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# Using the Sediment Flow Connectivity Index to assess the environmental risk of naturally occurring fluoro-edenite: the unique case of Biancavilla (Italy)

**Abstract:** Zingaro M., Capolongo D., Monforte P., Imposa S., Cirrincione R., Punturo R., Indelicato V., Scicchitano G., *Using the sediment Flow Connectivity Index to assess the environmental risk of naturally occurring Fluoro-edenite: the unique case of Biancavilla (Italy).* (IT ISSN 0391-9838, 2026). Monitoring soil pollution caused by contaminated sediment transport is an increasing concern, particularly in areas exposed to specific mineralogical hazards. This study introduces an innovative experimental application of the Sediment Flow Connectivity Index (SfCI) to enhance soil pollution monitoring at the Biancavilla site (Etna, Italy), an area severely affected by fluoro-edenite fiber contamination. By applying the SfCI, we aim to characterize sediment dynamics and identify regions potentially prone to the transport and accumulation of pollutants. A key contribution of the SfCI lies in its ability to enable the detection of potential pollution hotspots, offering an efficient means of preliminary monitoring. This capability allows us immediately identify areas that need further field investigation and detailed sampling. The most significant key finding is that the index identified two primary sediment pathways crossing the quarry, which then diverge through the urban area and surrounding territory before entering the watercourse. Although the current application remains theoretical, we propose future validation through targeted soil sampling and hyperspectral imaging to confirm model predictions and refine monitoring accuracy. This approach presents a promising framework for integrating geomorphological connectivity analyses into soil pollution management strategies, providing real-time insights and enhancing the efficiency of monitoring in contaminated environments.

**Key words:** Sediment connectivity, Soil pollution monitoring, Contaminated sites, Risk assessment.

**Riassunto:** Zingaro M., Capolongo D., Monforte P., Imposa S., Cirrincione R., Punturo R., Indelicato V., Scicchitano G., *Applicazione del Sediment Flow Connectivity Index per valutare il rischio ambientale della fluoro-edenite di origine naturale: il caso unico di Biancavilla (Italia).* (IT ISSN 0391-9838, 2026). Il monitoraggio dell'inquinamento del suolo legato al trasporto di sedimenti contaminati rappresenta una preoccupazione crescente, soprattutto nelle aree esposte a specifici rischi mineralogici. Questo studio presenta un'innovativa applicazione sperimentale del Sediment Flow Connectivity Index (SfCI) per migliorare le attività di monitoraggio dell'inquinamento del suolo nel sito di Biancavilla (Etna, Italia), un'area gravemente colpita dalla contaminazione da fibre di fluoro-edenite. Attraverso l'impiego dello SfCI, miriamo a caratterizzare la dinamica dei sedimenti e a individuare le zone potenzialmente soggette al trasporto e all'accumulo di contaminanti. Un aspetto di particolare rilievo dello SfCI è la sua capacità di evidenziare possibili hotspot di inquinamento, fornendo uno strumento efficiente per il monitoraggio preliminare. Questa funzionalità consente di identificare rapidamente le aree che richiedono ulteriori verifiche sul campo e attività di campionamento più dettagliate. Il risultato più significativo emerso dall'analisi è l'individuazione di due principali percorsi di trasporto solido che attraversano la cava, per poi divergere attraverso l'area urbana e il territorio circostante prima di confluire nel reticolo idrografico. Sebbene l'applicazione attuale abbia ancora un carattere teorico, proponiamo una validazione futura attraverso campagne di campionamento mirate e l'impiego di immagini iperspettrali, così da confermare le previsioni del modello e migliorare l'accuratezza del monitoraggio. Questo approccio offre un quadro promettente per integrare le analisi di connettività geomorfologica nelle strategie di gestione dell'inquinamento del suolo, fornendo indicazioni quasi in tempo reale e aumentando l'efficienza delle attività di monitoraggio in contesti contaminati.

**Termini chiave:** Connettività di sedimento, Monitoraggio dell'inquinamento del suolo, Siti contaminati, Valutazione del rischio.

## INTRODUCTION

Soil pollution (SP) is becoming an increasingly concern for the environment due to its adverse impacts on ecosystems, water quality, and human health. Europe serves alone, over 2.5 million potentially contaminated sites (PCS) with tens of thousands needs detailed investigation and remediation (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2014; European Environmental Agency, 2014; Panagos *et al.*, 2013).

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Among the leading causes of soil pollution are industrial activities and the mismanagement of urban and hazardous waste, with contaminants which are often transported through natural processes such as surface runoff and sediment flow (European Commission. Joint Research Centre., 2018; European Environmental Agency, 2021). These dynamics pose significant challenges for pollution monitoring and risk assessment, particularly in areas where point and diffuse pollution sources interact within complex hydrographic catchments.

Traditional models used to assess soil pollution (SP), including both process-based simulations and numerical approaches for evaluating point and non-point source contamination, are often resource-intensive (J.G. Arnold *et al.*, 2010; Liu *et al.*, 2023; Zhai *et al.*, 2014). These methods typically require extensive computational power, high-resolution spatial and temporal data, and the involvement of skilled experts to interpret the results effectively (Baciocchi *et al.*, 2005; Cachada *et al.*, 2018). Consequently, their practical application remains limited, especially for public agencies that operate under economic constraints or in regions where environmental data is sparse or outdated (Ferguson, 1999). In response to these limitations, there is a growing demand for the development and adoption ofpractical, scalable indicators that can facilitate rapid preliminary assessments and help prioritize areas for more detailed field investigations. Such tools are particularly valuable in contexts that require broad geographic coverage or where immediate decision-making is needed. This demand aligns with recent European policy initiatives, including the EU Soil Strategy for 2030 and the proposed Soil Monitoring Law (European Commission, 2021, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – EU Soil Strategy for 2030: Reaping the benefits of healthy soils for people, food, nature and climate"; European Commission, 2023, "Soil Moitoring Law: Proposal for a Directive on Soil Monitoring and Resilience"), which highlight the importance of using soil condition descriptors (OECD, 2021). These policies advocate for the integration of early-warning systems into environmental governance to enhance ecosystem resilience, support sustainable land management, and proactively address risks associated with soil degradation and contamination.

In this context, sediment connectivity has emerged as a promising geomorphological indicator for identifying areas prone to erosion, sediment transport, and pollutant dispersion (Baartman *et al.*, 2013; Bracken *et al.*, 2015; Zhu *et al.*, 2023). The Sediment Flow Connectivity Index (SfCI), originally developed by (Zingaro *et al.*, 2019), provides a simplified yet effective framework for assessing sediment transfer potential across landscapes (Zingaro, 2021; Zingaro *et al.*, 2020). By integrating structural component (e.g., topography, land use), functional aspect (e.g., flow direction, slope-driven accumulation) and intrinsic functional properties (soil characteristics) of connectivity (Heckmann *et al.*, 2018 and references therein; Najafi *et al.*, 2021 and references therein), the SfCI enables the delineation of sediment pathways and accumulation zones that may correspond to pollutant hotspots. As a fully integrated index, especially effective in characterizing surface soil mobility, it was consequently chosen for this experimental application. In fact, since a significant portion of pollutants (e.g., asbestos fibers, heavy metals, etc.) is strongly associated with the fine fraction of sediments, the SfCI – by quantifying the mobility potential of these vectors – serves as an operational and scalable indicator of contamination spread. This mapping approach offers a valuable opportunity to incorporate geomorphological processes into soil pollution monitoring, especially where pollutants are mobilized via sediment-bound transport.

