

A GIS-based approach for planning investigations in Seismic Microzonation studies of Level 3: methodology and application in the Etnean area, Italy

Attilio Porchia^{*,1,2}, Giuseppe Tortorici², Alberto D'Agostino¹, Edoardo Peronace², Gaetano Ortolano¹, Stefano Catalano^{1,2}

⁽¹⁾ University of Catania, Department of Biological, Geological and Environmental Sciences (DBGES), Section of Earth Science, Catania, Italy

⁽²⁾ Institute of Environmental Geology and Geoengineering of the Italian National Research Council, Monterotondo, Italy

Article history: received January 13, 2026; accepted April 14, 2026

Abstract

Seismic Microzonation studies of Level 3 (SM3) require a detailed and spatially homogeneous characterization of subsurface conditions, typically obtained by integrating geognostic and geophysical datasets. However, the distribution of existing investigations (boreholes (S), Multichannel Analysis of Surface Waves (MASW), Down-Hole test (DH), Horizontal to Vertical Spectral Ratio (HVSr)) is often irregular and clustered and, consequently, insufficient to represent the geological and geotechnical variability of the entire study area. This is particularly true in those geological contexts, such as volcanic settings, characterized by strong lateral and vertical heterogeneities. This paper presents a reproducible GIS-based approach for designing an optimal investigation plan for SM3 through the construction of a regular network of Control Points (CPs). The methodology is entirely implemented using open-source GIS tools and consists of: (i) generating two regular grids (size: 500 m and 1000 m), (ii) extracting and cleaning grid centroids by removing those located outside SM3 areas, (iii) integrating additional CPs where necessary, and (iv) associating each CP with pre-existing investigations within a significance-based distance threshold and within the same SM1 stable or instable zone (*stab/instab*). The method is tested in the Etnean area (Sicily, Southern Italy), where complex volcanic architectures strongly influence the local seismic response. Results indicate that the CP network allows for a rapid identification of data gaps and supports a rational design of new investigations, ensuring homogeneous spatial coverage and improving the reliability of the SM3 subsurface model. This GIS-based framework provides a transparent and fully reproducible workflow that can be applied to any SM3 municipality studies at national scale.

Keywords: Seismic Microzonation (SM); Geotechnical and Geophysical Investigations; Data-Driven Investigation Planning; GIS-Based Workflow

1. Introduction

Local site conditions play a major role in determining earthquake-induced damage scenarios, significantly influencing the level of local seismic hazard (Albarelo et al., 2015; Albarelo, 2017). The accurate knowledge of geological and geotechnical subsurface models is therefore essential for seismic hazard assessment and for both emergency and urban planning strategies (Markušić and Herak, 1999). Following the 2009 L'Aquila earthquake, Italy launched an extensive national project of Seismic Microzonation (SM) aimed at characterizing local seismic response at the municipal scale (1:10,000). Since then, thousands of SM studies have been performed in the municipalities with the highest seismic hazard, progressively building a unique nationwide geodatabase (Dolce et al., 2012; Dolce et al., 2019; Moscatelli et al., 2020). These studies are based on standardized guidelines (SM Working Group, 2008) and uniform data representation standards (Technical Commission for Seismic Microzonation, 2020), and their results are archived within the Italian Seismic Microzonation Database (DPC, 2018).

This national framework provides extensive geological, geophysical, and geotechnical datasets, which constitute the backbone for thematic products such as the Engineering-Geological Map (EG map) and the final Seismic Microzonation Map (SM map). In particular, the EG map describes the local lithostratigraphy using standardized Engineering-Geological units (EG units) that ensure consistency and comparability across municipalities (Catalano et al., 2019).

Within this consolidated national context, Level 3 Seismic Microzonation (SM3) represents the most detailed stage of analysis, requiring the integration of high-quality geognostic and geophysical investigations in order to define reliable subsurface models essential to evaluate the site-specific seismic response.

The effectiveness of SM3 studies largely depends on the density, spatial homogeneity, and representativeness of the available data (SM Working Group, 2008). However, in many areas (especially in volcanic or structurally complex settings), the distribution of pre-existing investigations is often irregular, clustered, or entirely absent across significant sectors. Such conditions can hinder the construction of a reliable geological-geotechnical subsoil model, with negative implications for the overall quality of the study.

The Etnean area (Sicily, Southern Italy) represents a paradigmatic case. In fact, the superposition of lava flows with highly variable geometries, the presence of extremely heterogeneous volcanic and volcanoclastic deposits, and the transition to deeper sedimentary substrata create sharp lateral and vertical discontinuities that profoundly influence the local seismic response. In such contexts, the absence of a systematic and spatially homogeneous distribution of investigations can hinder the definition of a representative subsurface model for SM3.

Within this framework, the design of an investigation campaign for Level 3 studies must be founded on two fundamental principles:

- (i) technical-scientific efficiency, which focuses on concentrating new investigations in data-poor areas or where uncertainties in the geological-geotechnical subsoil model are greatest;
- (ii) economic efficiency, aimed at avoiding duplicated or redundant surveys and limiting investigation costs in well-characterized sectors.

In this regard, Albarelo and Moscatelli (2021) emphasize that Seismic Microzonation, due to its extensive nature, requires cost-effective methodologies capable of providing reliable outcomes with a sustainable use of resources. The tool presented in this study fits precisely within this perspective, offering a GIS-based approach that supports a more efficient, rational, and economically consistent planning of SM3 investigations.

The method integrates geometric and thematic GIS analyses to: (i) generate a structured CP network, (ii) associate each CP with pre-existing investigations through objective spatial criteria, and (iii) identify under-sampled or data-scarce sectors requiring new surveys.

Developed and validated in 23 municipalities involved in the ETNA FAC+MS project (ETNA FAC+MS Working Group, 2022), the proposed approach provides a fully replicable framework that is particularly effective in optimizing the planning of SM3 investigations.

This tool also fits into the broader operational toolset framework recently developed to simplify, automate, and standardize the workflow of Seismic Microzonation studies. Among these, the tool introduced by D'Agostino et al. (2025) for the construction and spatialization of stratigraphic columns proposes an automated method that facilitates the generation of Stratigraphically Homogeneous Zones (SHZ) maps.

2. Geological context

The methodology was developed within the SM3 study area of the Municipality of Acireale, located on the eastern flank of Mt. Etna (Fig. 1), in the frame of the ETNA FAC+MS project (ETNA FAC+MS Working Group, 2022).

