ANNALS OF GEOPHYSICS, 68, 1, V112, 2025; doi:10.4401/ag-9171
OPEN ACCESS

Spatial data and GIS for the assessment of the environmental impact at Mount Etna

Michele Mangiameli[1], Annalisa Cappello[*,2], Giuseppe Mussumeci[3]

(1) Università di Catania, Dipartimento di Ingegneria Civile e Architettura, Catania, Italy
(2) Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy
(3) Università di Messina, Dipartimento di Ingegneria, Messina, Italy

Article history: received September 30, 2024; accepted November 12, 2024

Abstract

One of the fundamental tasks for environmental impact assessment and natural risk management is the accurate and updated cataloging of road infrastructures and buildings. This is particularly important in volcanic areas, in order to predict the range of damage and disruption, and therefore losses and reconstruction costs that could result from an eruption. GIS allows immediate access to spatial data with the ability to overlay location-based information for easy interpretation, providing a critical tool for assessing and mitigating risk from natural phenomena. In this work, we present an innovative GIS-based system for the identification of the values exposed to volcanic eruptions at Mount Etna, which can be used in both the readiness and response phases to a volcanic emergency. We carried out a precision mapping of buildings and road infrastructures on the flanks of the Etna volcano, giving particular attention to the exposed sensitive buildings (such as schools, barracks, hospitals, etc.) and to the construction and roofing characteristics. The result is an informative and dynamic platform that offers new opportunities and challenges to decision makers for the definition of both long-term strategies, such as territorial planning, and short-term strategies, for the prediction of the impact of eruptions or for managing evacuations during volcanic emergencies.

Keywords: Spatial data; GNSS; Remote Sensing; GIS technology; volcanic risk

1. Introduction

Disasters caused by natural hazards are increasing in frequency and having a greater impact on populations and economies around the world. For this reason, it is essential that scientists and stakeholders in hazardous areas have a greater understanding of the causes of disaster risk and better tools to assess their impact on vulnerable populations (Van Westen, 2013).

In the field of natural hazards, Risk is commonly defined as Hazard×Exposure×Vulnerability, where *Hazard* indicates the probability of occurrence of an event, *Exposure* is a quantification of the people, systems, and property potentially subject to the hazardous phenomenon, and *Vulnerability* is a quantification of the effective relative impact of the event. In case of volcanic eruptions, the hazardous events include for instance lava flows, tephra, pyroclastic flows, earthquake, etc. Therefore, studying the volcanic risk should involve the analysis of the hazardous events that affect an area, as well as the vulnerability of the exposed values possibly affected by volcanic phenomena (Blong, 1996; Jenkins et al., 2014; D'Amico et al., 2016; Del Negro et al., 2019; Centorrino et al., 2021; Azzaro et al., 2023). Overviews of vulnerability concepts, methods for measurement, and their applications in different hazard contexts, including volcanic hazards, are available, e.g., in Tilling (1989), Blaikie et al. (2004), and Bilotta et al. (2023).

Typically, for a single volcano, an estimate of future hazards can be made by systematic and accurate analyses of historical events, as well as by numerical modeling, in order to obtain probabilistic maps (e.g., Cappello et al., 2025; D'Amico et al., 2025; Scollo et al., 2025; Zuccarello et al., 2025). Conversely, the analysis of vulnerability comes from the knowledge of the consequences of the observed eruptions, from the general knowledge of the impacts of eruptions on the volcanic areas, and from the creation of possible eruptive scenarios that highlight how they can affect the surrounding territory (Cardona, 2004; Zuccaro and De Gregorio, 2019; Pessina et al., 2023).

Etna is the most active volcano in Europe and its continuous eruptive events produce different types of dangerous phenomena, including earthquakes, lava and pyroclastic flows, tephra and ash which can be transported by winds for thousands of kilometers. Indeed, during an eruption, tephra fragments of smaller dimensions and lighter weight can reach even very distant areas from the volcano, while fragments of dimensions greater than 2 mm and heavier generally fall a few dozen kilometers from the emission point. Unfortunately, at Etna, due to the high number of eruptive events, the volcano's flanks are covered with large quantities of ash, such as in July 2024, when approximately 17 tons of volcanic ash fell in the city of Catania alone. This causes economic losses, for example with the closure of the airport, and inconveniences due to the accumulation of ash on house roofs and streets, which requires considerable efforts for its removal both by the local population and by the municipalities involved.

Most studies on tephra fallout focus on hazard assessments, by analyzing volcanological data and using numerical models to obtain probabilistic estimates (e.g., Carey, 1996; Connor et al., 2001; Barsotti et al., 2010). Moreover, some studies use innovative technologies based on GIS and remote sensing both for the analysis of the risk assessment for tephra fallout and for the determination of Eruptive Source Parameters (ESPs), which is a major challenge especially for weak volcanic explosions that determine tephra fallout (Biass and Bonadonna, 2012).

GIS is particularly well suited for describing, analyzing and modeling environmental problems and datasets. Indeed, the GIS technology allows to dynamically manage different kinds of data, such as those from satellite missions and spatial data acquired in real time. It also provides numerous tools and plugins for geo-statistical analysis, providing an efficient Decision Support System (Mangiameli and Mussumeci, 2013a; 2013b; Scaini et al., 2014; Mangiameli et al., 2019; Ganci et al., 2023). Data handling is closely related to the data structure and the information technology that must manage the database to support the GIS application.

In this paper, we present an innovative GIS application for the assessment of the environmental impact that Etnean flank eruptions can have on buildings and infrastructures. A RDBMS (Relational DataBase Management System) was used for the optimized management of the spatial database (external to the GIS platform), which has proven effective for emergency management in different scientific fields (see e.g. Mangiameli et al., 2021; 2024). In particular, we carried out a census of the buildings present in a study area of the Etna territory (together with a characterization of roofs on a local scale) and a classification of the communication routes in order to obtain a basis for the planning of intervention strategies in case of eruptive emergencies. The hardware and software architecture developed is flexible and database-centric, with spatial data organically organized, accessible and readily usable by any stakeholder. The storage of additional data in different formats, such as images, photos and technical sheets, further improves the efficiency of the system, facilitating both relative and absolute assessments of the conditions of buildings and their components.