This study proposes an innovative methodological application of SfCI to aid in the detection of potentially contaminated sites. We focus on the town of Biancavilla (Etna mount, Sicily, Italy), designated a National Priority Contaminated Site (SIN) due to environmental exposure to fluoro-edenite fibers – a amphibole-group mineral whose natural occurrence is linked to elevated mesothelioma rates (Bruni *et al.*, 2014; Burragato *et al.*, 2005; Famoso *et al.*, 2012; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2017; Rapisarda *et al.*, 2015). Here, we use the SfCI as a proxy to identify zones of sediment accumulation and pollutant deposition, staking advantage of its low resource requirements and compatibility with Earth observation data. Although still theoretical, the proposed framework is designed to be validated through future targeted field sampling and hyperspectral imaging, with the goal of refining model outputs and improving the spatial accuracy of pollution detection.

By integrating sediment connectivity analysis with remote sensing tools, this approach addresses the immediate need for cost-effective, process-based indicators that can support environmental agencies in prioritizing monitoring and restoration efforts. The methodology aligns with current policy trends and offers the potential for widespread application in the management of contaminated landscape across Europe and beyond.

## STUDY AREA

Biancavilla is a municipality located on the southwestern flank of Mount Etna in eastern Sicily, Italy, approximately 30 km northwest of Catania (fig. 1). Situated at an elevation of around 500 meters above sea level, the area is characterized by a Mediterranean climate and a landscape shaped by volcanic activity. Geologically, Biancavilla lies atop Pleistocene benmoreitic lava flows (Branca, Stefano *et al.*, 2011; Groppelli and Norini, 2011), which have undergone hydrothermal

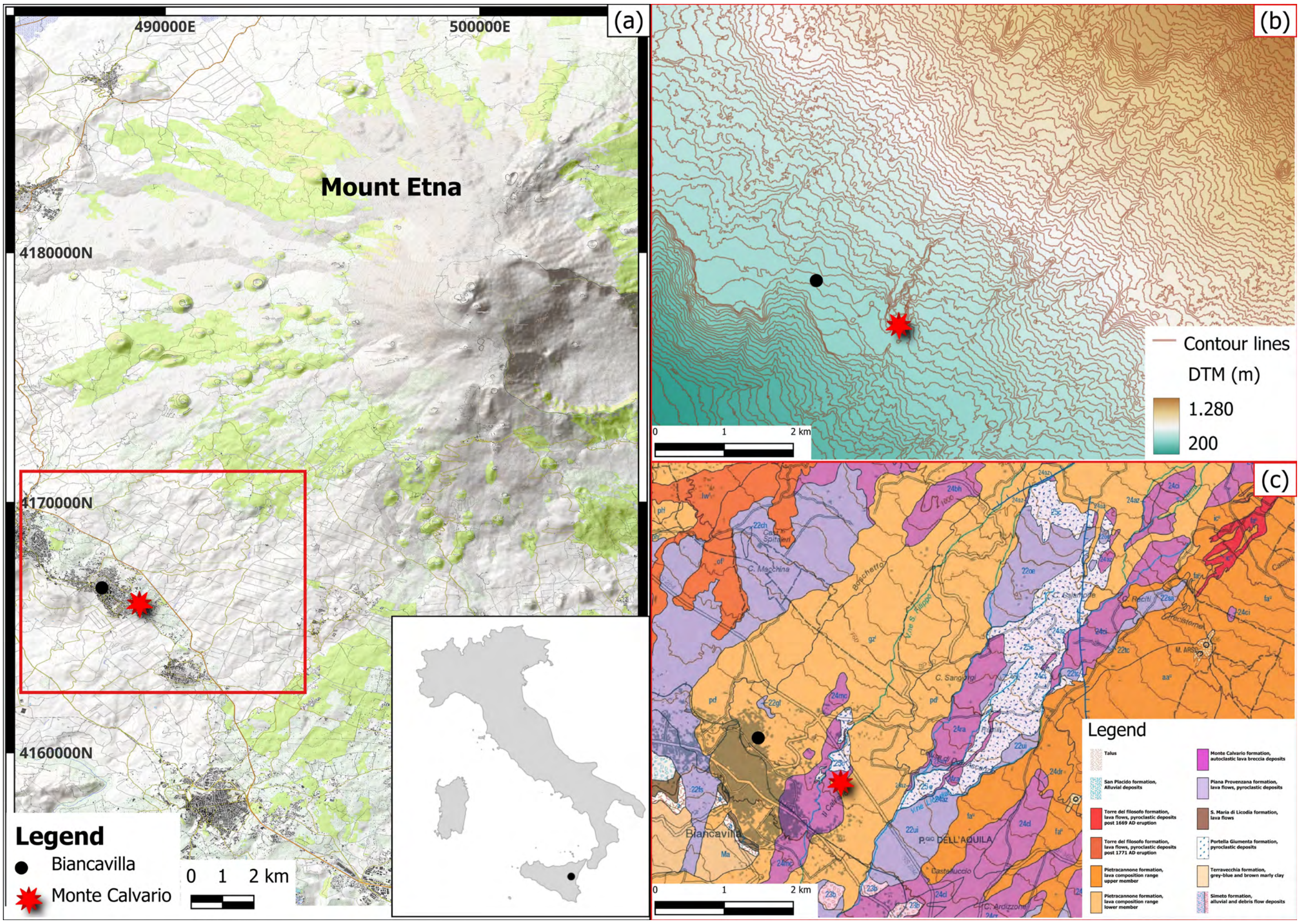


Figure 1 - a) Location of the Biancavilla site and Monte Calvario quarry on the flank of Mt. Etna in Sicily (southern Italy). The area within the square box is shown in detail in panels (b) and (c) (basemap: OpenTopoMap). Coordinates in the WGS84 / UTM zone 33N reference system. b) Topographic characterization of the site (Digital Terrain Model, DTM in color scale and hillshade as basemap). c) Geological map of the site (modified after Branca *et al.*, 2011).

alteration processes leading to the formation of late minerals, including amphiboles solid solutions which may develop fibrous habit. One such mineral, fluoro-edenite – a fluorine-rich amphibole (approved IMA 1999; IMA symbol Fled; Warr, 2021) – was identified in the late 1990s/early 2000s in the Monte Calvario quarry near Biancavilla (Gianfagna and Oberti, 2001) (fig. 2). This mineral shares morphological and compositional similarities with tremolite-actinolite series minerals and has been associated with adverse health effects (Ballirano *et al.*, 2008; Bruni *et al.*, 2006).

The Monte Calvario quarry had been extensively exploited since the 1950s for construction materials, leading to the widespread use of fluoro-edenite-containing rocks in local building practices. Epidemiological studies conducted in the late 1990s revealed a significantly elevated incidence of pleural mesothelioma among Biancavilla residents, particularly affecting women and individuals without occupational exposure to known carcinogens like asbestos (Burragato *et al.*, 2005; Comba *et al.*, 2003; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2017). Subsequent environmental investigations confirmed the presence of a new mineral, namely fluoro-edenite, whose occurrence in ambient air, soil, and indoor environments indicates a pervasive environmental contamination (Bruni *et al.*, 2006; Grimaldi and Pinizzotto, 2018; Gunter *et al.*, 2007; Paoletti *et al.*, 2000; Pinizzotto *et al.*, 2018).