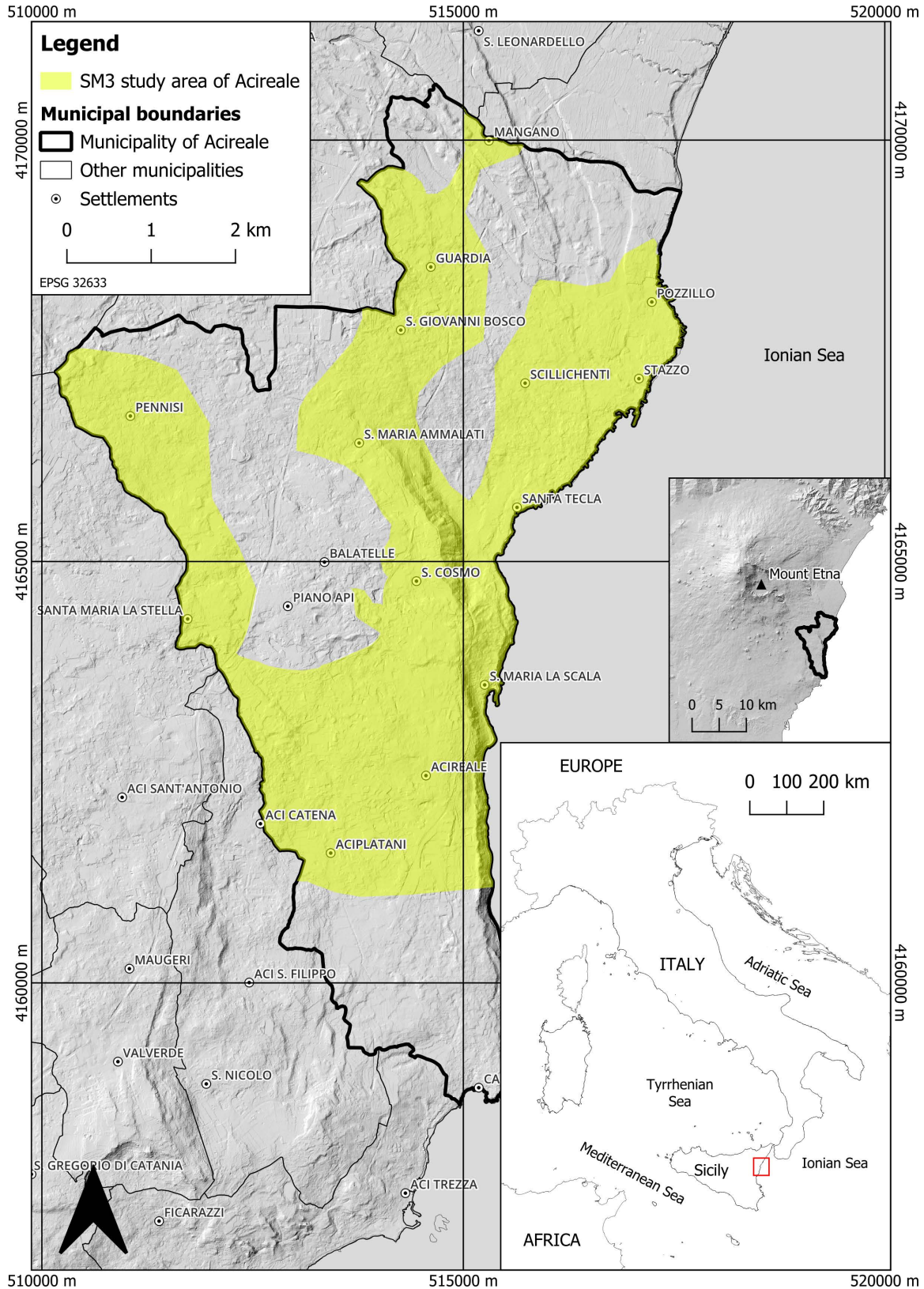


Figure 1. Location of the Acireale SM3 study area in the frame of Sicily Region and of Mt. Etna edifice (see insets).

The Mt. Etna edifice results from the growth of different volcanic edifices during the last 500 ky, covering a deep and highly complex sedimentary basement (Branca et al., 2011). The current stratovolcano is the result of the volcanic activity of the last 60 ky whose products conceal a deeply incised paleo-topography modelled on the sedimentary substratum and on the remnants of ancient volcanic edifices (Branca and Catalano, 2000). In addition, epiclastic horizons are interleaved within the Etnean volcanostratigraphic succession (Fig. 2a) (De Beni et al., 2011), marking the main unconformities modelled during periods of erosion and sedimentation, which are strictly related to the main Late Quaternary deglaciation processes. Similarly, the terraced marine deposits that outcrop in the lower south-eastern flank of the volcano have been associated to the main interglacial peaks.

As a consequence, the Acireale study area is characterized by marked geological complexity, arising from the superposition of several volcanic units, characterized by strong lateral and vertical heterogeneity due to the variability of their lithofacies. Each lava flow, in fact, is made of a portion of scoriae, which is similar to a sandy deposit with centimeter to decimeter-sized lava blocks, and a portion of massive lavas (Fig. 2a). Furthermore, continental sandy and gravelly deposits (alluvial sediments, alluvial fan, detritus, etc.) locally separate the volcanic units (see yellow and green levels of the cross-section in Fig. 2b). These poorly consolidated deposits, together with the scoriaceous and epiclastic horizons, play a fundamental role in defining impedance contrasts and S-wave velocity inversions. The inversions occur both at the contact between different Engineering-Geological units and within the same unit, resulting in a highly heterogeneous subsurface structure documented by the Engineering-Geological cross-sections developed during SM3 studies (see Fig. 2b for example).

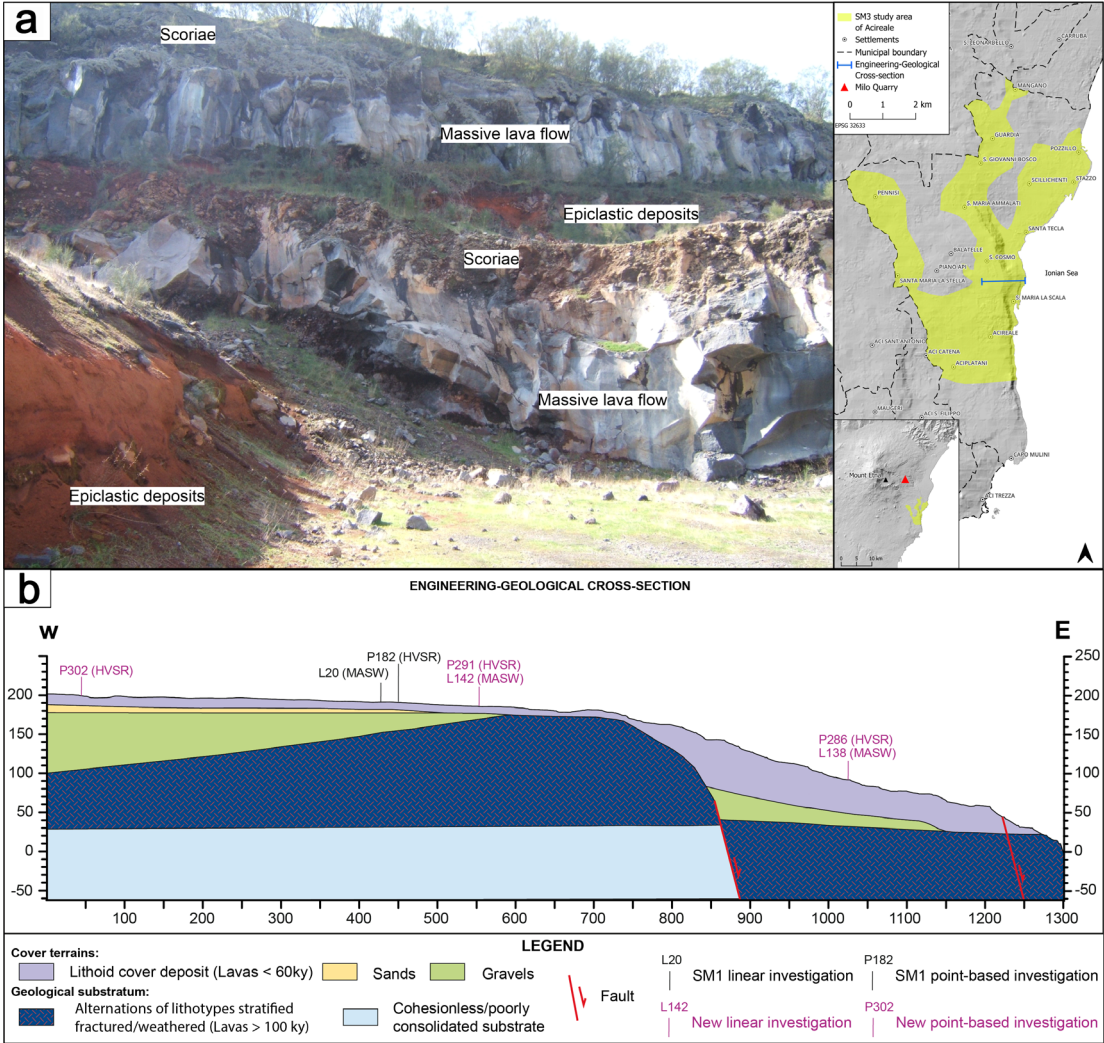


Figure 2. (a) Alternation of epiclastic deposits and scoriaceous and massive litofacies of the lava flows exposed in a quarry located inside Milo municipality (see inset for location). (b) Engineering-Geological cross-section provided in the Acireale SM3 studies (see inset for location).

Such geological configuration produces a subsurface framework characterized by sudden lateral and vertical variations, far from the simplified stratigraphic models assumed in standard local seismic response analyses. Consequently, constructing a reliable geological-geotechnical subsoil model requires an adequate, homogeneous, and geologically representative distribution of experimental data. This condition is rarely satisfied by pre-existing investigations, which are often clustered along infrastructure corridors and are absent in large portions of the territory.

These characteristics require the adoption of a GIS-based procedure capable of designing a regular network of measurement points and ensuring adequate coverage for Level 3 of Seismic Microzonation studies.

3. Method

3.1 Required datasets and structure of the GIS-based workflow

The execution of the GIS-based tool requires the availability of a minimal set of input datasets, structured in accordance with the national standards for Seismic Microzonation studies (Technical Commission for Seismic Microzonation, 2020). These datasets are loaded into the QGIS (QGIS Development Team, 2024). Table of Contents (TOC) through the MZSTools plugin (Cosentino et al., 2024; 2025), which enables the import of SM1 datasets into the GIS environment while ensuring a consistent field structure, a uniform coordinate reference system, and standardized naming conventions. These conditions are essential for the automated execution of the tool's modules.

The main input data includes the SM3 study area, represented by a municipal or sub-municipal polygon defining the spatial extent of the analysis. Additional required datasets are those derived from SM1, in particular the stable (*stab*/MOPS – Italian acronym for homogeneous microzones in seismic perspective) and unstable (*instab*) Level 1 zones, which provide the zonal codes (*Tipo_z* and *Tipo_i*, respectively) used to ensure geological consistency between Control Points and pre-existing investigations. The workflow also requires the layers of existing point-based investigations (*Ind_pu*, e.g., Horizontal to Vertical Spectral Ratio (HVSr), Down-Hole test (DH), boreholes (S)) and linear investigations (*Ind_ln*, e.g., Multichannel Analysis of Surface Waves (MASW), Refraction Microtremor (ReMi), Electrical Resistivity Tomography (ERT)).