This work was carried out in the framework of a Research Agreement between Istituto Nazionale di Geofisica e Vulcanologia and Dipartimento di Ingegneria Civile e Architettura of the University of Catania, within the "Probabilistic AssessmeNt of volCano-related multi-hazard and multi-risk at Mount EtnA" – PANACEA project.

2. Materials and methods

We developed a GIS application using only free and open source software technologies, with the aim of easily dealing with all the data exposed to the risk due to the Etnean eruptions.

In the following sections, we describe the main components that were developed, including the software and hardware architecture, the data structure, and the Desktop GIS application.

2.1 The software and hardware architecture

The software and hardware architecture was designed by adapting a designing pattern that we have successfully used in different research fields of the civil engineering, such as transportation, management of hydrological emergencies and navigation of autonomous robots (e.g., Famoso et al., 2012; Mangiameli et al., 2013; Mangiameli and Mussumeci, 2015).

The software architecture (Fig. 1) is characterized by a GIS, namely a computer system capable of capturing, storing, analyzing, and displaying geographically referenced information (i.e., data identified according to location) and an RDBMS, which is a type of database management system that organizes data into a set of formally described tables for efficient data manipulation and retrieval. In our software structure, the RDBMS holds a central position with respect to the GIS software and the input/output data.

For our application, QGIS ver.3.28 was used as GIS software, while the PostGIS spatial extension of PostgreSQL ver.9.5 was used to develop the relational database.

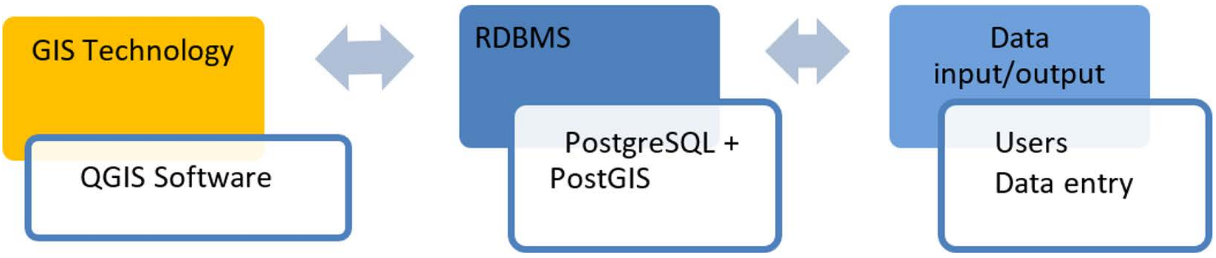


Figure 1. Block diagram of the software architecture.

Regarding the hardware architecture, the Desktop GIS is located in an external device and the RDBMS in a dedicated server. This enables exploiting all the features of the RDBMS and improving the performance of querying, updating and visualization of the data included in the spatial database.

The deployment diagrams for the GIS client and the RDBMS server in Fig. 2 show the system architecture in UML (Unified Modeling Language), where the nodes represent the hardware devices and software platforms, while the relationships reveal the physical implementation of components.

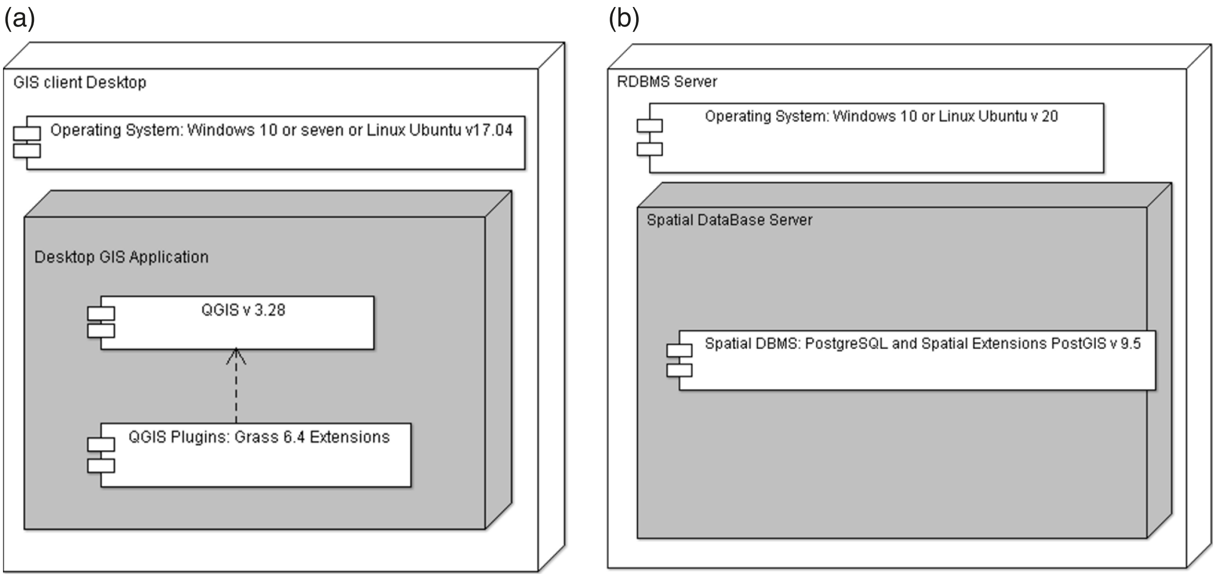


Figure 2. UML deployment diagram of the GIS client (a) and the RDBMS server (b).

2.2 The data structure

The implementation of the data structure within the spatial RDBMS involved the following tasks:
- Identification of the entities exposed to the volcanic risk, with particular regard to the tephra fall;
- Definition of the relationships between the entities previously identified;
- Conceptual design of the data structure using the entity relationship diagram;
- Physical implementation of the data structure within the spatial RDBMS.

For the entities exposed to the volcanic risk, we decided to focus on buildings and roads on the southeast flank of Etna. Therefore, the relational data structure is composed of three entities, namely the roads, the buildings and the administrative boundaries of the municipalities. The relationships among these entities are shown in the E-R diagram reported in Fig. 3. The spatial database was then physically implemented within the PostgreSQL RDBMS with three tables (corresponding to the three entities), the cardinality constraints and the relationships between the different tables shown in the E-R diagram of Fig. 3.

