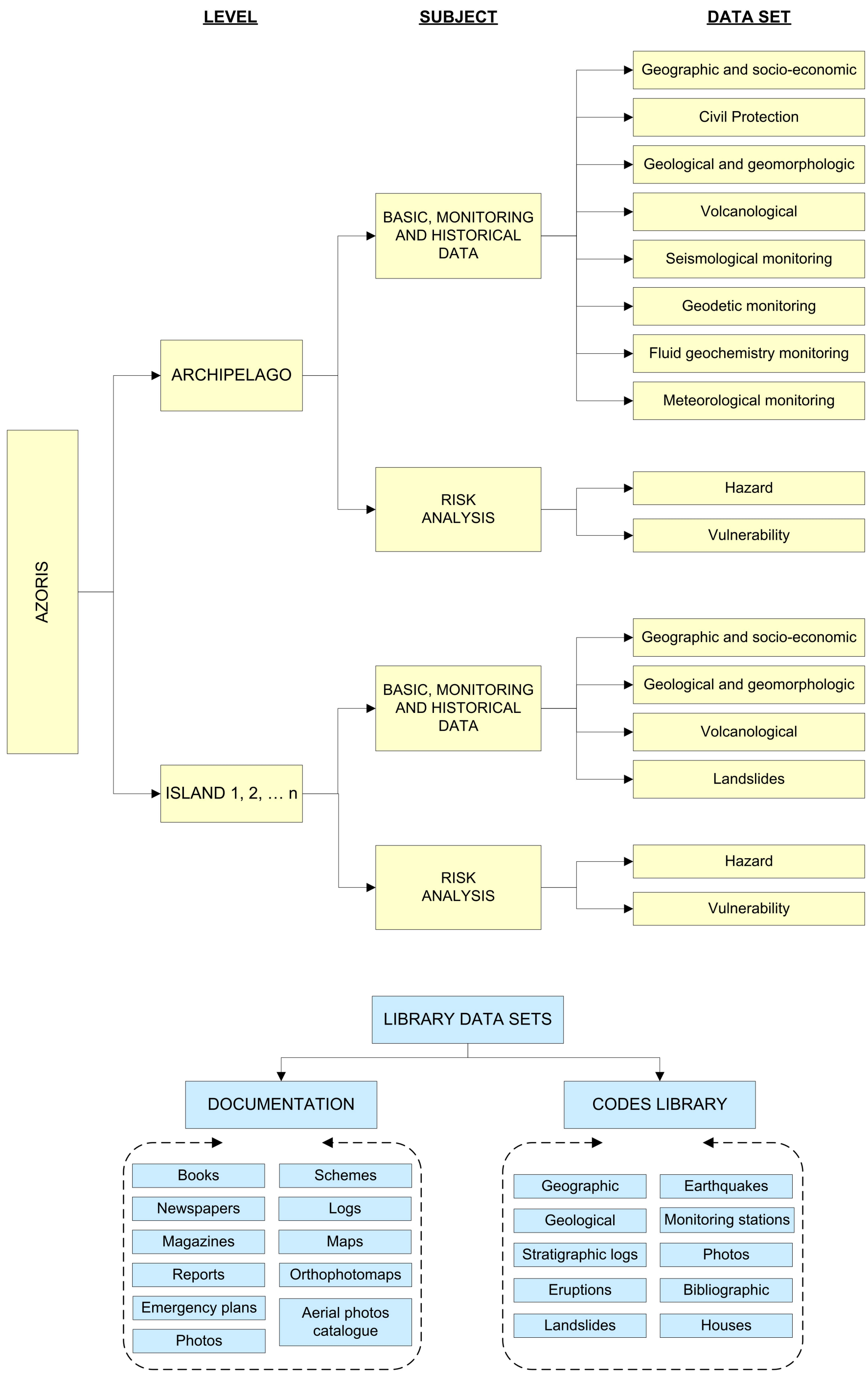

Fig. 5. Organizational scheme of the information available in AZORIS.