In addition to the geometric layers, MZSTools supplies the parameter tables for point and linear investigations, which include the field indicating the measurement reliability (*attend_mis*). These tables are used by the tool to assign a synthetic quality index to each investigation, which is subsequently employed in selecting the most reliable data during the association phase with the Control Points.

Before execution, the tool performs an automatic pre-processing phase, verifying the presence of the required layers, the validity of geometries, the consistency of the coordinates reference system (EPSG:32633), the availability of mandatory fields, and the absence of “null” values in key attributes. Only after this preliminary check does the system enable the operational sequence.

Based on this set of input data, the tool is organized into independent modules, which can be executed individually according to a defined logical sequence. In general terms, the modules are responsible for:

- (i) constructing complete investigation layers by integrating geometry, parameters, and information on the corresponding zone (*stab* or *instab*);
- (ii) generating and refining the network of CPs;
- (iii) associating existing investigations to each CPs according to spatial and geological consistency criteria;
- (iv) producing the final CP-investigation matrix, which can be used for planning Level 3 investigation campaigns.

3.2 Conceptual framework for the generation of control points

The construction of the Control Point (CP) network represents the core element of the entire workflow and provides the reference structure used to assess both the informational coverage of existing investigations and the requirements for the implementation of the Level 3 investigation campaign. The adopted approach is based on the generation of a regular grid of points distributed across the study area, designed to ensure a homogeneous sampling of the different geological contexts and to define a limited but representative set of locations through which the quality and spatial distribution of available experimental data can be evaluated.

The framework defines three types of Control Points, each addressing specific objectives related to SM3 investigation planning:

- Type 1 CPs, derived from a 1000-m regular grid (default value), represent the reference locations for geotechnical and geophysical investigations that directly contribute to the reconstruction and parametrization of the geological-geotechnical subsoil model, such as boreholes (S), Down-Hole (DH) tests performed in properly conditioned boreholes for the measurement of shear-wave velocities, and MASW profiles.
- Type 2 CPs, derived from a 500-m regular grid (default value), are dedicated to evaluating the spatial distribution of HVSR measurements that, because of their intrinsic simplicity, rapid acquisition, and low cost, are expected to be available at a higher spatial density than traditional geotechnical or geophysical investigations. The finer grid, therefore, allows verification of the actual coverage of HVSR measurements across the study area and, at the same time, the identification of sectors where additional recordings would be appropriate in order to better capture lateral variations in subsurface conditions, impedance contrasts, and resonance frequencies.
- Type 3 CPs, generated in a targeted manner, are introduced exclusively within stable SM1 zones that lack Type 1 or Type 2 CPs. Their purpose is to ensure the minimum representation of each geological context within the CP network, preventing the occurrence of entire sectors of the study area without sampling points.

The default grid spacing of 1000 m (Type 1) and 500 m (Type 2) were selected as reference values to ensure a balance between the territorial representativeness and the feasibility at the municipal scale typical of SM3 studies. However, these values are not fixed constraints. The cell size of both grids can be modified by the user according to two main factors: (i) the spatial extent of the SM3 study area, and (ii) the geological complexity of the investigated context. Smaller study areas generally require a finer grid spacing to maintain an adequate number of Control Points, while geologically complex settings characterized by strong lateral and vertical heterogeneities may require reduced spacing for both CP families in order to better capture the spatial variability. Conversely, in large and relatively homogeneous areas, a coarser spacing may be sufficient. The selection of grid resolution should therefore result from a balanced evaluation of study-area size and geological complexity, ensuring both technical effectiveness and economic sustainability of the investigation planning.

The generation of CPs is based on the superimposition of regular grids onto the SM3 study area and on the subsequent selection of only those points falling within its boundary. It is noteworthy that in the default configuration, CPs located within unstable SM1 zones (*instab*) are excluded from the network, as such sectors generally require dedicated investigation planning and cannot be adequately addressed through the regular sampling approach adopted for the baseline characterization of stable areas. However, the tool also allows to include these sectors if required.

3.3 Tool architecture and module description

The tool is organized into four operational modules that must be executed in sequence, as each module produces the layers required by the subsequent ones:

- Module 1 – Construction of complete investigation layers;
- Module 2 – Construction and refinement of the Control Point network;
- Module 3 – Assignment of investigations to Control Points;
- Module 4 – Synthesis and production of final outputs.

Figure 3 provides a conceptual overview of the GIS-based workflow and its modular structure. Detailed descriptions of each module are provided in the following sections.

Execution takes place within QGIS (QGIS Development Team, 2024) through the Python console, and each module adds to the TOC the intermediate layers needed for the following processing steps.

3.3.1 Module 1 – Construction of complete investigation layers

The first module aims to reconstruct the Level 1 investigation layers, integrating geometric information, typological attributes, measurement reliability, and the spatial classification with respect to the stable and unstable SM1 zones within a unified and standardized structure. This process produces two “complete” investigation layers,

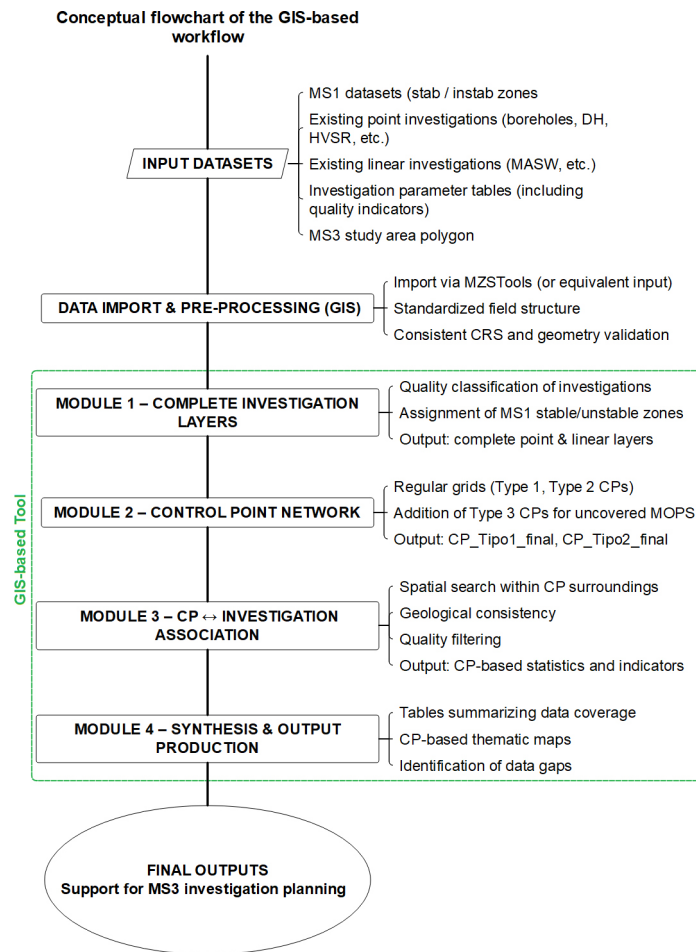


Figure 3. Conceptual flowchart of the GIS-based modular workflow developed to support the planning of SM3 investigation campaigns.

one point-based and one linear, which constitute the informational basis for subsequent analyses and for the association of investigations to the CPs. The main inputs, configurable parameters, and outputs of the module are summarized in Appendix A (Table A1).

The module operates on datasets imported into QGIS (QGIS Development Team, 2024) through MZSTools (Cosentino et al., 2024; 2025), including point and linear investigation sites, their associated investigation tables, parameter tables, and the polygons representing stable (MOPS) and unstable SM1 zones. For point investigations, each investigation record is linked to its corresponding site through a unique identifier, ensuring coherence between spatial geometry and descriptive attributes.

Measurement reliability is not computed by the module itself but is directly retrieved from the parameter tables, where the reliability field (*attend_mis*) is already defined according to the SM standards. The module extracts this field and translates it into a standardized numerical quality index (1 = High, 2 = Medium, 3 = Low), accompanied by a descriptive label. This procedure ensures consistency with the original SM1 database and preserves the traceability of quality assessments. If revisions to the reliability classification are required, the operator must modify the *attend_mis* value in the parameter tables prior to executing Module 1.

An analogous procedure is applied to linear investigations. In both cases, the resulting features are subsequently enriched with zonation attributes through spatial association with stable and unstable SM1 polygons, enabling each investigation to inherit its corresponding geological context.