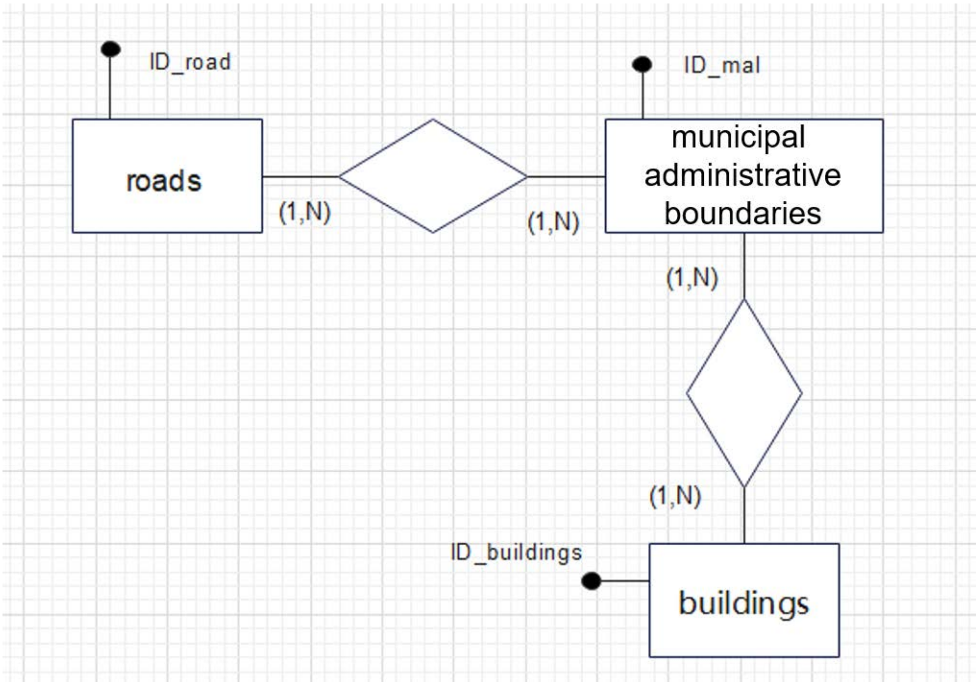


Figure 3. Generalized Entity-Relationship (E-R) diagram related to the conceptual design of the data structure designed for the RDBMS.

2.3 The desktop GIS application

The Desktop GIS application was developed using QGIS, a user-friendly open source Geographic Information System for the analysis of geospatial data and the visualization/production of georeferenced maps.

As a cartographic basis, we used the orthophotos acquired in 2012 and 2013 and the regional technical map with a nominal scale of 1/10000 (Fig. 4). This cartographic raster data, which are available as a WMS service in the cartographic portal of the Sicily region (https://www.sitr.regione.sicilia.it/), were georeferenced according to the EPSG (European Petroleum Survey Group) 6708, as established by the Italian Istituto Geografico Militare (IGM).

For the development of the GIS application, we considered the southeast flank of Etna, including the municipalities of Santa Venerina, Milo, Zafferana Etnea, Acireale, Giarre and Riposto. These municipalities were chosen since they were historically affected by the earthquakes and the volcanic products emitted during the Etnean eruptions. In particular, they are the ones that suffer the greatest damage from the tephra fallout due to the prevailing wind

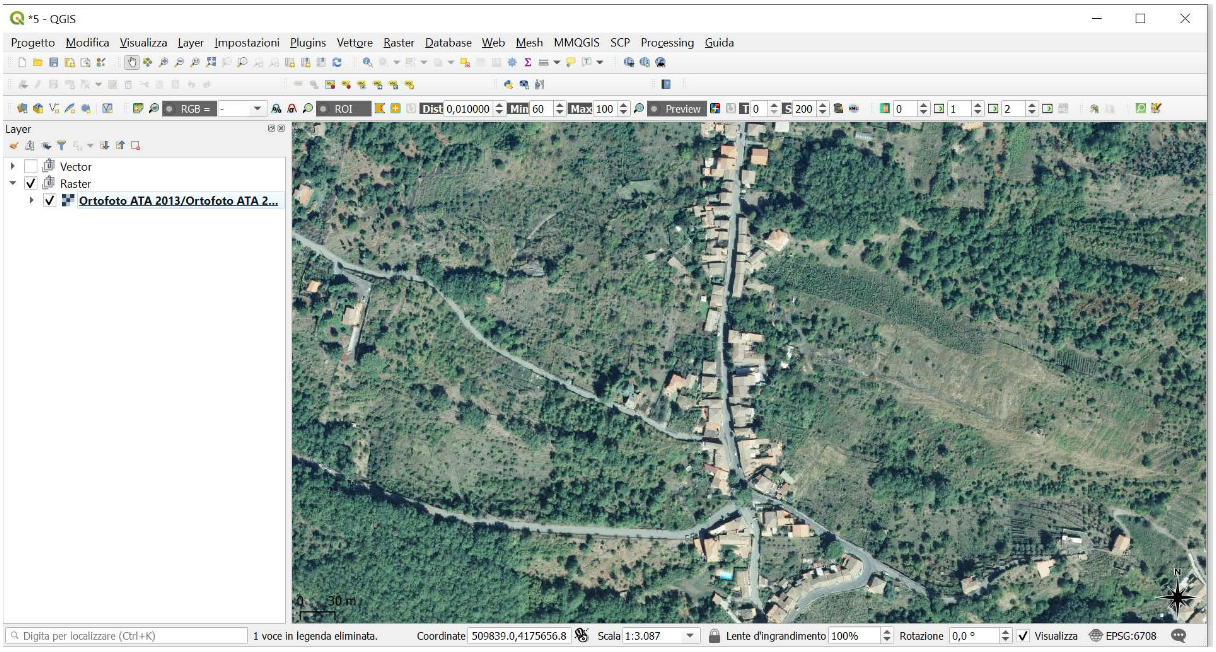


Figure 4. Zoom of the orthophotos acquired in 2012 and 2013 and used as a WMS in QGIS.

direction, which can compromise the structural stability of buildings and road infrastructures, and the health of the inhabitants. Therefore, a polygonal thematism was developed to mark these six municipalities.