In response to these findings, the Italian Ministry for the Environment designated Biancavilla as a Site of National Interest (SIN) in 2002, initiating remediation efforts that included the cessation of quarrying activities, removal of contaminated materials, and urban decontamination measures (Pacella, A., 2005). Despite these interventions, the persistence of fluoro-edenite in the environment necessitates ongoing monitoring and assessment (e.g. Bellomo *et al.*, 2018; Pinizzotto *et al.*, 2018). The unique geological and environmental context of Biancavilla, coupled with its documented public health implications, renders it an exemplary case study for evaluating remote sensing methodologies aimed at detecting and monitoring soil contamination and associated risks.

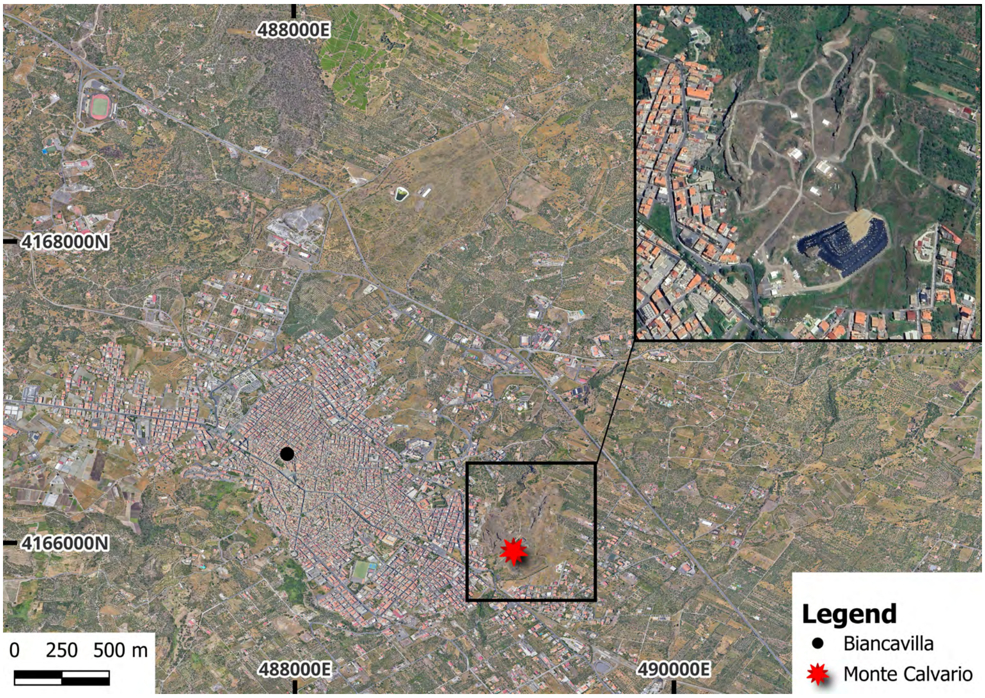


Figure 2 - The Monte Calvario quarry in Biancavilla town (Google satellite). Coordinates in the WGS84 / UTM zone 33N reference system.

## MATERIALS AND METHODS

### *SfCI computation*

The SfCI, developed by (Zingaro *et al.*, 2019), integrates both structural and functional components of sediment connectivity by defining connected areas based on transport within a hydrographic catchment. This geomorphological indicator visualizes water and sediment pathways by assessing connectivity from sources to sinks through the channel network as material is transported. Connections among different areas are identified by analyzing sediment mobilization (erosion) and its transfer along channels to the outlet (target), in both lateral and longitudinal directions. Using a mapping approach in two main steps, the SfCI first estimates sediment mobility by considering factors controlling sediment erosion and mobilization and then calculates sediment fluxes by applying slope-driven flow accumulation (Zingaro *et al.*, 2019). Structured in this way, the algorithm assumes that in the absence of sediment mobility, no connection exists, and that greater mobility implies a higher likelihood of connectivity. Specifically, the sediment mobility (SM) is considered as:

$$SM = SM_1 \cdot SM_2 \qquad (1)$$

with:

$$SM_1 = \frac{R}{SI} LI, \qquad (2)$$

$$SM_2 = \frac{S}{Ru}, \qquad (3)$$

where $SM_1$ and $SM_2$ are the two mobility factors respectively, R is a rainfall index, SI is a soil stability index, LI is a land cover index, S is a slope index and Ru is a ruggedness index. In particular, $SM_1$ defines the potential sediment detachment within a cell, which can be estimated by considering rainfall (the driving factor), soil stability (a functional aspect), and land cover. In contrast, $SM_2$ describes the potential mobilization of detached sediment toward surrounding cells, determined by slope and surface ruggedness (topographical factors). R, SI, LI, S, and Ru are dimensionless indices ranging from 0.05 to 1, derived from classifying the corresponding variables according to erosion process assessment based on their increasing potential to generate and to transport sediment. The assignment and ordering of numerical interval ranges for the R, SI, and L indices are qualitative and specific to the catchment being analyzed. These indicators make it possible to account for the variables responsible for surface sediment connectivity, considering both facilitating elements and obstacles; anthropogenic discontinuities are not incorporated, as they pertain to factors that can be addressed through complementary analyses when needed.

SfCI is defined as:

$$SfCI = \log_{10} F(SM) \qquad (4)$$

where F is a classical flow-accumulation algorithm that identifies active water and sediment cells by calculating the contributing area based on the steepest slope principle. Specifically, the normalized SM raster is used as a weight raster during iterations to calculate the accumulated sediment of cells flowing into each downslope cell.

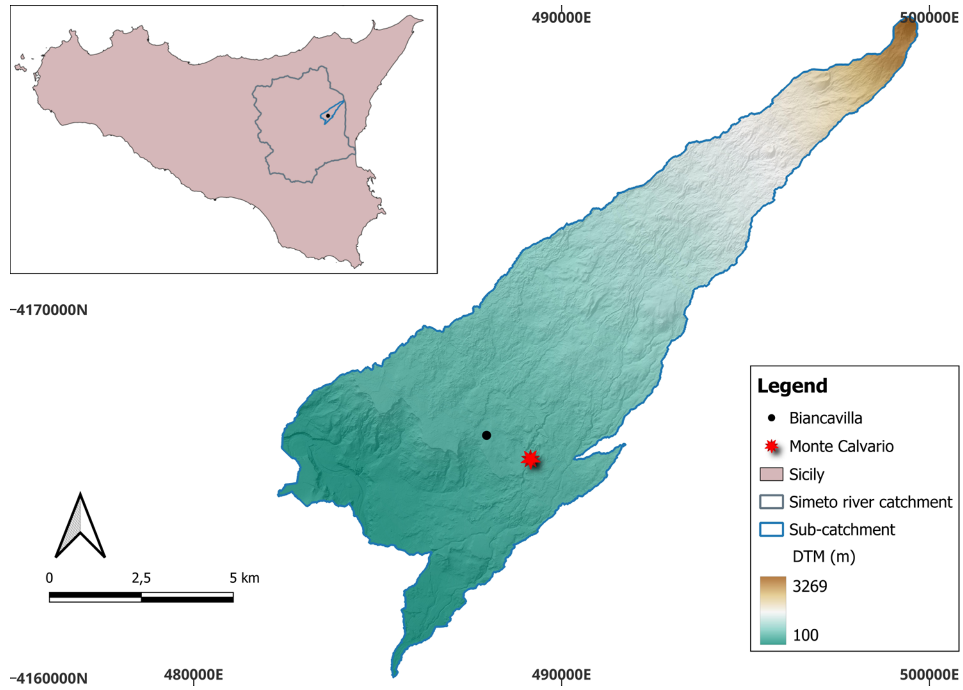


Figure 3 - Sub-catchment of the Simeto River (location of the basin within the Sicilian region shown in the upper left inset), where the Biancavilla site and the Monte Calvario quarry are located (basemap: hillshade of the DTM). Coordinates in the WGS84 / UTM zone 33N reference system.