- Fluid geochemistry
- Meteorological

The geographical and socio-economic data set (Table 1) includes the topographic maps available for the Azores and the basic data needed for vulnerability analysis. The most recent topographic data existing for all the islands constitute the 1:25 000 scale digital maps edited in 2001 by the Instituto Geográfico do Exército de Portugal. Besides altitude, these maps incorporate additional information such as urban areas, roads and hydrology. The information contained in the package may be up-dated as required. Supplementary layers were added to the system, including counties and parishes administrative boundaries, population, energy and water supply systems, land-use classification and infrastructures for telecommunications (Fig. 1). For detailed studies all

Table 1. Geographical and socio-economic data sets. Items between brackets are entered in these, or other data sets.

Layers	Data	Features type
Elevation contours	Major contour lines, minor contour lines, elevation points, geodetic vertices	Points, lines
Coastlines	Zero metre contour line	Lines, polygons
Streams	Main streams, tributary streams	Lines
Administrative boundaries	Counties, parishes	Lines, polygons
Location Details	Names of islands, counties, cities, villages, parishes, localities, places, lighthouses, main roads, streams, lakes, mountains, harbours	Images
Buildings	(Houses), historical monuments, public buildings, schools, churches, hospitals, public health centres, cemeteries, (civil protection headquarters), (fire department headquarters), police headquarters, lighthouses	Polygons
Houses	Street, address number, type, number of floors, basement, attic, type of external walls, type of internal walls, basement floor material, ground floor material, other floors material, attic floor material, roof covering, roof inclination, draining roof systems, observations (id_house), (id_geograph), (id_photo)	Polygons
Roads	Highways, main roads, streets, forestry paths, tracks, bridges	Lines
Air transport infrastructures	Airports, heliports, aerodromes, air traffic control towers	Polygons
Harbours	Docks, fishing harbours, marinas	Points, polygons
Population	People, men, women and families at parish level, (id_geograph)	Points
Land use	Urban areas, industrial areas, classified natural areas	Polygons
Energy and fuel supply systems	(Geothermal), wind, hydraulic, thermal, fuel	Points, lines, polygons
Geothermal infrastructures	Power plants, pipe lines, (production wells), re-injection wells, thermometric wells	Points, lines
Geothermal production wells	Name, altitude, depth, situation, (id_photo)	Points
Water supply systems	(Springs), (lakes), (water wells), reservoirs, water lines	Points, lines, polygons
Springs	Name, altitude, type, situation, (id_photo)	Points
Lakes	Area, altitude, depth, situation, (id_photo)	Polygons
Water wells	(Superficial wells), tide wells, (drilled wells)	Points
Superficial wells	Name, altitude, depth, situation, (id_photo)	Points
Drilled wells	Name, altitude, depth, situation, (id_photo)	Points
Telecommunication systems	Towers, antennas, lines for TV, radio and telephones	Points, lines
Submarine cables		Points, lines

Table 2. Civil protection data set.

Layers	Data	Features type
Civil protection headquarters	People, vehicles, principal equipment, (id_geograph), (id_photo)	Points
Fire headquarters	People, vehicles, main equipment, (id_geograph), (id_photo)	Points
Emergency data transmission links	Towers, repeaters, UHF, freewave, telephone	Points, lines
Emergency plans	(id_geograph), (id_bbl)	Points

buildings (e.g. houses, public buildings, monuments) were individualized and characterized taking into account several parameters that are crucial to an assessment of their direct vulnerability to geological hazards (e.g. type of construction, number of floors, roof stability).

Resources for civil protection form a specific data set (Table 2) taking into account their importance for emergency response and vulnerability reduction when facing a catastrophic event. In this case all the information related to civil protection and the fire department was considered because these two groups form the core of the Azores Regional Civil Protection Service (SRPCBA).