The data structure was designed so that the areas of the municipalities are inserted as rows of a single table and include the name of the municipality and the ISTAT code as attributes.

We also created vector layers for all road infrastructures within the study area. Specifically, we digitized linear geometries, making a classification according to the administrative needs and with reference to the use and types of connections, in municipal roads, provincial roads, state roads and motorway sections. Using the geoprocessing functions, the complete road graph in shapefile format was implemented within the municipal boundaries chosen as the study area, inserting different types of information into the associated database, such as the functional and administrative classification, geometric characteristics, etc.

Finally, the polygonal vector theme relating to the buildings was created. For this data structure, an automatic procedure for data entry into the spatial database was implemented in order to acquire all possible useful information from public databases, such as OpenStreetMap (https://www.openstreetmap.org/). The automatic procedure allowed enriching the database of the buildings with essential data regarding the roofs, such as the typology, geometry and inclination. Moreover, it includes dynamic links to multimedia data, such as images, photos and technical sheets associated with the building, when available. Particular attention was paid to the strategic buildings (barracks, fire stations and hospitals), buildings of historical interest and schools. For these buildings, a sample field check was carried out, both for testing the data structure and the correct georeferencing using a topographic GNSS in differential positioning.

3. Results

In this Section, we show some screenshots of the GIS application developed.

Figure 5 displays the boundaries of the municipalities selected in the southeast flank of Etna, i.e. Santa Venerina, Milo, Zafferana Etnea, Acireale, Giarre and Riposto. To each polygon, an attribute table is associated, which includes different information, such as the municipal surface, the name and the ISTAT code.

Figure 6 shows the road infrastructure classified in municipal roads, provincial roads, state roads and motorway sections. A table is associated with each road, including different attributes, such as the name, the administrative classification, length and width.

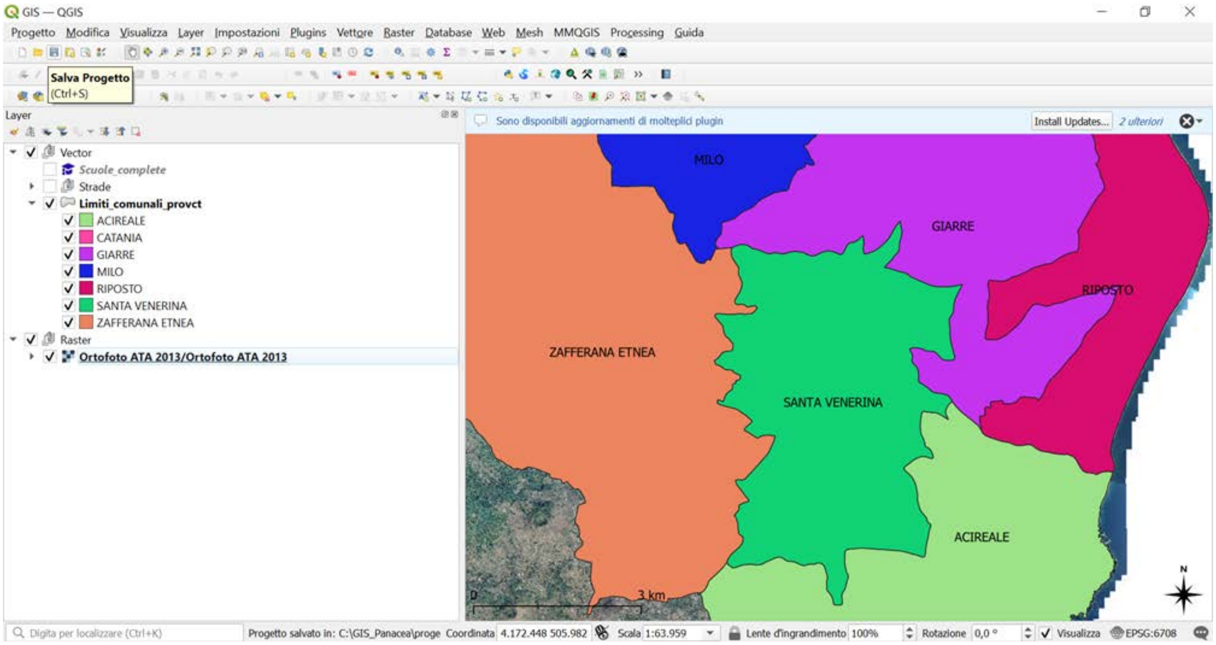


Figure 5. Polygonal vector thematism of the six municipalities chosen as study areas.