SfCI was applied to the Simeto river sub-catchment, where Biancavilla site is located (fig. 3).

### *SfCI data*

The study utilized regional dataset to generate sediment mobility variables such as R, SI, LI, S, Ru maps which are the key components for sediment mobility computation. All the maps were prepared using Monte Mario/Italy zone 2 projection system, with a spatial resolution of 2 m. The definition of the projection system and the spatial resolution were determined by the properties of regional DTM used to extract surface characteristics. The regional DTM, updated to 2013, was generated using LiDAR data and has a vertical accuracy of 30 cm (https://www.sitr.regione.sicilia.it/geoportale/it/metadata/details/947).

The R map was derived from rainfall data representing the mean annual precipitation (MAP) measured at rain gauge stations in central-eastern Sicily during the period 1924-2021. Rainfall datasets from Osservatorio distrettuale permanente sugli utilizzi idrici (https://www.regione.sicilia.it/istituzioni/regione/strutture-regionali/presidenza-regione/autorita-bacino-distretto-idrografico-sicilia/osservatorio-distrettuale-permanente-sugli-utilizzi-idrici) and Servizio informativo agrometeorologico siciliano (http://www.sias.regione.sicilia.it/) were used (Monforte and Imposa, 2025). The R map consists of MAP values extracted from an isohyet map generated using inverse distance-weighted interpolation (Shepard, 1968), rescaled into index values ranging from 0.05 to 1 (tab. 1).

The SI map was created by classifying soil properties such as permeability and soil unit thickness, based on the hydrological map of the Biancavilla site (Piano Regolatore Generale, Comune di Biancavilla) and the geological map of Mount Etna (Branca *et al.*, 2011). Specifically, permeability and thickness classes were combined to define three classes of soil stability index (tab. 2) with values from 0.05 to 1. The classification is based on an a priori interpretation of the role of soil properties in the processes of layer saturation, drainage-runoff capacity of the soil surface, and their effects on soil stability.

The LI map was generated by assigning value classes ranging from 0.05 to 1 to the land use categories derived from the regional land use map (updated to 2022, available on the webGIS site of Sicily region, https://www.sitr.regione.sicilia.it/portal/home/). Considering surface dynamics, high values were assigned to categories favoring sediment detachment (poorly vegetated areas), while low values were assigned to categories preventing sediment detachment (such as grasslands and pastures) (tab. 3).

S and Ru maps were derived from the classification of slope and ruggedness maps obtained from the regional DTM. Specifically, slope and ruggedness range values were rescaled into values from 0.05 and 1 (tabs 4, 5). Ruggedness refers to topographic ruggedness and was obtained by calculating the Terrain Ruggedness Index (TRI) through the “gdaldem” module implemented in gdal library (Zingaro *et al.*, 2019, 2020, 2023).

The analysis and the processing of the maps were carried out by using ArcMap™ (version 10.8, ESRI, www.esri.com; accessed on 30 May 2025), Qgis® (version 3.16.1, Open Source Geospatial Foundation Project, http://qgis.org; accessed on 30 SMay 2025) and Matlab® (version R2019a, Math Works, https://it.mathworks.com; accessed on 30 May 2025) software.

Table 1 - Rainfall data classified into R index values.

| Rainfall (mm/y) | R index |
|---|---|
| 634-638 | 0.05 |
| 638-690 | 0.25 |
| 691-742 | 0.50 |
| 743-794 | 0.75 |
| 795-846 | 1 |

Table 2. Soil classes aggregated and categorized into SI index values. LP = low permeability; MP = medium permeability; HP = high permeability; LT = low thickness; MT = medium thickness; HT = high thickness.

| Soil properties conditions | SI index |
|---|---|
| LP & LT | 0.05 |
| MP & LT | |
| LP & MT | 0.5 |
| MP & MT | |
| HP & LT | |
| HP & MT | |
| LP & HT | |
| MP & HT | 1 |
| HP & HT | |

Table 3 - LI index values attributed to land use classes.

| Land use classes | LI index |
|---|---|
| Urban areas | 0.05 |
| Grassland, pastures, shrubs | 0.25 |
| Woods, forests | 0.50 |
| Arable fields, croplands | 0.75 |
| Bare soils, sparse vegetated areas | 1 |

Table 4 - Slope values classified into S index values.

| Slope index range | S index |
|---|---|
| 0-1.1 | 0.05 |
| 1.2-21.1 | 0.25 |
| 21.2-41.1 | 0.50 |
| 41.2-61.1 | 0.75 |
| 61.2-80 | 1 |

Table 5 - Terrain ruggedness index range classified into Ru index values.

| TRI range | Ru index |
|---|---|
| 0-0.7 | 0.05 |
| 0.8-7.4 | 0.25 |
| 7.5-14.2 | 0.50 |
| 14.3-20.9 | 0.75 |
| 21-27.7 | 1 |

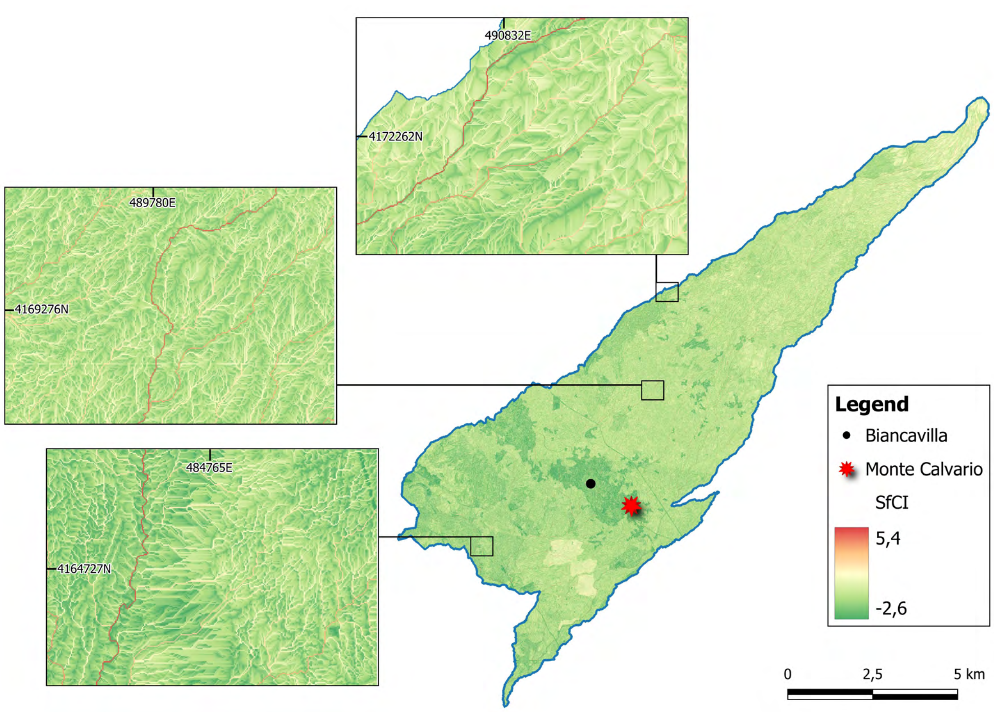


Figure 4 - SfCI map of Biancavilla sub-catchment. Detailed views of selected map areas are shown in the insets. Coordinates in the WGS84 / UTM zone 33N reference system.