The module, therefore, produces two complete investigation layers that combine geometry, typology, standardized quality indicators, and zonation attributes (*Tipo_z* for stable zone and *Tipo_i* for unstable zone) within a coherent database structure. These layers constitute the direct input for Module 3, in which investigations are systematically associated with the Control Points.

3.3.2 Module 2 – Construction and refinement of the Control Point network

Module 2 is dedicated to the construction and refinement of the Control Point (CP) network, including Type 1, Type 2, and Type 3 CPs, within the SM3 study area. The main inputs, configurable parameters and outputs of the module are summarized in Appendix A (Table A2). Its objective is to generate two final CP layers based on regular grids with different spatial resolutions (1000 m and 500 m as default values, user-modifiable), ensuring a systematic territorial coverage while preserving a minimum representation of the geological contexts defined by the SM1 zonation.

The module operates on three main spatial datasets: the SM3 study-area polygon, the stable SM1 zones (MOPS), and the unstable SM1 zones. Starting from the spatial extent of the SM3 area, two regular grids are generated and their centroids are extracted to produce the initial sets of Type 1 and Type 2 CPs. Only points falling within the study area are retained.

Depending on the selected configuration, CPs located within unstable SM1 zones may be either excluded (default setting) or retained in the network. This flexibility allows the user to decide whether unstable zones are treated separately through ad hoc investigation planning or included within the same CP-based assessment procedure.

Each CP is then spatially associated with the SM1 zonation, inheriting the corresponding zone code (stable or unstable). A dedicated attribute distinguishes between CPs derived from the coarser grid (Type 1) and those derived from the finer grid (Type 2).

To guarantee that each SM1 zone is represented in the network, the module verifies coverage separately for the two grid resolutions. Where a zonation polygon does not contain any CP of the corresponding type, an additional CP (Type 3) is automatically generated within that polygon to ensure representativeness.

The location of Type 3 CPs is not defined as the geometric centroid of the polygon, since centroids may fall outside irregular or concave geometries. Instead, the module generates an internal point using a point-on-surface algorithm, which ensures that the Control Point is always located within the boundaries of the corresponding zonation polygon. This choice avoids geometric inconsistencies and guarantees that each MOPS (or unstable zone, if included) is represented by at least one CP physically contained within its spatial extent. These supplementary CPs are generated separately for each grid resolution and are merged with the corresponding grid-based CPs, producing the final Type 1 and Type 2 Control Point layers used in the subsequent association phase.

The resulting Control Point network constitutes the structural framework for the spatial evaluation of existing investigations and forms the direct input for Module 3.

3.3.3 Module 3 – Assignment of investigations to Control Points

Module 3 is dedicated to the assignment of existing investigations to the Control Points, distinguishing between Type 1 and Type 2 CPs. The main inputs, configurable parameters, and outputs of the module are summarized in Appendix A (Table A3). The procedure performs a distance-based spatial matching between CPs and both point and linear investigations, combined with zone stability, geological consistency with the corresponding MOPS, and data quality. The output consists of two synthetic layers (for Type 1 CPs and for Type 2 CPs, respectively) in which each point is associated with a summary of the investigations found around it and with a synthetic quality indicator as described below.

As input data, the module uses the final CP layers generated by Module 2 and the “complete” investigation layers produced by Module 1, which already integrate geometry, investigation typology, zonal classification, and standardized quality information. For each CP, a circular search neighborhood is defined, with radius derived from the grid spacing adopted for the corresponding CP family. By default, the radius is computed as half of the grid-cell diagonal, although alternative settings can be adopted. Candidate investigations are retrieved through spatial indexing and subsequently filtered by applying an explicit metric condition: the distance between the CP and the investigation geometry must be \leq to the search radius. The same criterion is applied to both point investigations (distance from CP to point geometry) and linear investigations (minimum distance from CP to line geometry).

After the spatial proximity check, additional constraints are applied. Investigations located inside unstable SM1 zones may be excluded or included depending on the selected configuration. A quality filter can also be activated, retaining only investigations with a numerical quality class at least equal to the user-defined threshold.

A geological-consistency criterion is then enforced: an investigation is associated with a CP only if both fall within the same SM1 zone. This means that the zone code inherited by the CP (assigned in Module 2) must correspond to the zone code attributed to the investigation (assigned in Module 1). This rule ensures that the association is not based solely on spatial proximity but also reflects coherence with the geological context defined by the SM1 zoning framework.

The module allows the user to select which investigation types are considered in the analysis and to define which of the active types are associated with each CP family (Type 1 or Type 2), according to the standardized typological framework reported in Table 1 (Technical Commission for Seismic Microzonation, 2020). By default, Type 1 CPs are associated with boreholes (S), Down-Hole tests (DH), and Multichannel Analysis of Surface Waves (MASW), whereas Type 2 CPs are associated with Horizontal-to-Vertical Spectral Ratio measurements (HVSR). For each CP, the accepted investigations are counted by type, and their identifiers are stored.

A synthetic CP-level quality indicator is finally derived from the quality classes of the associated investigations, inherited from SM1 studies, using a conservative aggregation criterion whereby the CP quality corresponds to the highest numerical value (i.e., the lowest reliability) among the accepted investigations. This approach ensures that the CP-level quality reflects the weakest element within the dataset supporting that Control Point.

The module produces two in-memory output layers (CP_Associate_Type1 and CP_Associate_Type2), in which each feature retains the geometry of the original Control Point together with its SM1 zone attributes and CP family identifier. These layers are enriched with the counts of associated investigations by type, the list of investigation identifiers linked to each CP, and the synthetic CP-level quality indicator. The resulting datasets, automatically added to the QGIS project, constitute the structured informational basis for the evaluation of investigation coverage and for the subsequent planning of SM3 investigation campaigns.

Table 1. List of point and linear investigation types included in the Graphic and data archiving standards of the Italian Seismic Microzonation v. 4.2 (ref. Tab. 2.1.9.2 – Technical Commission for Seismic Microzonation, 2020).

Type of investigation	Acronym
Point investigations	
Soil sample analysis	SM
Oedometer test	ED
Direct shear test	TD
Consolidated drained triaxial test	CD
Consolidated undrained triaxial test	CU
Unconsolidated undrained triaxial test	UU
Free lateral expansion test	ELL
Resonant column test	CR
Bender element test	BE
Cyclic simple shear test	TSC
Cyclic torsional shear test	TTC
Cyclic triaxial test	TC

Type of investigation	Acronym
Cone Penetration Test	CPT
Electric Cone Penetration Test	CPTE
Piezocone Penetration Test	CPTU
Standard Penetration Test	SPT
Marchetti Dilatometer Test (DMT)	DMT
Vane shear test (VST)	VT
Super heavy dynamic penetration test	DS
Heavy dynamic penetration test	DP
Medium dynamic penetration test	DN
Light dynamic penetration test	DL
Pressuremeter test (PMT)	PP
Plate load test	PLT
Continuous coring borehole	S
Continuous coring borehole reaching bedrock	SS
Rotary drilling borehole	SD
Rotary drilling borehole reaching bedrock	SDS
Sampling borehole	SC
Piezometer installation borehole	SP
Inclinometer borehole	SI
Hydrocarbon exploration well	PI
Exploratory trench / test pit	T
Geomechanical survey	RGM
Paleoseismological trench	TP
Geomechanical station	GEO
Water well	PA

Type of investigation	Acronym
Piezometric test	SP
Lefranc permeability test	LF
Slug test	ST
Pumping test	PE
Seismic Dilatometer Test	SDMT
Seismic Cone Penetration Test	SCPT
Down-hole test	DH
Cross-hole test	CH
Up-hole test	UH
Horizontal-to-Vertical Spectral Ratio	HVSR
Accelerometric recordings	ACC
Extended Spatial Auto Correlation / Spatial Auto Correlation (ESAC / SPAC)	ESAC_SPAC
Gravimetric station	GM
Linear investigations	
Vertical Electrical Sounding (VES)	SEV
Horizontal electrical sounding	SEO
Resistivity profile	PR
Electrical Resistivity Tomography	ERT
Seismic reflection	SL
Seismic refraction	SR
Ground Penetrating Radar (GPR)	RAD
Multichannel Analysis of Surface Waves	MASW
Spectral Analysis of Surface Waves	SASW
Refraction Microtremor (ReMi)	REMI
Frequency-Time Analysis	FTAN

3.3.4 Module 4 – Synthesis and production of final outputs

Module 4 provides the final synthesis of the results obtained in the previous modules and produces the output layers used for the interpretation and the planning of Level 3 investigation campaigns. The main inputs, configurable parameters, and outputs of the module are summarized in Appendix A (Table A4). Unlike the analytical modules, Module 4 is primarily devoted to the aggregation, visualization, and reporting of the information associated with the Control Points.

The module operates on the Control Point association layers produced by Module 3 and aggregates their attributes at the scale of the SM1 zones. For each zone, the total number of associated investigations and the distribution of investigation types are computed by combining the identifiers linked to the Control Points located within that zone. The resulting statistics are exported as CSV tables and stored in polygon layers representing the SM1 zones, which summarize investigation coverage at the zonal scale.