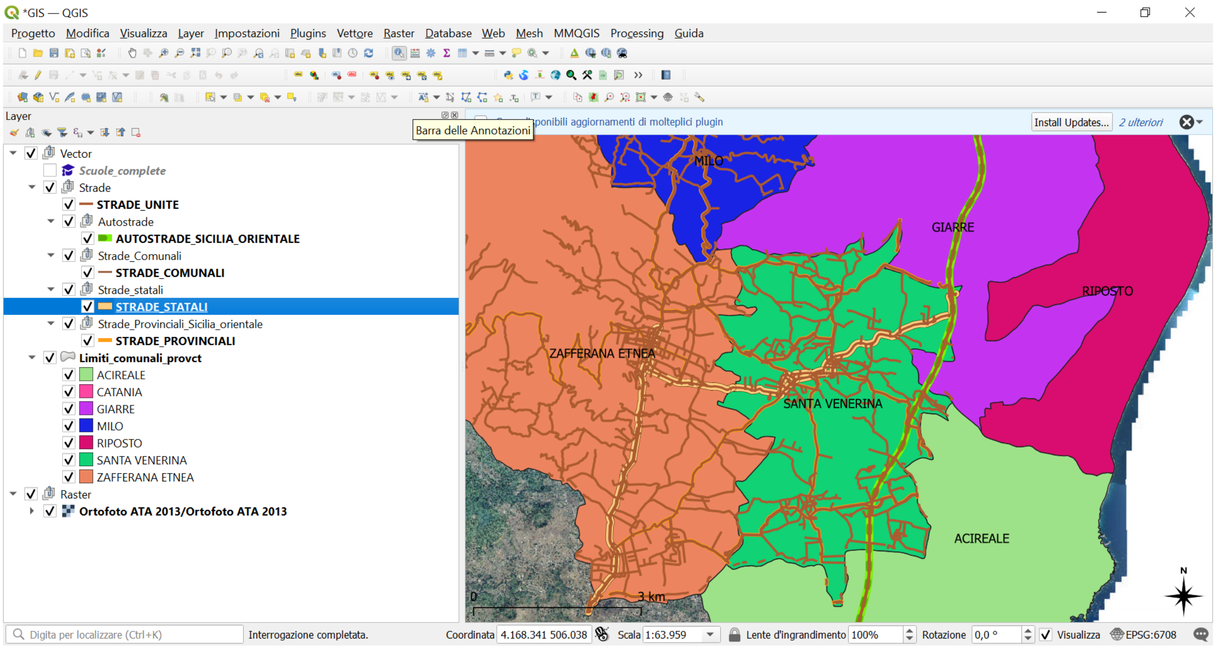


Figure 6. Linear vector themes of road infrastructure.

Figure 7 shows the GIS layer including the strategic buildings in the six selected municipalities, namely the primary and secondary schools. For each school, different useful information was collected, partially taken from the MIUR "Scuola in chiaro" website, available at https://www.miur.gov.it/-/scuola-in-chiaro. This includes the name of the school, the mechanographic code, the address, the number of students, the number of classes, etc. (Fig. 8).

Thanks to the RDBMS associated with the GIS software, it is also possible to query the individual layers and obtain specific information, for example the geometric characteristics of the building roofs, in order to calculate the mechanical resistance to the tephra fall or to download any technical documentation attached to the layer (Fig. 9). Similarly, different queries can be made on the road vector to perform targeted selections based on geometric characteristics, for example to find all roads with a width below a certain threshold that could be completely closed in the event of a volcanic emergency.

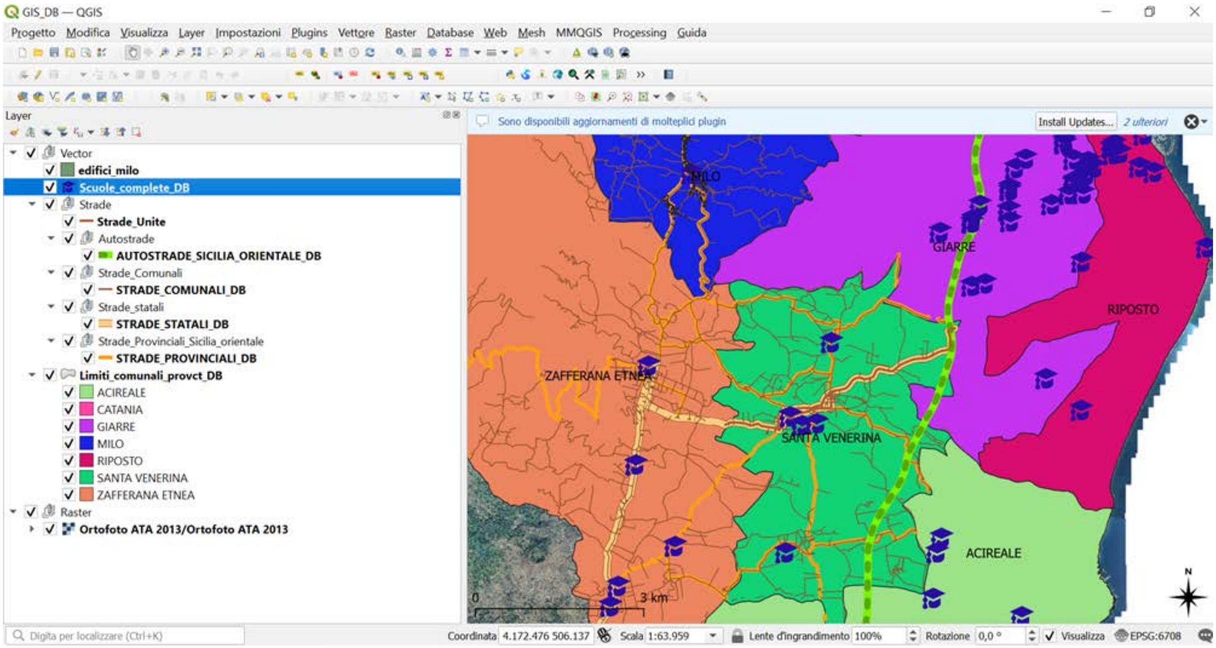
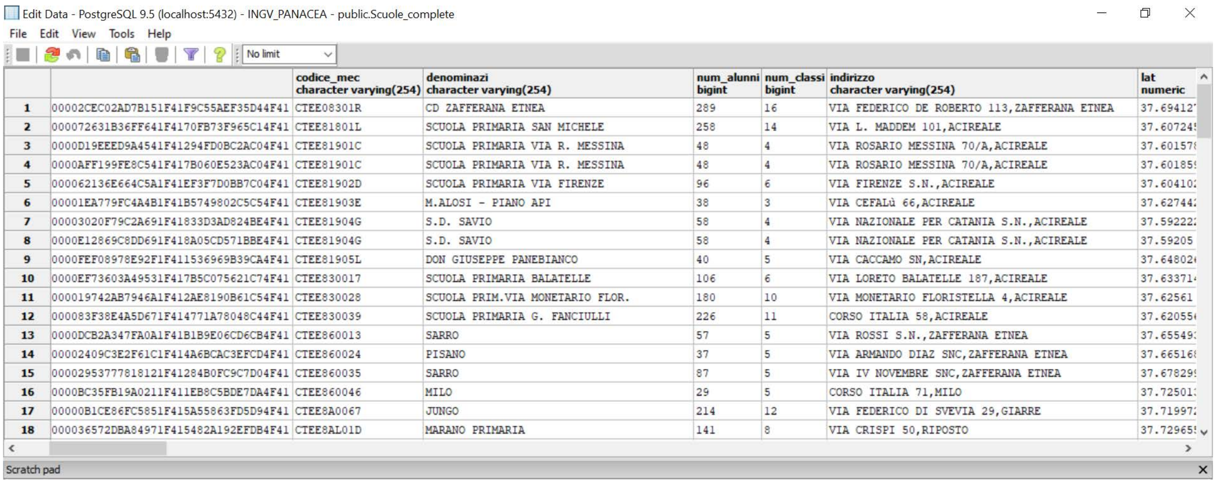


Figure 7. Vector layer of primary and secondary schools.