The geological and geomorphologic data set (Table 3) comprises descriptive and interpretative data obtained from

Table 3. Geological and geomorphologic data set.

Layers	Data	Features type
Lithology	Basalts, trachyts, limestone, sandstones, alluvium, beach sand, beach gravel, clay	Polygons
Volcanic landforms	Central volcanoes, cinder cones, spatter cones, spatter ramparts, pumice cones, tuff cones, maars, domes, spines, lava flow fields, caldera rim, crater rim, pit crater, (id_eruption)	Lines, polygons
Volcanic products and deposits	Scoria, pumice, lava flows, tephra fall deposits, pyroclastic flow deposits, scoria flows, ignimbrites, block and ash flows, lahars, hydrothermal deposits (id_eruption)	Polygons
Soils		Polygons
Stratigraphy	Ages, dating methods, (id_geology), (id_log)	Points, polygons
Samples	Sample reference number, geochemical analysis, petrographic data, (id_geology), (id_bbl)	Points
Tectonic features	(Faults), scarp faults	Lines
Faults	Type, geometry, kinematics, age, dip, plunge, striations, (id_photo)	Points, lines
Erosion landforms	Active cliffs, fossil cliffs, valleys, (landslides scars)	Lines, polygons
Hydrothermal systems	(Fumaroles), degassing areas, thermal springs, cold springs	Points, polygons
Fumaroles	Name, type, (id_photo)	Points

Table 4. Volcanological data set.

Layers	Data	Features type
Pre-historic volcanic eruptions	Age, name of eruptive centre, eruption type, (id_geograph), (id_eruption), (id_geology), (id_photo), (id_log)	Points
Historical volcanic eruptions	Date, time interval, name of eruptive centre, eruption type, precursory signals, (id_geograph), (id_eruption), (id_geology), (id_bbl), (id_photo), (id_log)	Points
Eruptive parameters	Isopachs, isopleths, (id_eruption), (id_log)	Points, lines, polygons
Volcanic eruption impact data	Volcanic hazard, deaths, injured, dislodged people, damaged buildings, others (id_geograph), (id_eruption), (id_bbl), (id_photo)	Points

geological mapping surveys and aerial photo analysis (i.e. volcanic, structural and erosion landforms, lithology and tectonic structures; Fig. 2). Additionally, it contains analytical data germane to the petrography and geochemistry of samples related to the established geological units. Geological mapping of the Azores is published at different scales depending on the island (1:50 000; 1:35 000; 1:25 000; 1:15 000 and 1:10 000) and is being digitized using the new 2001 topographic maps.

Despite the fact that some volcanological data were inserted in the geological and geomorphologic data set it was decided to define a specific volcanological data set (Table 4), to include the information related to the historical volcanic eruptions and their impact. In this group is also considered the information obtained from the study of the eruptive deposits from particular events.

The landslide data set (Table 5) was defined to archive information related to historical and contemporary slope movements, as well as their impact. Major historical events are being identified and catalogued based on a detailed study of old documents, while recent occurrences, with preserved scars, are being mapped using aerial photos. Layers for quantitative data related to the morphometric characteristics of landslide scars and associated deposits were also considered.

Taking into account the monitoring networks that are being operated in the Azores archipelago by the Centre of Volcanology and Geological Risk Assessment, data sets for seismology (Table 6), geodesy (Table 7), fluid geochemistry (Table 8) and meteorology (Table 9) were envisaged. In a general way, all these data sets contain information about the characteristics of the monitoring stations, their location and the existing data transmission facilities (Fig. 3). Moreover, they comprise the acquired data, both in their original form and after being processed. Seismological information refers to all the seismic waves, hypocentre parameters and macroseismic data (Fig. 4). Geodetic data includes the GPS

Table 5. Landslides data set.