## RESULTS

### *SfCI map*

Applying formulas (1-3) for sediment mobility and formula (4) for connectivity in the Biancavilla sub-catchment produced the SfCI map. The map illustrates sediment displacement along the water runoff paths that originate from the Etna mountain slopes, traverse the territory of Biancavilla, and eventually flow into the Simeto river (fig. 4). Specifically, SfCI values range from -2.6 to 5.4, distinguishing sediment-active cells (shown as orange-red on the map) that link areas of the sub-catchment both laterally and longitudinally, from sediment-inactive cells (depicted in green on the map) that indicate disconnected areas within the sub-catchment. Two sediment pathways cross the quarry (fig. 5a-b), with one continuing toward the town center and the other heading southeast (Figure 5c,d) before both proceed westward, flowing almost parallel until merging into the river (fig. 5e-f). These sediment flows traverse a substantial portion of the territory of Biancavilla before reaching the watercourse, receiving input from additional minor pathways and surface runoff. Along their entire course, they continuously transport and redistribute sediment, progressively mobilized from both natural and anthropogenic surfaces.

## DISCUSSION

This study explored the potential of using the SfCI (Zingaro *et al*., 2019) as a geomorphological indicator to support the remote identification of PCS in Biancavilla, a SIN in southern Italy. The site is known for environmental exposure to fluoro-edenite, a natural amphibole whose

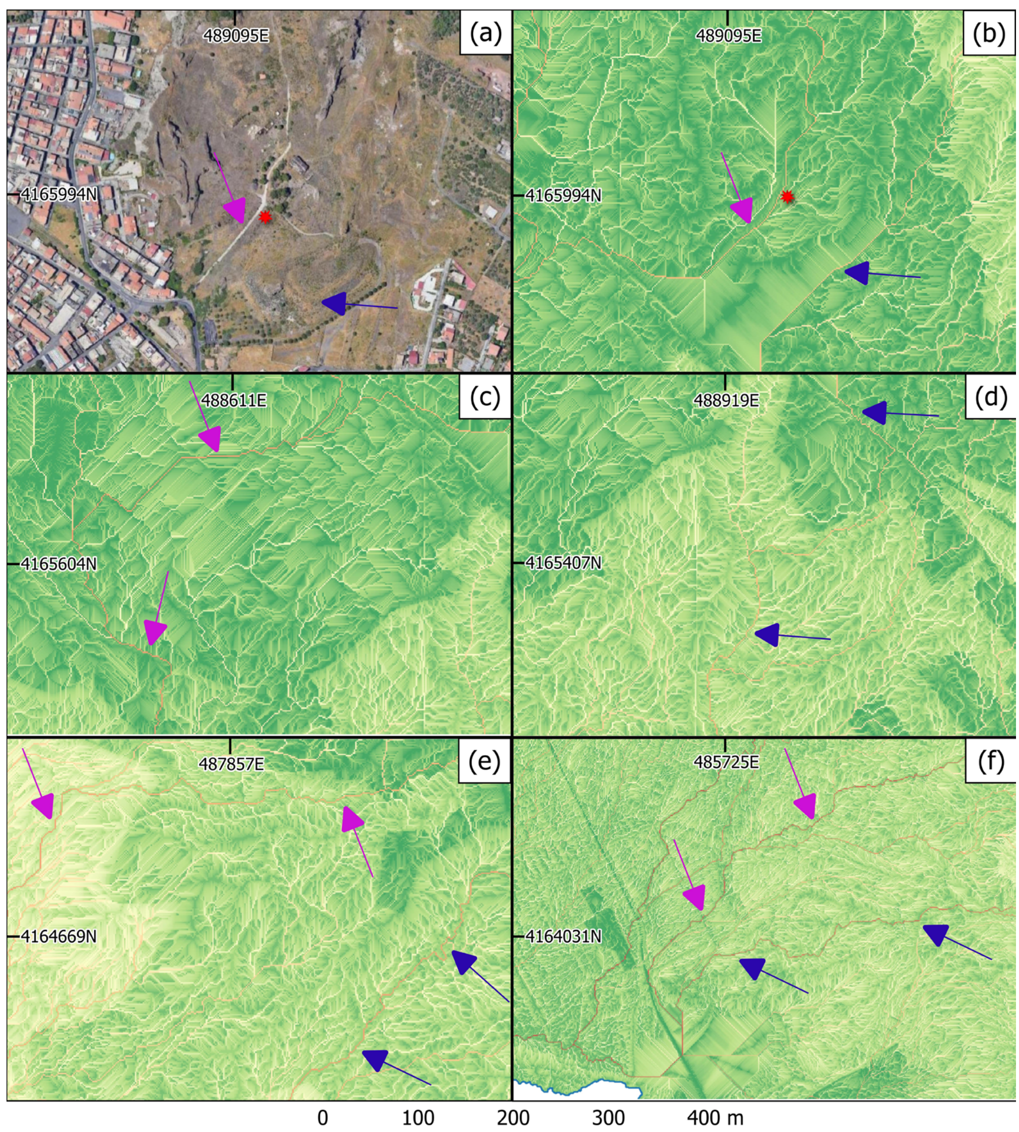


Figure 5 - The two sediment flows, described by the SfCI and indicated by the purple and blue arrows respectively, cross the quarry and then travel through the territory south of Biancavilla until they discharge into the Simeto River. a-b) The two paths crossing the quarry. c-d) Sections of the two paths. e-f) Sections where the two paths run parallel. Coordinates in the WGS84 / UTM zone 33N reference system.

occurrence is associated with severe health risks (Bruni *et al.*, 2014; Comba *et al.*, 2003). By applying the SfCI to the hydrographic context of Biancavilla, we mapped the surface dynamics of sediment and water movement that could facilitate the dispersion of contaminated materials from the Monte Calvario quarry, the known source of pollution (fig. 4).

Using geomorphological and environmental data integrated into the SfCI model, the analysis revealed two main sediment pathways originating from the quarry (fig. 5). These pathways traverse urban and peri-urban areas of Biancavilla before converging into the Simeto River. This persistent movement of sediment not only accumulates contributions from upstream sources but also entrains new material along the way, resulting in an ongoing, surface-level displacement of sediment masses. The pathways thus function as dynamic conveyors of sediment, shaping the terrain and influencing sediment delivery to the receiving river system. SfCI captures surface sediment dynamics that may lead to various scenarios: (i) the transport of contaminated soil from the quarry to surrounding areas; (ii) uncontaminated soil entering pathways of contaminated sediment; and (iii) uncontaminated soil following uncontaminated sediment pathways. However, it should be considered that the presence of contaminated (or uncontaminated) soil may not necessarily be due to sediment transport but rather to the presence (or absence) of a pollution source different from the quarry.