Edit Data - PostgreSQL 9.5 (localhost:5432) - INGV_PANACEA - public.Scuole_complete

		codice_mec character varying(254)	denominazi character varying(254)	num_alunni bigint	num_classi bigint	indirizzo character varying(254)	lat numeric
1	00002CEC02AD7B151F41F9C55AEF35D44F41	CTEE08301R	CD ZAFFERANA ETNEA	289	16	VIA FEDERICO DE ROBERTO 113,ZAFFERANA ETNEA	37.69412
2	000072631B36FF641F4170FB73F965C14F41	CTEE81801L	SCUOLA PRIMARIA SAN MICHELE	258	14	VIA L. MADDEM 101,ACIREALE	37.60724
3	0000D19EEED9A4541F41294FD0BC2AC04F41	CTEE81901C	SCUOLA PRIMARIA VIA R. MESSINA	48	4	VIA ROSARIO MESSINA 70/A,ACIREALE	37.60157
4	0000AFF199FE8C541F417B060E523AC04F41	CTEE81901C	SCUOLA PRIMARIA VIA R. MESSINA	48	4	VIA ROSARIO MESSINA 70/A,ACIREALE	37.60185
5	000062136E664C5A1F41EF3F7D0BB7C04F41	CTEE81902D	SCUOLA PRIMARIA VIA FIRENZE	96	6	VIA FIRENZE S.N.,ACIREALE	37.60410
6	00001EA779FC4A4B1F41B5749802C5C54F41	CTEE81903E	M.ALOSI - PIANO API	38	3	VIA CEFALù 66,ACIREALE	37.62744
7	00003020F79C2A691F41833D3AD824BE4F41	CTEE81904G	S.D. SAVIO	58	4	VIA NAZIONALE PER CATANIA S.N.,ACIREALE	37.59222
8	0000E12869C8DD691F418A05CD571BBE4F41	CTEE81904G	S.D. SAVIO	58	4	VIA NAZIONALE PER CATANIA S.N.,ACIREALE	37.59205
9	0000FEF08978E92F1F411536969B39CA4F41	CTEE81905L	DON GIUSEPPE PANEBIANCO	40	5	VIA CACCAMO SN,ACIREALE	37.64802
10	0000EF73603A49531F417B5C075621C74F41	CTEE830017	SCUOLA PRIMARIA BALATELLE	106	6	VIA LORETO BALATELLE 187,ACIREALE	37.63371
11	000019742AB7946A1F412AE8190B61C54F41	CTEE830028	SCUOLA PRIM.VIA MONETARIO FLOR.	180	10	VIA MONETARIO FLORISTELLA 4,ACIREALE	37.62561
12	000083F38E4A5D671F414771A78048C44F41	CTEE830039	SCUOLA PRIMARIA G. FANCIULLI	226	11	CORSO ITALIA 58,ACIREALE	37.62055
13	0000DCB2A347FA0A1F41B1B9E06CD6CB4F41	CTEE860013	SARRO	57	5	VIA ROSSI S.N.,ZAFFERANA ETNEA	37.65549
14	00002409C3E2F61C1F414A6BCAC3EFCD4F41	CTEE860024	PISANO	37	5	VIA ARMANDO DIAZ SNC,ZAFFERANA ETNEA	37.66516
15	00002953777818121F41284B0FC9C7D04F41	CTEE860035	SARRO	87	5	VIA IV NOVEMBRE SNC,ZAFFERANA ETNEA	37.67829
16	0000BC35FB19A0211F411EB8C5BDE7DA4F41	CTEE860046	MILO	29	5	CORSO ITALIA 71,MILO	37.72501
17	00000B1CE86FC5851F415A55863FD5D94F41	CTEE8A0067	JUNGO	214	12	VIA FEDERICO DI SVEVIA 29,GIARRE	37.71997
18	000036572DBA84971F415482A192EFDB4F41	CTEE8AL01D	MARANO PRIMARIA	141	8	VIA CRISPI 50,RIPOSTO	37.72965

Scratch pad

Figure 8. Attribute table associated with the vector thematism of schools in the RDBMS.

4. Conclusions

Spatial data and GIS are indispensable to comprehensively assess and manage the environmental impacts of volcanic eruptions, providing the necessary tools to understand the immediate and long-term effects on the environment and helping in planning effective responses and mitigation strategies.

In this work, we have presented a new system based on a spatial database and GIS technologies that can be used for the assessment of vulnerability and, subsequently, of risk due to an earthquake or a volcanic eruption on Etna. The main advantages of our system include the spatial data structure, which is managed by an RDBMS external to the GIS platform, and the free and open-source GIS application that facilitates systematic searches for relationships and patterns among municipalities, buildings and roads, supporting the planning of risk mitigation strategies. Access to the database is done through a dedicated graphical interface implemented in QGIS that also includes possible dynamic links to different types of multimedia data, such as images and technical sheets, associated to simulate possible intervention scenarios, reducing the time and costs of any interventions by public administrations. Indeed, for the management of volcanic risk, it is essential to survey the potentially vulnerable buildings, but also to manage