Layers	Data	Features type
Landslide events	Date, type of movement, main constituents, trigger, (landslide scar), (landslide deposit), (id_landslide), (id_bbl), (id_photo)	Points
Landslide scar	Maximum elevation point, minimum elevation point, maximum width, average width, perimeter, area, landslide scar, (id_landslide)	Points, lines, polygons
Landslide deposit	Maximum width, average width, maximum length, average length, maximum thickness, average thickness, perimeter, area, volume (id_landslide)	Points, lines, polygons
Landslides impact	Deaths, injured, displaced people, damaged buildings, others (id_geograph), (id_landslide), (id_bbl), (id_photo)	Points

Table 6. Seismological data set.

Layers	Data	Features type
Seismic stations	Station name, type, owner, altitude, station brand, station model, seismometer brand, seismometer components, frequency, (id_station), (id_photo)	Points
Data transmission links	Towers, repeaters, UHF, freewave, telephone	Points, lines
Instrumental data	Date, time, first station, number of stations, epicentre, rms, depth, Md, ML, type, observations (id_quake)	Points
Macroseismic data	Local intensity, intensity scale, deaths, injured, dislodged people, damaged buildings, (id_geograph), (id_quake), (id_bbl), (id_photo)	Points
Isoseismic lines	(id_quake)	Lines, polygons

observations made with the permanent antennas and during regular field surveys. Fluid geochemistry data consists of CO_2 and H_2S flux, CO_2 concentration, composition of fumaroles and thermal waters, Rn activity, and water wells and lakes physical parameters.

With GIS, data can be accessed and analysed interactively in order to produce new and combined information (Aronoff, 1989). In the present case, risk analysis comprises hazard assessment and vulnerability evaluation using diverse methodologies and precise predicting models. The generated data sets results from spatial, 3-D and geostatistical analysis and are the main frames for risk assessment and management.

3 Library data sets

In order to minimize data redundancy without interfering with the performance of the system a codes library was defined, containing specific identification pointers that facilitate the links between layers and data sets (Table 10). Another major set of data that increases the capacity and the utility of AZORIS is the significant collection of available documents that can be automatically displayed from any view. This library data set includes a copy of documents that describe historical catastrophic occurrences related to geological hazards, namely: books; magazines; newspapers; reports and other written information. This includes regional and muni- cipal emergency plans and the alert level codes. Moreover, it provides access to a large set of images like orthophotomaps, photographs, maps, logs and schemes, as well as to useful catalogues (e.g. maps, aerial photographs).

4 Data archive

The amount and nature of data that can be acquired, generated and collected, requires a physical support to store information in a structured way. In the present case, the chosen structure (Fig. 5) was thought-out keeping in mind the fact that the geological risk assessment will be carried out at different scales (archipelago, island, county, parish or place), depending on the type and magnitude of the geological event under consideration. Strong earthquakes and high magnitude volcanic eruptions may affect several islands, while minor volcanic events and landslides have an impact in a restricted area within each island.

Table 7. Geodetic data set.

Layers	Data	Features type
GPS stations	Station name, altitude, station brand, station type, antenna brand, antenna type, (id_station), (id_photo)	Points
Data transmission links	Towers, repeaters, UHF, freewave, telephone	Points, lines
GPS benchmark network	Benchmark name, benchmark type, benchmark foundation, network name, network type (id_station)	Points
GPS data	Date, x, y, z, dx, dy, dz (id_station)	Points

Table 8. Fluid geochemical data set.