The index successfully identified sediment-active areas along these routes, highlighting the potential for sediment-bound contaminants to be mobilized and transported across the landscape. These results suggest that the SfCI can serve as a valuable proxy for surface-level contaminant transport, delineating zones where monitoring and sampling should be prioritized. Clearly, applying an index grounded in a simplified – and thus advantageous – approach, such as SfCI, also introduces limitations in the analysis of sediment-transport dynamics, potentially constraining or overlooking the complexity of the processes involved in the surface mobilization of contaminated sediment. Moreover, the underlying mechanisms can differ widely, and identifying all of them is often difficult because they tend to be heterogeneous and highly site-specific.

If validated through targeted field sampling, this method could represent a breakthrough in soil contamination monitoring – enabling the remote detection of pollutant dispersion patterns based on sediment dynamics without the need for intensive ground-based surveys. However, the field validation process presents practical challenges, including uncertainties related to the spatial resolution of input data, access constraints, and the inherent complexity of linking sediment transport to contaminant presence. These issues need to be resolved to fully operationalize the approach and realize its potential as a cost-effective tool for assessing environmental risks in contaminated areas.

Based on the results obtained from the SfCI, we propose a novel field sampling methodology aimed at enhancing the validation and application of remote soil contamination monitoring. Rather than using spot-based sampling points, this approach proposes a comprehensive grid system that would cover the entire area influenced by sediment transport pathways identified through the SfCI index (fig. 6). This grid would be especially dense around key morphological features – such as channels, valleys, hollows and depositional flats – where sediment movement and accumulation are most significant.

To ensure a spatially representative sampling scheme and to address the intrinsic uncertainty of point-based data relative to pixel-based observations (e.g., from DEM-derived indices), it could be applied a multi-level nested grid approach. As illustrated in fig. 6, this system is composed of three hierarchical grids (Grid 1, 2, and 3), each with increasing spatial resolution. The coarsest grid (Grid 1) defines a base-level coverage of the region crossed by the sediment pathway, allowing an initial stratified sampling across both sediment-connected and disconnected areas. Sample points located on this grid (Soil sample point 1) serve as a first diagnostic layer. Subsequent refinement is achieved through the denser Grid 2, which is activated in zones of higher geomorphological complexity or relevance – such as slope breaks, convergence zones – improving sampling granularity and precision. These regions are further refined in critical sectors (e.g., depositional basins or erosion-prone hollows) with Grid 3, which provides the highest resolution level and is crucial for capturing fine-scale processes often missed by coarser grids. By intensifying soil sampling within Grid 2 and 3, it becomes possible to more accurately capture the role of morphological features in controlling surface sediment dynamics. This sample approach could be applied to two sediment pathways that cross the querry in Biancavilla (fig. 5).

This hierarchical gridding strategy not only ensures consistent coverage across the area, but also aligns sampling density to match the expected spatial variability, maximizing efficiency without compromising representativeness. The design enables scale-aware sampling, applying higher resolution only where it is justified, thus optimizing fieldwork efforts. Additionally, by anchoring sampling decisions to morphometric and hydrological indicators, this approach increases the probability of capturing contaminant accumulation zones and improves the spatial accuracy of interpolation or modeling results derived from field data (Calace, 2007).

However, while this comprehensive coverage is ideal from a methodological perspective, practical limitations must be considered. Access restrictions due to private ownership, safety concerns in urbanized or industrial zones, and other logistical challenges could limit the full implementation of such a grid. These factors highlight the

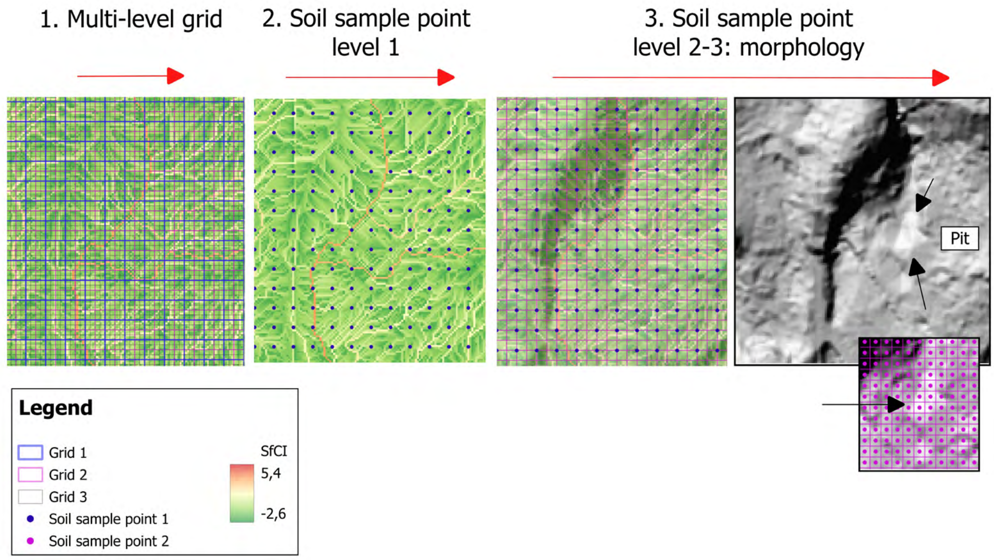


Figure 6 - Schematic representation of the proposed soil sampling methodology. A hierarchical grid is used to identify sampling points (centroids) with increasing density levels, based on the geomorphological characteristics of the area. In the example, denser sampling (levels 2 and 3) is applied around a concavity (pit), where sediment is more likely to have accumulated.

importance of incorporating accessibility assessments early in the planning phase, allowing for adaptive strategies that prioritize the most critical locations for contamination monitoring.

To overcome some of these limitations – and to support the proposed grid-based approach as a complementary method – high-resolution hyperspectral imagery could be employed (Agrawal *et al.*, 2024; Guglietta *et al.*, 2025; Mishra *et al.*, 2021; Sudharsan *et al.*, 2019). Such imagery make it possible to map surface mineral composition in great detail, which is especially useful to identify areas potentially affected by specific contaminants such as fluoro-edenite. By analyzing the specific spectral signatures associated with this fibrous mineral, it becomes possible to delineate where it is most likely to occur across the landscape. These hyperspectral-derived maps can then be combined with the connectivity index, either as a guide to refine sampling locations or, in situations where field access is limited, to provide a preliminary indication of potential contamination. Integrating morphological and mineralogical information in this way improves the spatial accuracy of monitoring efforts, helps allocate resources efficiently, and offers a flexible framework for adaptive sampling in complex terrain.

Overall, the soil monitoring strategy proposed here represents a logical extension of the SfCI method, providing a scalable and spatially informed framework to guide future field campaigns. The validation methodology has inherent limitations at each level, such as the need for full access to the field for the sampling grid and the spatial resolution of hyperspectral imagery. While these limitations cannot be entirely avoid, they could be addressed in future studies by expanding field surveys, integrating high-resolution UAV or drone-based imagery, and combining remote sensing data with targeted on-site measurements. A multi-scale, hybrid approach would help fill data gaps and improve the robustness of validation, reducing the impact of restricted accessibility or coarse spatial resolution. This new approach bridges the gap between remote sensing observations andfield-based evidence, offering a pathway toward more effective and efficient soil pollution assessment.