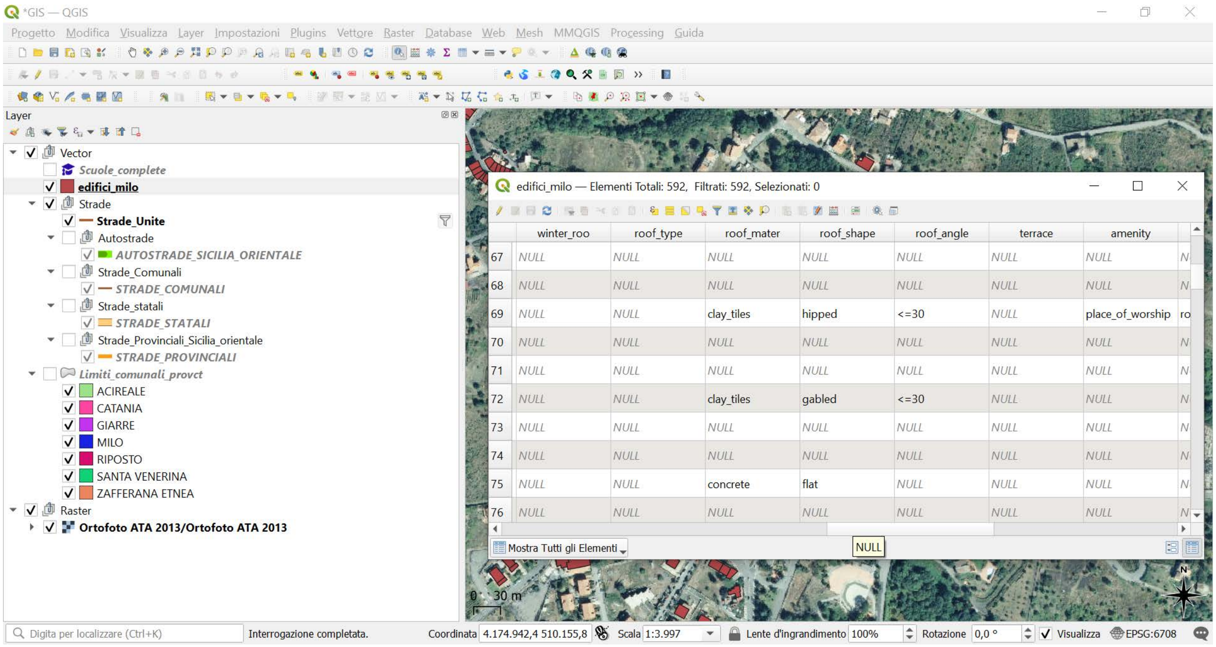


Figure 9. Attribute table obtained in output of the query of intersection of buildings with the polygon of the municipality of Milo.

the road graph in the area of interest in order to evaluate the vulnerability of road sections that may, for example, be affected for example by large quantities of tephra. This is because a road section covered by tephra is impassable and therefore cannot be used by emergency vehicles in the case of intervention.

During the development of the GIS application and the data structure, much attention was paid to the symbolism and graphics, to make the application and the products as intuitive as possible for both scientific and practical purposes. This provides an effective, easy usage and fast-sharing platform that has a significant potential as a Decision Support System (DSS) to optimize the planning of risk mitigation actions. With regard to risk reduction, the application can be used to identify and model hazards, and to map the potential footprint of disastrous natural events, together with more complex algorithms for the modelling of the hazard itself.

The system was developed in the framework of a research project focusing on the volcano-induced multi-hazard and multi-risk assessment at Etna. However, its flexibility allows it to be easily extended to any other area at risk from any other natural hazards, such as floods, inundations and landslides. It represents the basis for any type of vulnerability assessment, providing the most influential parameters and main inputs of most vulnerability models, i.e. the height (or number of floors), the roof slope and the age of construction of buildings. It can be used for land use planning as a tool for consultation and delimitation of zones, and to assess the safety of roads, buildings and populations with respect to any natural hazard. In addition, it allows to easily identify the value exposed for protective actions, such as optimal routes in real time for evacuation (see e.g. Mangiameli et al., 2013), and to evaluate the consequences of potential emergencies.

Future development will include the continuous updating of all spatial data included in the database, to ensure that the information received is the most up-to-date. Moreover, a Web GIS will be developed to allow the user to operate on the data structure from WEB platforms or from operational centers, making the system efficient and effective even during field surveys.

Data availability statement. Figures were generated using the free and open source QGIS software.

Acknowledgements. This work was supported by the INGV project Pianeta Dinamico (CUP D53J19000170001) funded by MIUR ("Fondo finalizzato al rilancio degli investimenti delle amministrazioni centrali dello Stato e allo sviluppo del Paese", legge 145/2018), Tema 8 – PANACEA 2021-2023. We thank Steve Conway for revising the English language of the manuscript.

References

Azzaro, R., S. D'Amico, T. Esposti Ongaro, G. Ganci et al. (2023). Towards a Multi-Hazard Assessment at Etna Volcano (Italy): The PANACEA Project, in Advances in Natural Hazards and Volcanic Risks: Shaping a Sustainable Future, NATHAZ 2022, A. Malheiro, F. Fernandes and H. I. Chaminé (Editors), Adv. Sci. Technol. Innov., Springer, Cham, 31-35, doi:10.1007/978-3-031-25042-2_6.

Barsotti, S., D. Andronico, A. Neri, P. Del Carlo et al. (2010). Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation, J. Volcanol. Geotherm. Res., 192, 1-2, 85-96, doi:10.1016/j.jvolgeores.2010.02.011.

Biass, S. and C. Bonadonna (2012). A fast GIS-based risk assessment for tephra fallout: the example Cotopaxi volcano, Ecuador – Part I: Probabilistic hazard assessment, Nat. Haz., 65, 477-495, doi:10.1007/s11069-012-0378-z.

Bilotta, G., A. Cappello and G. Ganci (2023). Formal Matters on the Topic of Risk Mitigation: A Mathematical Perspective, Appl. Sci., 13, 265, doi:10.3390/app13010265.

Blaikie, P., T. Cannon, I. Davis and B. Wisner (2004). At Risk: Natural Hazards, People's Vulnerability and Disasters, Routledge, London, 496, doi:10.4324/9780203714775.

Blong, R. J. (1996). Volcanic hazards risk assessment, in Monitoring and mitigation of volcanic hazards, R. Scarpa and R. Tilling (Eds.), Springer, Berlin, Heidelberg, New York, 675-698, doi:10.1007/978-3-642-80087-0_20.

Cappello, A., G. Bilotta, F. Zuccarello, C. Proietti et al. (2025). An improved methodology for lava flow hazard mapping at Etna volcano, Ann. Geophys., 68, doi:10.4401/ag-xxxx, in press.

Cardona, O. D. (2004). The Need for Rethinking the Concepts of Vulnerability and Risk from a Holistic Perspective: A Necessary Review and Criticism for Effective Risk Management, in Mapping Vulnerability: Disasters, development and people, Earthscan publishers, London, 38-51, doi:10.4324/9781849771924.