In parallel, the module generates a set of thematic point layers derived from the Control Points, one for each investigation type considered in the analysis. These layers retain the original Control Point geometry and attributes, including the SM1 zone code and the synthetic CP-level quality indicator defined in Module 3, and are automatically styled to represent the density of investigations associated with each CP. The synthetic quality indicator remains defined exclusively at the Control Point level and is not further aggregated at the zonal scale.

All output layers and tables are automatically added to the QGIS project, providing a structured environment for visual inspection of investigation coverage, identification of data-poor sectors, and support for the informed planning of SM3 investigation campaigns.

4. Application to the Acireale SM3 study area

The application of the workflow to the SM3 study area of the Municipality of Acireale was limited to the Level-1 stable zones (MOPS – Italian acronym for homogeneous microzones in seismic perspective), since the unstable zones located inside the study area were the object of an independent investigation campaign aimed at the characterization of Active and Capable Faults (FAC). For this reason, the option *include_instab = False* was adopted throughout the procedure, and the Control Point (CP) network was generated only within the MOPS included in the SM3 study area.

Table 2 reports the total number of points and linear investigations acquired in the municipality of Acireale as part of the Level-1 Seismic Microzonation studies.

Table 2. Point and linear investigations from the Level-1 study in the Municipality of Acireale, grouped by type (see Table 1 for abbreviation details).

Total linear investigations	ERT	MASW	REMI	SR			
102	5	45	13	39			
Total point investigations	DH	HVSR	S	SC	SM	TD	
219	18	95	87	4	8	7	

Focusing on the point investigations most relevant for reconstructing the subsurface model (geognostic boreholes, Down-Hole tests, MASW profile, and HVSR measurements), Fig. 4 shows their distribution within the SM3 area, highlighting their relationship with the Level-1 stable and unstable zones. These investigations display a clustered, spatially irregular, and heterogeneous distribution, with a lot of data falling within unstable areas, which were excluded a priori from the analysis, and large portions of the study area lacking in useful information. This required a systematic assessment of data coverage in order to properly plan the new SM3 investigation campaign.

In this context, we applied the tool described in the previous sections. Type-1 CPs (1000 m grid spacing) were associated with the geotechnical and geophysical investigations most directly relevant for reconstructing the

subsurface model and for characterizing the dynamic properties of the materials (namely boreholes, Down-Hole tests and MASW profiles) to identify data-poor sectors and improve the control on key stratigraphic parameters (e.g., layer thicknesses) and dynamic parameters (e.g., soil S-wave velocities). Type-2 CPs (500 m grid spacing) were instead associated with HVSR measurements, in order to evaluate their areal coverage and to detect potential information gaps, thereby supporting the interpretation of lateral variations in stratigraphic conditions and in local seismic impedance contrasts.

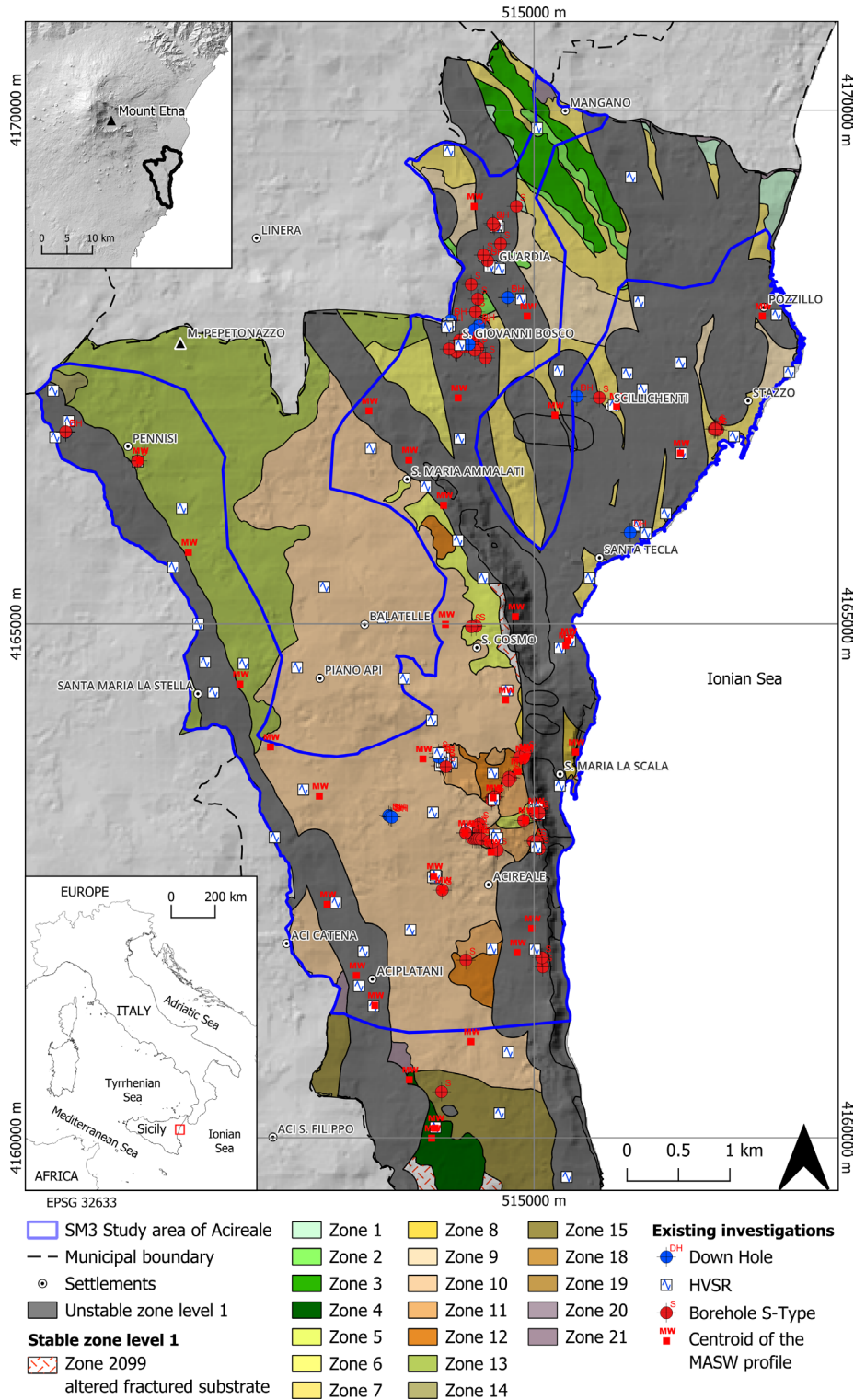


Figure 4. Distribution of Level-1 SM investigations in relation to Level-1 stable zones susceptible to local seismic amplification (Zones 1–21, corresponding to the mapped MOPS units) and unstable zones.

Figures 5a–d illustrate the distribution of investigations associated with the Control Points (CPs) within the defined search radius. In each map, CPs are colored according to the number of investigations falling within the search radius, thus providing a spatial overview of data availability. Specifically, Fig. 5a shows the distribution of HVSR measurements associated with Type-2 CPs, whereas Figs. 5b–d refer to Type-1 CPs and display the number of boreholes, MASW profiles, and Down-Hole tests, respectively, falling within the search radius of each CP. The maps highlight that the available investigations are concentrated in limited sectors of the study area, while large portions