In fact, in the broader context of SP monitoring, several existing studies rely on process-based or numerical models that, while robust, demand extensive datasets, detailed environmental parameters, and significant computational resources (Duarte *et al.*, 2018; Arnold *et al.*, 2010; Liu *et al.*, 2023; Zhai *et al.*, 2014). These models often need site-specific calibration, which limits their applicability in data-poor regions or over large spatial scales. Other research has focused on the use of geochemical tracers, isotopic analyses, or laboratory-intensive techniques to track pollutant movement in soils- approaches that provide precise insights but demand substantial effort and resources. By contrast, the methodology proposed in this study represents an innovative and accessible alternative. Using a geomorphological indicator such as the SfCIallows remote identification of water and sediment pathways – and, consequently, the potential redistribution of soil-bound contaminants – through a simplified, data-efficient approach (Kushabaha *et al.*, 2025; Zingaro *et al.* 2020, 2024). This aligns with the principles of the EU Soil Strategy for 2030, which calls for scalable and early-warning tools to support preliminary assessment and decision-making. The SfCI thus adds a valuable new dimension to the growing set of spatial indicators available for soil-health monitoring, with strong potential for practical use in contaminated-land management.

## CONCLUSION

This study presents an innovative application of the Sediment Flow Connectivity Index (SfCI) as a geomorphological indicator to support the identification of potentially contaminated sites, using the Biancavilla SIN as a case study. The SfCI successfully highlighted two main sediment pathways originating from the fluoro-edenite source area, demonstrating its ability to trace surface water and sediment dynamics that may drive pollutant dispersion across the landscape.

The results underscore the potential of SfCI to serve as a preliminary screening tool for soil pollution monitoring, especially in data-limited contexts. Its implementation needs of minimal input data and is compatible with regional-scale assessments, aligning with EU policy goals for scalable and cost-effective environmental indicators.

Future research should focus on field validation through targeted sampling and the integration of high-resolution hyperspectral data to refine contamination mapping. If validated, this approach could offer a valuable complement – or even an alternative – to traditional methodologies that require substantial time and resources.

## AUTHORS CONTRIBUTION

Marina Zingaro: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft preparation, Writing – review and editing, Visualization, Project administration. Domenico Capolongo: Methodology, Formal analysis, Writing – original draft preparation, Writing – review and editing. Pietro Monforte: Methodology, Investigation, Resources, Data curation, Writing – review and editing, Writing – review and editing, Visualization. Sebastiano Imposa: Resources, Data curation, Writing – original draft preparation, Writing – review and editing. Rosolino Cirrincione: Formal analysis, Writing – original draft preparation, Writing – review and editing. Rosalda Punturo: Investigation, Formal analysis, Writing – original draft preparation, Writing – review and editing. Valeria Indelicato: Investigation, Formal analysis, Writing – original draft preparation, Writing – review and editing. Giovanni Scicchitano: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft preparation, Writing – review and editing, Visualization, Supervision.

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## CONFLICTS OF INTEREST

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the involved universities. The authors declare that they have no conflicts of interest.

## DATA AVAILABILITY

Data will be made available on request to corresponding author.

## REFERENCES

Agrawal N., Govil H., Chatterjee S., Mishra G., Mukherjee S., 2024. *Evaluation of machine learning techniques with AVIRIS-NG dataset in the identification and mapping of minerals.* Advances in Space Research, 73 (2), 1517-1534. https://doi.org/10.1016/j.asr.2022.09.018

Arnold J.G., Allen P.M., Volk M., Williams J.R., Bosch D.D., 2010. *Assessment of different representations of spatial variability on SWAT Model Performance.* Transactions of the ASABE, 53 (5), 1433-1443. https://doi.org/10.13031/2013.34913

Baartman J.E.M., Masselink R., Keesstra S.D., Temme A.J.A.M., 2013. *Linking landscape morphological complexity and sediment connectivity.* Earth Surface Processes and Landforms, 38 (12), 1457-1471. https://doi.org/10.1002/esp.3434

Baciocchi R., Marella G., D'Aprile L., Musmeci L., 2005. *Criteri metodologici per l'applicazione dell'analisi assoluta di rischio ai siti contaminati.* Ecomondo, 2, 271-285.

Ballirano P., Andreozzi G.B., Belardi G., 2008. *Crystal chemical and structural characterization of fibrous tremolite from Susa Valley, Italy, with comments on potential harmful effects on human health.* American Mineralogist, 93 (8-9), 1349-1355. https://doi.org/10.2138/am.2008.2869

Bellomo D., gargano C., Guercio A., Punturo R., Rimoldi B., 2018. *Workers' risks in asbestos contaminated natural sites.* Journal of Mediterranean Earth Sciences (10), 97-106 https://doi.org/10.3304/JMES.2018.019

Bracken L.J., Turnbull L., Wainwright J., Bogaart P., 2015. *Sediment connectivity: a framework for understanding sediment transfer at multiple scales.* Earth Surface Processes and Landforms, 40 (2), 177-188. https://doi.org/10.1002/esp.3635

Branca S., Coltelli M., Groppelli G, 2011. *Geological evolution of a complex basaltic stratovolcano: Mount Etna, Italy.* Italian Journal of Geosciences, 130 (3), 306-317. https://doi.org/10.3301/IJG.2011.13

Bruni B.M., Soggiu M.E., Marsili G., Brancato A., Inglessis M., Palumbo L., Piccardi A., Beccaloni E., Falleni F., Tagliani S.M., Pacella A., 2014. *Environmental concentrations of fibers with fluoro-edenitic composition and population exposure in Biancavilla (Sicily, Italy).* Annali dell'Istituto Superiore di Sanità, 50 (2). https://doi.org/10.4415/ANN_14_02_03

Bruni B.M., Pacella A., Mazziotti Tagliani S., Gianfagna A., Paoletti L., 2006. *Nature and extent of the exposure to fibrous amphiboles in Biancavilla.* Science of The Total Environment, 370 (1), 9-16. https://doi.org/10.1016/j.scitotenv.2006.05.013

Burragato F., Comba P., Baiocchi V., Palladino D.M., Simei S., Gianfagna A., Paoletti L., Pasetto R., 2005. *Geo-volcanological, mineralogical and environmental aspects of quarry materials related to pleural neoplasm in the area of Biancavilla, Mount Etna (Eastern Sicily, Italy).* Environmental Geology, 47 (6), 855-868. https://doi.org/10.1007/s00254-004-1217-7

Cachada A., Rocha-Santos T., Duarte A.C., 2018. *Soil and Pollution.* Soil Pollution, 1-28. Elsevier. https://doi.org/10.1016/B978-0-12-849873-6.00001-7

Calace N., 2007. *Manuale per le indagini ambientali nei siti contaminati.* APAT, Roma.

Comba P., Gianfagna A., Paoletti L., 2003. *Pleural mesothelioma cases in Biancavilla are related to a new fluoro-edenite fibrous amphibole.* Archives of Environmental Health: An International Journal, 58 (4), 229-232. https://doi.org/10.3200/AEOH.58.4.229-232

Duarte A.C., Cachada A., Rocha-Santos T. (Eds), 2018. *Soil Pollution: from Monitoring to Remediation*. Academic Press, an imprint of Elsevier, London San Diego Cambridge, MA Kidlington, Oxford, 296 pp.

European Commission. Joint Research Centre., 2018. *Status of local soil contamination in Europe: revision of the indicator «Progress in the management contaminated sites in Europe».* Publications Office, LU.