Carey, S. N. (1996). Modeling of Tephra Fallout from Explosive Eruptions, in Monitoring and mitigation of volcanic hazards, R. Scarpa and R. Tilling (Eds.), Springer, Berlin, 429-461, doi:10.1007/978-3-642-80087-0_13.

Centorrino, V., G. Bilotta, A. Cappello, G. Ganci et al. (2021). A particle swarm optimization-based heuristic to optimize the configuration of artificial barriers for the mitigation of lava flow risk, Environ. Model. Softw., 139, 105023, doi:10.1016/j.envsoft.2021.105023.

Connor, C. B., B. E. Hill, B. Winfrey, N. M. Franklin et al. (2001). Estimation of volcanic hazards from tephra fallout, Nat. Hazard. Rev., 2, 33-42, doi:10.1061/(asce)1527-6988(2001)2:1(33).

D'Amico, S., R. Azzaro, G. Tusa, T. Tuvè et al. (2025). Volcano-tectonic seismicity and related hazard: a component of the multi-hazard assessment in the highly exposed region of Mt. Etna (Italy), Ann. Geophys., 68, doi:10.4401/ag-xxxx, in press.

D'Amico, S., F. Meroni, M. L. Sousa and G. Zonno (2016). Building vulnerability and seismic risk analysis in the urban area of Mt. Etna volcano (Italy), Bull. Earthquake Eng., 14, 2031-2045, doi:10.1007/s10518-015-9804-4.

Del Negro, C., A. Cappello, G. Bilotta, G. Ganci et al. (2019). Living at the edge of an active volcano: Risk from lava flows on Mt. Etna, Geol. Soc. Am. Bull., 132, 1615-1625, doi:10.1130/B35290.1.

Famoso, D., M. Mangiameli, P. Roccaro, G. Mussumeci et al. (2012). Asbestiform fibers in the Biancavilla site of national interest (Sicily, Italy): Review of environmental data via GIS platforms, Rev. Environ. Sci. Bio Technol., 11, 417-427, doi:10.1007/s11157-012-9284-9.

Ganci, G., G. Bilotta, M. Mangiameli, G. Mussumeci et al. (2023). Roof Covering Classification Using Skysat Multispectral Imagery, AIP Conf. Proc., 2849, 1, 260002, doi:10.1063/5.0163757.

Jenkins, S., R. J. S. Spence, J. F. B. D. Fonseca, R. U. Solidum et al. (2014). Volcanic risk assessment: quantifying physical vulnerability in the built environment, J. Volcanol. Geotherm. Res., 276, 105-120, doi:10.1016/j.jvolgeores.2014.03.002.

Mangiameli, M., G. Muscato and G. Mussumeci (2013). Road network modeling in open source GIS to manage the navigation of autonomous robots, AIP Conf. Proc., 1558, 1, 1224-1227, doi:10.1063/1.4825731.

Mangiameli, M. and G. Mussumeci (2013a). Real time integration of field data into a GIS platform for the management of hydrological emergencies, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., doi:10.5194/isprsarchives-XL-5-W3-153-2013.

Mangiameli, M. and G. Mussumeci (2013b). GIS approach for preventive evaluation of roads loss of efficiency in hydrogeological emergencies, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., doi:10.5194/isprsarchives-XL-5-W3-79-2013.

Mangiameli, M. and G. Mussumeci (2015). Real time transferring of field data into a spatial DBMS for management of emergencies with a dedicated GIS platform, AIP Conf. Proc., 1648, 780012, doi:10.1063/1.4912992.

Mangiameli, M., G. Mussumeci, P. Roccaro and F. G. A. Vagliasindi (2019). Free and open-source GIS technologies for the management of woody biomass, Appl. Geomat., 11, 309-315, doi:10.1007/s12518-019-00265-8.

Mangiameli, M., G. Mussumeci and A. Cappello (2021). Forest Fire Spreading Using Free and Open-Source GIS Technologies, Geomatics, 50-64, doi:10.3390/geomatics1010005.

Mangiameli, M., A. Cappello and G. Mussumeci (2024). A new bridge management system based on spatial database and open source GIS, Environ. Syst. Decis., 44, 3, 500-513, doi:10.1007/s10669-023-09949-4.

Pessina, V., A. Garcia, F. Meroni, L. Sandri et al. (2023). From Multi-Hazard to Multi-Risk at Mount Etna: Approaches and Strategies of the PANACEA Project, in Advances in Natural Hazards and Volcanic Risks: Shaping a Sustainable Future, NATHAZ 2022, Adv. Sci. Technol. Innov., A. Malheiro, F. Fernandes, H. I. Chaminé, (Eds), Springer, Cham, doi:10.1007/978-3-031-25042-2_7.

Scaini, C., A. Folch, T. Bolić and L. Castelli (2014). A GIS-based tool to support air traffic management during explosive volcanic eruptions, Transp. Res. Part C, Emerg. Technol., 49, 19-31, doi:10.1016/j.trc.2014.09.020.

Scollo, S., C. Bonadonna, A. Garcia, L. Mereu et al. (2025). New developments in the estimation of tephra fallout hazard at Mt. Etna, in Italy, during the PANACEA project, Ann. Geophys., 68, doi:10.4401/ag-xxxx, in press.

Tilling, R. (1989). Volcanic hazards and their mitigation: progress and problems, Rev. Geophys., 27, 237-269, doi:10.1029/RG027i002p00237.

Van Westen, C. J. (2013). Remote Sensing and GIS for Natural Hazards Assessment and Disaster Risk Management, Treatise on Geomorphology, 259-298, doi:10.1016/b978-0-12-374739-6.00051-8.

Zuccaro, G. and D. De Gregorio (2019). Impact assessments in volcanic areas – The Vesuvius and Campi Flegrei case studies, Ann. Geophys., 62, 1, VO02, doi:10.4401/ag-7827.

Zuccarello, F., M. de' Michieli Vitturi, T. Esposti Ongaro, G. Ganci et al. (2025). Dynamics and hazards of pyroclastic avalanches at Etna volcano (Italy), Ann. Geophys., 68, doi:10.4401/ag-xxxx, in press.

***CORRESPONDING AUTHOR: Annalisa CAPPELLO**,
Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy
e-mail: annalisa.cappello@ingv.it