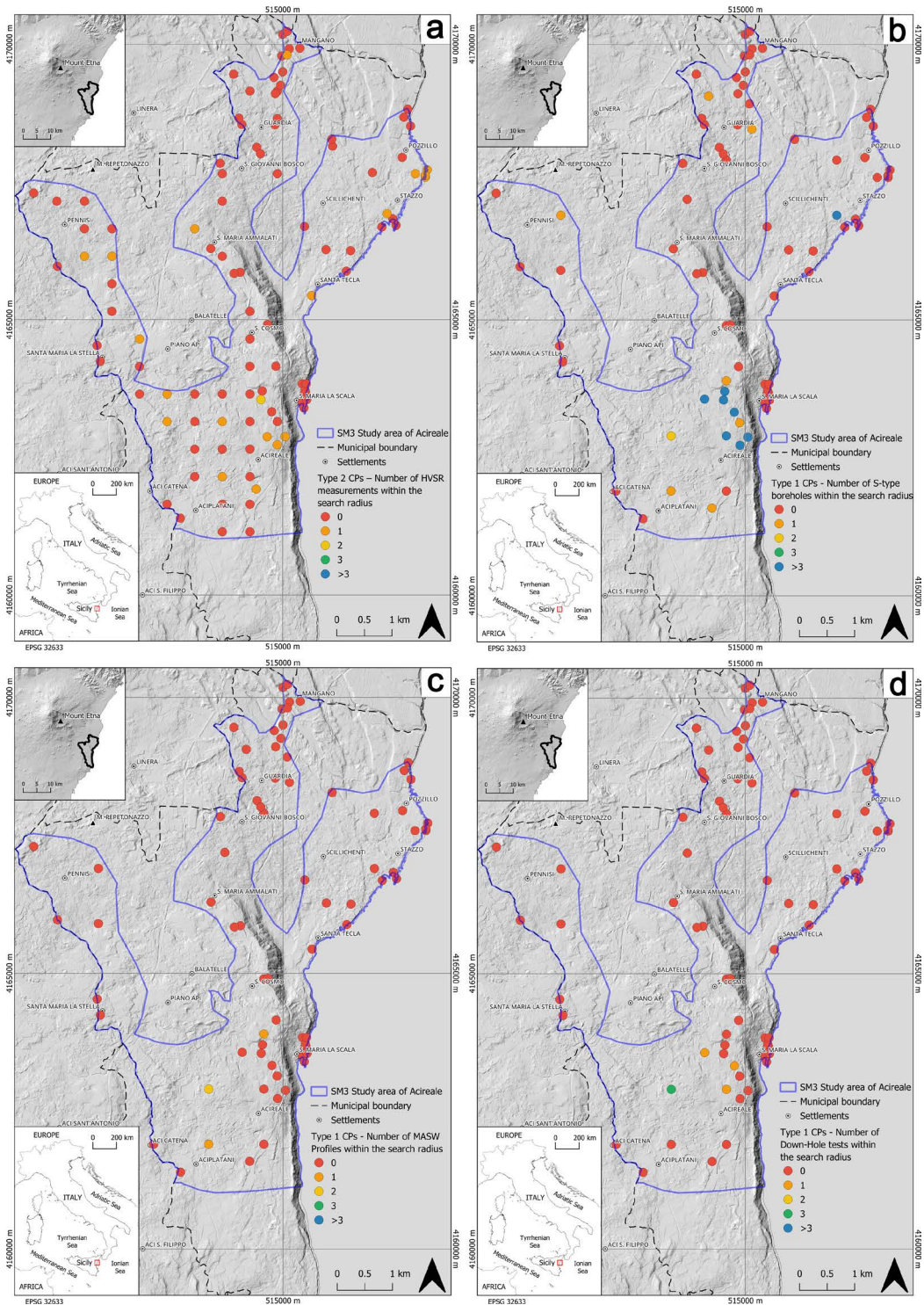


Figure 5. Type-2 Control Points classified by the number of HVSR measurements located within their surroundings (a). Type-1 Control Points classified by the number of boreholes (S-type) (b), MASW profile (c) and Down-Hole tests (d) located within their surroundings in the Acireale SM3 study area.

of the territory remain poorly constrained by subsurface data suitable for directly supporting the reconstruction of the geological-geotechnical model.

Figures 6a–d (MOPS Report) show the aggregated synthesis of results at the scale of the Level-1 stable zones. Each map refers to one of the investigation types considered in the analysis, namely HVSR measurements (a), S-type boreholes (b), MASW profiles (c), and Down-Hole tests (d). For each investigation type, the figures report the total number of investigations associated with each MOPS type.

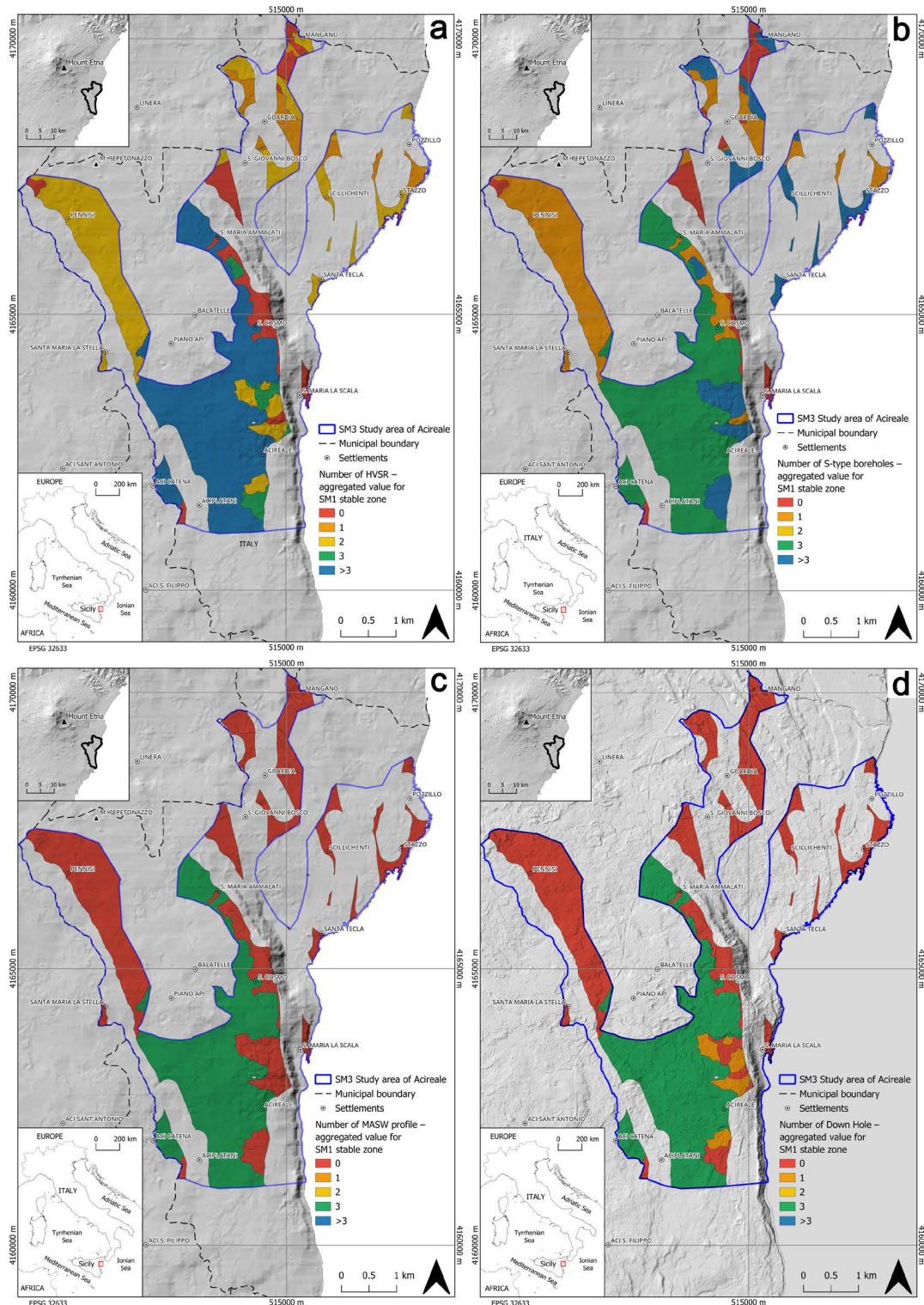


Figure 6. Aggregated count of HVSR measurements (a), boreholes (S-type) (b), MASW profile (c) and Down-Hole tests (d) for each MOPS typology, derived from the CP-based analysis in the Acireale SM3 study area.

These values must therefore be interpreted as aggregated indicators of information coverage referring to the MOPS typology rather than a geometric count of investigations contained within individual polygons. This representation is preparatory for the homogeneous comparison between the different types of stable zones (MOPS) in the study area and, by means of the adopted color scale, clearly highlights the MOPS types that are well supported by existing data and those that require a targeted integration during the SM3 investigation campaign.

As a summary, Table 3 (attribute table of the aggregated layer) shows that, among the 18 MOPS types identified in the study area, only 8 are supported by investigations, whereas the remaining 10 are completely devoid of such data. As an example, only 7 MOPS types are supported by boreholes (column nS), while the remaining 11 lack this type of information. Similar considerations can be inferred for the other investigation types included in the analysis. The last column (*Investigation IDs*) lists the identifiers of the investigations associated with each MOPS type, corresponding to the original IDs defined in the SM1 database in accordance with the national Graphic and Data Archiving Standards for Seismic Microzonation (Technical Commission for Seismic Microzonation, 2020), thus preserving traceability to the source dataset.

Table 3. Attribute table of the MOPS Report layer. For each MOPS typology (*Tipo_z*), the table lists the aggregated number of associated investigations (e.g., DH, HVSR, MASW, boreholes (S-type), together with the corresponding investigation IDs derived from the CP-based analysis.