Layers	Data	Features type
CO_2 flux stations	Station name, altitude, station brand, station type, CO_2 sensor, (id_station), (id_photo)	Points
CO_2 air concentration stations	Station name, altitude, station brand, station type, CO_2 sensor, (id_station), (id_photo)	Points
CO_2 benchmark network	Altitude, benchmark type, (id_station)	Points
H_2S flux stations	Station name, altitude, station brand, station type, H_2S sensor, (id_station), (id_photo)	Points
Rn stations	Station name, altitude, station brand, station type, Rn sensor, (id_station), (id_photo)	Points
Water well/lake stations	Station name, altitude, station brand, station type, water level sensor, temperature sensor, conductivity sensor, (id_station), (id_photo)	Points
Data transmission links	Towers, repeaters, UHF, freewave, GSM	Points, lines
CO_2 data	Date, time, CO_2 flux, CO_2 concentration, (id_station)	Points
H_2S flux data	Date, time, H_2S flux, (id_station)	Points
Rn data	Date, time, Rn, (id_station)	Points
Gas geochemical data	Date, CO_2, H_2S, H_2, CH_4, N_2, Ar, O_2, temperature, pH, (id_station)	Points
Water wells/lakes data	Date, time, water level, water temperature, water conductivity, (id_station)	Points

5 Metadata

The definition of Metadata files for the AZORIS data layers became an essential step aiming to guarantee the quality and harmonization of the input data and inform any system user about its quality. Following an analysis of every type of data, in order to assemble all the information needed to describe each data layer, a metadata form was generated with the purpose of validating entry into the system. This metadata file, in a table format, has five main topics.

5.1 Data ID

Basic information about the data layer
Name
Responsibility for the creation and update of the file
Date of creation/import
Date of the last update
Comments

5.2 Data creation

Information about the origin of the data if it was created outside the system and imported
Author
Reference
Description

5.3 Data spatial features

Information on how the spatial elements are displayed
Type of unitary elements (vector – point, line, polygon/raster – pixel)
Number of elements
Coordinate system
Reference scale
Area covered
Comments

Table 9. Meteorological data set.

Layers	Data	Features type
Meteorological stations	Station name, altitude, soil temperature sensor, soil humidity sensor, barometric pressure sensor, rainfall sensor, wind speed sensor, wind direction sensor, air humidity sensor, air temperature sensor, (id_station), (id_photo)	Points
Data transmission links	Towers, repeaters, UHF, freewave, GSM	Points, lines
Meteorological data	Date, time, soil temperature, soil humidity, barometric pressure, rainfall, wind speed, wind direction, air humidity, air temperature, (id_station)	Points

Table 10. Codes library.

Codes	Data
Bibliographic codes (id_bbl)	Code for each book, paper, magazine, newspaper, report
Eruption codes (id_eruption)	Code for each volcanic eruption
Earthquakes codes (id_quake)	Code for each earthquake
Geographic codes (id_geograph)	Code for islands, counties, cities, villages, parishes, localities, places
Geological units codes (id_geology)	Code for geological units such as complexes, groups, formations, members, deposits and beds
Houses codes (id_house)	Code for each house
Landslides codes (id_landslide)	Code for each landslide
Monitoring stations codes (id_station)	Codes for seismological, fluid geochemical, geodetic and meteorological stations
Photo codes (id_photo)	Code for each photo
Stratigraphic log codes (id_log)	Code for each stratigraphic log

5.4 Data attributes

Description of all attributes for each entity in a data layer
Name
Type
Range
Description

5.5 Data quality

Elements about the quality of the data
Accuracy of spatial features
Accuracy of attributes data
State-of -the-art
Import data method

6 Conclusions

The AZORIS database was conceived to archive, manipulate, model and display spatial referenced data for risk analysis. The defined logical and physical dynamic structures allow the system to evolve according to the collected and generated data keeping coherence and enlarging its capabilities. The maintenance of AZORIS will depend on the basic data update taking into account the main parameters that control changes in risk. In order to assure its usefulness, official agreements are being established with regional and local authorities that produce new information.

A major step in the development of the system is related to the application of models for hazard and vulnerability assessment. This will lead to the definition of risk zones based on critical values that can be used for emergency and land-use planning. Another potential of AZORIS results from its link to the monitoring networks operated by the Centre of Volcanology and Geological Risk Assessment. Such potential can be used to implement alarm and warning systems and is of major importance for crisis management.

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