Tipo_z	nDH	nHVSR	nMASW	nS	nTOT	Investigation IDs
2001	0	0	0	0	0	
2002	0	1	0	0	1	087004P156HVSR246
2003	0	0	0	0	0	
2005	0	0	0	1	1	087004P20S143
2006	0	0	0	0	0	
2007	0	2	0	5	7	087004P162HVSR252;087004P168HVSR258;087004P82S135;087004P83S136;087004P84S137;087004P86S139;087004P87S140
2008	0	0	0	0	0	
2009	0	1	0	1	2	087004P161HVSR251;087004P94S150
2010	3	4	0	3	10	087004P123DH204;087004P123S203;087004P124DH206;087004P125DH208;087004P150S240;087004P169HVSR259;087004P186HVSR276;087004P188HVSR278;087004P193HVSR283;087004P71S110
2011	1	2	0	5	18	087004P132S215;087004P17S18;087004P189HVSR279;087004P195HVSR285;087004P204DH294;087004P205S295;087004P31S32;087004P32S33;087004P33S34;087004P34S35;087004P35S36;087004P36S37;087004P37S38;087004P39S40;087004P55S54;087004P57S58;087004P61S238;087004P64S69
2012	0	3	0	7	10	087004P11S12;087004P131S214;087004P185HVSR275;087004P18S19;087004P191HVSR281;087004P19S20;087004P56S55;087004P73S112;087004P74S113;087004P76HVSR115

Tipo_z	nDH	nHVSr	nMASW	nS	nTOT	Investigation IDs
2013	0	2	0	1	3	087004P173HVSR263;087004P178HVSR268; 087004P54S53
2014	0	0	0	0	0	
2018	0	0	0	0	0	
2019	0	0	0	0	0	
2020	0	0	0	0	0	
2021	0	0	0	0	0	
2099	0	0	0	0	0	

The resulting CP-based maps and synthesis layers allow for the rapid identification of information gaps within the study area that should be filled either by retrieving additional existing data, where available, or by conducting new targeted investigations. In the case history of Acireale, the budget made available to achieve the SM3 studies allowed to add n.69 HVSR measurements and n. 39 MASW profiles in order to obtain a homogeneous distribution of geophysical data along the study area (Figs. 7a-b).

In conclusion, the application of the methodology to the Municipality of Acireale demonstrates the effectiveness of the workflow in synthesizing the distribution of existing investigations and in supporting a targeted, coherent, and geologically representative SM3 investigation plan.

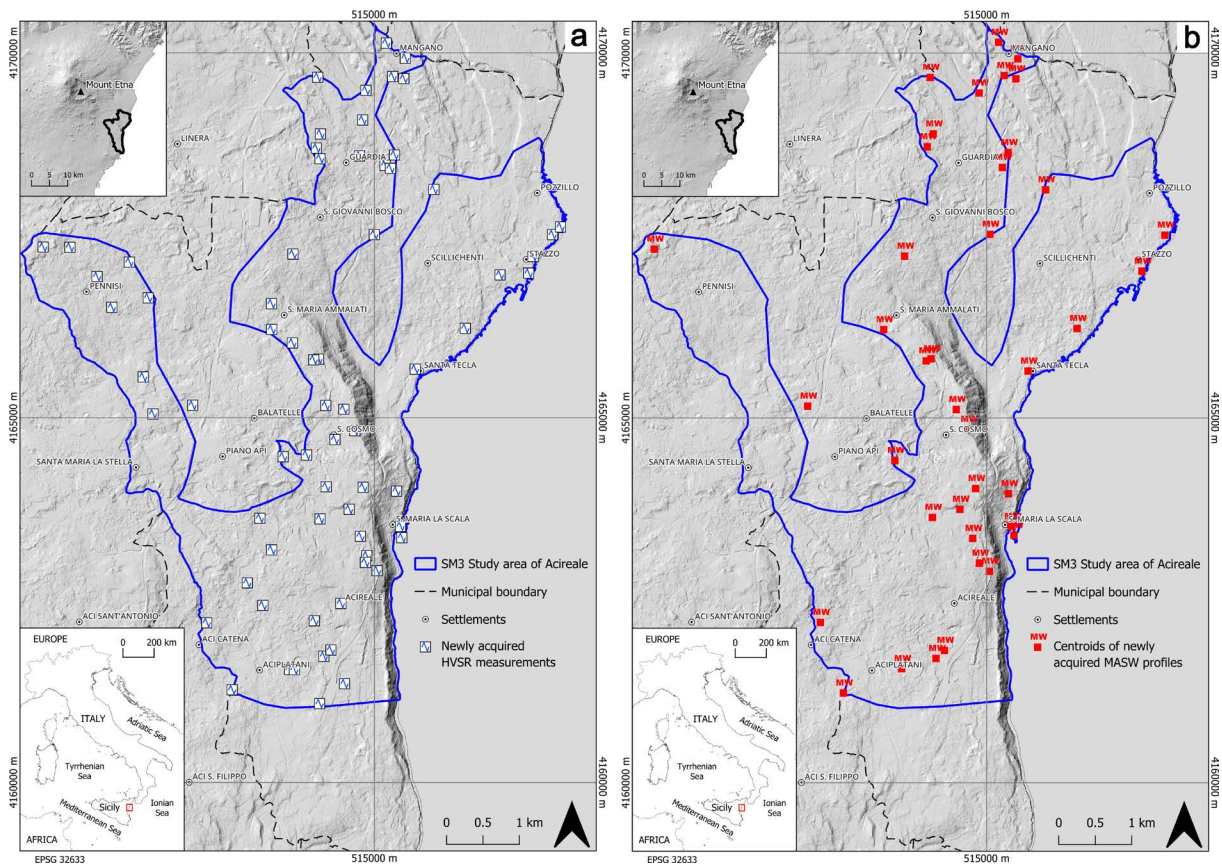


Figure 7. Distribution of newly acquired geophysical investigations performed during the SM3 campaign: (a) HVSR measurements and (b) MASW profiles.

5. Conclusions

The GIS-based approach presented in this work provides a structured, transparent, and fully reproducible tool useful to support the planning of Level-3 investigations within the framework of Seismic Microzonation (SM3). By integrating geometric, geological, and quality-related information from existing investigations, archived in the SM1 database, into a single framework, the tool allows users to objectively identify those areas that are genuinely lacking in data and to plan new targeted investigation campaigns. This approach aligns with the principles of technical-scientific efficiency and economic efficiency that underpin Seismic Microzonation studies, promoting an informed design process based on the spatial distribution representativeness and coherence with local geological contexts of the available measurements, rather than exclusively on their quantity.

A key aspect of the workflow is that the analysis does not simply count existing investigations but evaluates their spatial arrangement in relation to the potential variability of the geological setting. In this way, the subsurface geological-geotechnical model, based on the interpretation of the subsoil data, can account for possible lateral variations in stratigraphy, which are crucial for a correct assessment of local seismic response. The grid sizes adopted for the Control Point (CP) network (1000 m and 500 m), used as default values, proved appropriate for the Acireale case study; however, these parameters should be suitably adapted to the scale and geological complexity of each municipality, since smaller areas or those with pronounced stratigraphic heterogeneity may require finer grids.

In its current implementation, the workflow relies on the MZSTools plugin (Cosentino et al., 2024; 2025) for the standardized import of Level-1 data, ensuring consistency in layer structure, field nomenclature, and reference system in accordance with national guidelines. Nevertheless, the required layers can be manually produced following the expected structure of the tool without the use of MZSTools.

The Control-Point-based approach ensures methodological homogeneity across different studies and significantly reduces errors associated with manual selection, verification, and classification of existing investigations. The ability to rapidly synthesize the available information – both at the point scale and in aggregated form across MOPS types – also facilitates validation and quality-control activities carried out by scientific coordinators and by regional reviewers, improving transparency and verifiability of the entire process.

In a future perspective, the next step of the project will consist in integrating the four modules into a single QGIS plugin, thereby further simplifying its use and promoting broader adoption by professionals and public administrations.

Data availability statement. The Python source codes implementing the GIS-based workflow presented in this study are openly available through a Zenodo repository (Porchia et al., 2026). The repository provides the complete set of four modular scripts and related documentation required to reproduce the analyses described in this paper, doi:10.5281/zenodo.18214590.

Acknowledgements. We thank Annals of Geophysics Editor Dr. Simona Pierdominici and the two anonymous reviewers for constructive review that significantly improved the manuscript.

References

- Albarelo, D. (2017). Extensive application of seismic microzoning in Italy: Methodological approaches and socio-political implications, *Boll. Geofis. Teor. Appl.*, 58, 4, 253-264, doi:10.4430/bgta0205.
- Albarelo, D. and M. Moscatelli (2021). Extensive Microzonation as a Tool for Seismic Risk Reduction: Methodological and Political Issues, in *Building Knowledge for Geohazard Assessment and Management in the Caucasus and other Orogenic Regions*, Springer, Berlin, 329-341, doi:10.1007/978-94-024-2046-3_18.
- Albarelo, D., V. L. Socco, M. Picozzi and S. Foti (2015). Seismic hazard and land management policies in Italy: the role of seismic investigations, *First Break*, 33, 8, 87-93, doi:10.3997/1365-2397.33.8.82009.
- Branca, S. and S. Catalano (2000). Stratigraphical and morphological criteria for the reconstruction of UBSU in the peripheral area of Mt. Etna, Italy, *Mem. Soc. Geol. It.*, 55, 181-187.
- Branca, S., M. Coltelli, G. Groppelli and F. Lentini (2011). Geological map of Etna volcano, 1:50.000 scale, *It. J. Geosci.*, 130, 3, 265-291, doi:10.3301/IJG.2011.15.

- Catalano, S., S. Grassi, S. Imposa, G. Tortorici et al. (2019). The subsoil model for seismic microzonation study: The interplay between geology, geophysics and geotechnical engineering, in *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions*, Proceeding of the VII ICEGE 7th International Conference on Earthquake Geotechnical Engineering Silvestri and Moraci (Eds.), Rome, Italy, 17-20 June, 948-959, ISBN:978-0-367-14328-2.
- Cosentino, G., F. Pennica and E. Tarquini (2024). MzS Tools, 2.0.2, Zenodo, <https://explore.openaire.eu/search/result?pid=10.5281%2Fzenodo.17202163>.
- Cosentino, G., F. Pennica and E. Tarquini (2025). MzS Tools, 2.0.4, Zenodo, doi:10.5281/zenodo.17202163.
- D'Agostino, A., A. Porchia, G. Tortorici, F. Pavano et al. (2025). Stratigraphically Homogeneous Zones: automated construction and restitution procedure for engineering geology use, *J. Maps*, 21, 1, 2504064, doi:10.1080/17445647.2025.2504064.
- De Beni, E., S. Branca, M. Coltelli, G. Groppelli et al. (2011). 40Ar/39Ar isotopic dating of Etna volcanic succession, *It. J. Geosci.*, 130, 3, 292-305, doi:10.3301/IJG.2011.14.
- Dolce, M. (2012). The Italian national seismic prevention program, in *Proceedings of 15th world conference on earthquake engineering*, Lisbon, September, 24-28, <http://www.civil.ist.utl.pt/~mlopes/conteudos/SISMOS/DOLCE.pdf>.
- Dolce, M., F. Brammerini, S. Castenetto and G. Naso (2019). The Italian policy for Seismic Microzonation, in *Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering*, 7ICEGE, Rome, ISBN:978-0-367-14328-2.
- DPC, Dipartimento della Protezione Civile (2018). Commissione tecnica per il supporto e monitoraggio degli studi di Microzonazione Sismica, ex art.5, OPCM3907/10, WebMs, WebCLE, a cura di M. S. Benigni, F. Brammerini, G. Carbone, S. Castenetto et al.
- ETNA FAC and MS Working Group (2022). R2 – Relazione tecnico-scientifica di progetto, Accordo ai sensi dell'art. 15 della legge 241/1990 e del decreto legislativo 50/2016 e ss.mm.ii. tra il Dipartimento Regionale della Protezione Civile della Presidenza della Regione Siciliana e il C.N.R. Istituto di Geologia Ambientale e Geoingegneria, CUP:B75F21002880002, 113.
- Markušić, S. and M. Herak (1999). Seismic zoning of Croatia, *Nat. Hazards*, 18, 3, 269-285, doi:10.1023/A:1026484815539.
- Moscatelli, M., D. Albarello, G. Scarascia Mugnozza et al. (2020). The Italian approach to seismic microzonation, *Bull. Earthquake Eng.*, 18, 5425-5440, doi:10.1007/s10518-020-00856-6.
- Porchia, A., A. D'Agostino, G. Tortorici, E. Peronace et al. (2026). Python modules for GIS-based planning of Level 3 Seismic Microzonation investigation campaigns, Version 1.0.0, Zenodo, doi:10.5281/zenodo.18214590.
- QGIS Development Team (2024). QGIS Geographic Information System, QGIS Association, <https://www.qgis.org>.
- SM Working Group (2008). Guidelines for Seismic Microzonation, Conference of Regions and Autonomous Provinces of Italy-Civil Protection Department, 3 vol. and DVD, English edition published online in 2015, Rome, <https://www.centromicrozonazioneismica.it/it/strumenti/linee-guida-ms/>.
- Technical Commission for Seismic Microzonation (2020). Graphic and data archiving standards, Version 4.2, Department of Civil Protection of the Presidency of the Council of Ministers, Rome.

Appendix A. Technical structure of the modular workflow

The GIS-based workflow presented in this study is implemented through four sequential Python modules developed within the QGIS environment (QGIS Development Team, 2024). The complete source code is publicly available in a Zenodo repository (Porchia et al., 2026), which also includes a dedicated quick guide providing installation instructions, software requirements, and detailed explanations of the configurable parameters.

The purpose of this Appendix is to provide a structured overview of the technical architecture of the workflow without reproducing the operational documentation available in the repository. In particular, Tables A1-A4 summarize, for each module, the required input datasets, their provenance within the Seismic Microzonation framework (SM1-derived datasets or outputs from previous modules), the main configurable parameters (where applicable), and the generated outputs.

Table A1 refers to Module 1 (Construction of complete investigation layers) and summarizes the datasets required to reconstruct the harmonized point and linear investigation layers, including the integration of measurement reliability and SM1 zone attributes.

Table A1. Technical structure of Module 1 (Construction of complete investigation layers), including required SM1 input datasets imported through MZSTools, configurable parameters, and generated output layers integrating geometry, typology, measurement reliability, and SM1 zone attributes.

Category	Description
Input datasets	SM1 site layers (point and linear), investigation tables, parameter tables (with <i>attend_mis</i> field), stable and unstable SM1 zones
Input source	Imported from SM1 database through MZSTools plugin
Configurable parameters	Names of input layers in the QGIS TOC
Output layers	<i>Point_Investigations_Complete_join, Linear_Investigations_Complete_join</i> (including geometry, typology, quality index, and SM1 zone attributes)

Table A2 refers to Module 2 (Construction and refinement of the Control Point network) and describes the input datasets and configurable parameters governing the generation of the regular Control Point grids and the creation of additional Type 3 CPs to ensure representativeness of SM1 zones.

Table A2. Technical structure of Module 2 (Construction and refinement of the Control Point network), summarizing input datasets, user-defined parameters controlling grid generation and unstable-zone inclusion, and the resulting Type 1 and Type 2 Control Point layers.

Category	Description
Input datasets	SM3 study-area polygon; SM1 stable zones (MOPS); SM1 unstable zones
Input source	SM1 via MZSTools + manually loaded SM3 study-area layer
Configurable parameters	Grid spacing (<i>CELL_type1, CELL_type2</i>); <i>INCLUDE_INSTAB</i> flag
Output layers	<i>CP_Type1_final, CP_Type2_final</i> (including Type 3 CPs where required)

Table A3 refers to Module 3 (Assignment of investigations to Control Points) and outlines the datasets and parameters involved in the spatial and geological association between Control Points and existing investigations, including search-radius definition, typological activation, stability filtering, and quality constraints.

Table A3. Technical structure of Module 3 (Assignment of investigations to Control Points), detailing required input layers, configurable spatial and quality constraints, typological activation options, and the generated Control Point association layers with investigation counts and synthetic quality indicators.

Category	Description
Input datasets	<i>CP_Type1_final</i> , <i>CP_Type2_final</i> layers from Module 2; complete investigation layers from Module 1
Input source	Modules 1 and 2
Configurable parameters	Search radius definition; INCLUDE_INSTAB; quality threshold (MIN_QUALITY); activation of investigation types; CP-investigation association rules
Output layers	<i>CP_Associate_Type1</i> , <i>CP_Associate_Type2</i> (including counts of investigations and CP-level synthetic quality indicator)

Table A4 refers to Module 4 (Synthesis and production of final outputs) and summarizes the inputs and outputs related to the aggregation and reporting phase, including the generation of zone-level summary tables and GIS layers derived from the Control Point associations.

Table A4. Technical structure of Module 4 (Synthesis and production of final outputs), summarizing input association layers and the resulting aggregated summary tables and GIS layers supporting interpretation and planning of SM3 investigation campaigns.

Category	Description
Input datasets	CP association layers produced by Module 3
Input source	Module 3
Configurable parameters	(none)
Output layers and tables	Aggregated SM1 zone layers; CPs layers; CSV summary tables of investigation coverage

This structured summary complements the methodological description provided in Section 3 and facilitates the reproducibility and technical understanding of the proposed workflow, while detailed implementation procedures remain available in the publicly accessible repository.

***CORRESPONDING AUTHOR: Attilio PORCHIA,**

University of Catania, Department of Biological, Geological and Environmental Sciences (DBGES),

Section of Earth Science, Catania, Italy

e-mail: attilio.porchia@cnr.it

© 2026 the Author(s). All rights reserved.

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International