European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2014. *Progress in the management of contaminated sites in Europe.* Publications Office, LU.

European Environmental Agency, 2014. *Progress in Management of Contaminated Sites.*

European Environmental Agency, 2021. *Land and Soil Pollution - Widespread, Harmful and Growing.*

Famoso D., Mangiameli M., Roccaro P., Mussumeci G., Vagliasindi F.G.A., 2012. *Asbestiform fibers in the Biancavilla site of national interest (Sicily, Italy): review of environmental data via GIS platforms.* Reviews in Environmental Science and Bio/Technology, 11 (4), 417-427. https://doi.org/10.1007/s11157-012-9284-9

Ferguson C.C., 1999. *Assessing risks from contaminated sites: policy and practice in 16 European countries.* Land Contamination and Reclamation, 7 (2), 87-108.

Gianfagna A., Oberti R., 2001. *Fluoro-edenite from Biancavilla (Catania, Sicily, Italy): Crystal chemistry of a new amphibole end-member.* American Mineralogist, 86 (11-12), 1489-1493. https://doi.org/10.2138/am-2001-11-1217

Grimaldi R., Pinizzotto M.R., 2018. *Scavi nel sin di Biancavilla, l'attività di Arpa Sicilia.* Ecoscienza, 218 (1), 44-45.

Groppelli G., Norini G., 2011. *Geology and tectonics of the southwestern boundary of the unstable sector of Mt. Etna (Italy).* Journal of Volcanology and Geothermal Research, 208 (1-2), 66-75. https://doi.org/10.1016/j.jvolgeores.2011.08.006

Guglietta D., Salzano R., Wafik A., Conte A.M., Paciucci M., Punturo R., Salvatori R., Senesi G.S., Vaccaro C., 2025. *Hyperspectral investigation of an abandoned waste mining site: the case of Sidi Bou Azzouz (Morocco).* Remote Sensing, 17 (11), 1838. https://doi.org/10.3390/rs17111838

Gunter M.E., Belluso E., Mottana A., 2007. *Amphiboles: environmental and health concerns.* Reviews in Mineralogy and Geochemistry, 67 (1), 453-516. https://doi.org/10.2138/rmg.2007.67.12

Heckmann T., Cavalli M., Cerdan O., Foerster S., Javaux M., Lode E., Smetanová A., Vericat D., Brardinoni F., 2018. *Indices of sediment connectivity: opportunities, challenges and limitations.* Earth-Science Reviews, 187, 77-108. https://doi.org/10.1016/j.earscirev.2018.08.004

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2017. *Some Nanomaterials and Some Fibres.* International Agency for Research on Cancer, Lyon (FR).

Kushabaha A., Capolongo D., Scicchitano G., Rizzo F., Zingaro M., 2025. *Sediment flow connectivity index data for the Apulia region (Italy): an open-source geodatabase and the innovative CONNECTOSED WebGIS platform.* Data in Brief, 58, 111210. https://doi.org/10.1016/j.dib.2024.111210

Liu J., Kang H., Tao W., Li H., He D., Ma L., Tang H., Wu S., Yang K., Li X., 2023. *A spatial distribution. Principal component analysis (SD-PCA) model to assess pollution of heavy metals in soil.* Science of The Total Environment, 859, 160112. https://doi.org/10.1016/j.scitotenv.2022.160112

Mishra G., Govil H., Srivastava P.K., 2021. *Identification of malachite and alteration minerals using airborne AVIRIS-NG hyperspectral data.* Quaternary Science Advances, 4, 100036. https://doi.org/10.1016/j.qsa.2021.100036

Monforte P., Imposa S., 2025. *Future dynamics of drought in areas at risk: an interpretation of RCP projections on a regional scale.* Hydrology, 12 (6), 143. https://doi.org/10.3390/hydrology12060143

Najafi S., Dragovich D., Heckmann T., Sadeghi S.H., 2021. *Sediment connectivity concepts and approaches.* CATENA, 196, 104880. https://doi.org/10.1016/j.catena.2020.104880

OECD, 2021. *Environmental Indicators: Towards Sustainable Development 2001.* OECD Publishing, Paris. https://doi.org/10.1787/9789264193499-en.

Pacella, A., 2005. *Applicazioni mineralogiche per lo studio dei siti di interesse nazionale: il Caso Biancavilla.* ISPRAmbiente, Educazione e Formazione Ambientale Archivio Tesi e Tirocini.

Panagos P., Van Liedekerke M., Yigini Y., Montanarella L., 2013. *Contaminated sites in Europe: review of the current situation based on data collected through a European Network.* Journal of Environmental and Public Health, 2013, 1-11. https://doi.org/10.1155/2013/158764

Paoletti L., Batisti D., Bruno C., Di Paola M., Gianfagna A., Mastrantonio M., Nesti M., Comba P., 2000. *Unusually high incidence of malignant pleural mesothelioma in a town of Eastern Sicily: An epidemiological and environmental study.* Archives of Environmental Health: An International Journal, 55 (6), 392-398. https://doi.org/10.1080/00039890009604036

Pinizzotto M.R., Cantaro C., Caruso M., Chiarenza L., Petralia C., Turrisi S., Brancato A., 2018. *Environmental monitoring of airborne fuoro-edenite fbrous amphibole in Biancavilla (Sicily, Italy): a nine-years survey.* Journal of Mediterranean Earth Sciences, 10, 89-95. https://doi.org/10.3304/JMES.2018.018

Rapisarda V., Ledda C., Ricceri V., Arena F., Musumeci A., Marconi A., Fago L., Bracci M., Santarelli L., Ferrante M., 2015. *Detection of pleural plaques in workers exposed to inhalation of natural fluoro-edenite fibres.* Oncology Letters, 9 (5), 2046-2052. https://doi.org/10.3892/ol.2015.2978

Shepard D., 1968. *A two-dimensional interpolation function for irregularly-spaced data.* Proceedings of the 23rd ACM national conference, 517-524. https://doi.org/10.1145/800186.810616

Sudharsan S., Hemalatha R., Radha S., 2019. *A survey on hyperspectral imaging for mineral exploration using machine learning algorithms.* 2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), 206-212. https://doi.org/10.1109/WiSPNET45539.2019.9032740

Warr L.N., 2021. *IMA-CNMNC approved mineral symbols.* Mineralogical Magazine, 85 (3), 291-320. https://doi.org/10.1180/mgm.2021.43

Zhai X., Zhang Y., Wang X., Xia J., Liang T., 2014. *Non-point source pollution modelling using Soil and Water Assessment Tool and its parameter sensitivity analysis in Xin'anjiang catchment, China.* Hydrological Processes, 28 (4), 1627-1640. https://doi.org/10.1002/hyp.9688

Zhu K., Chen L., Li L., Wang Y., Yan X., Chen J., Feng C., Shen Z., 2023. *New distributed model for predicting erosion-type pollution by integrating sediment connectivity and watershed model.* Environmental Modelling & Software, 162, 105662. https://doi.org/10.1016/j.envsoft.2023.105662

Zingaro M., 2021. *Advanced analysis and integration of remote sensing and in situ data for flood monitoring*. Rendiconti Online della Società Geologica Italiana, 54, 41-47. https://doi.org/10.3301/ROL.2021.08

Zingaro M., Refice A., D'Addabbo A., Hostache R., Chini M., Capolongo D., 2020. *Experimental spplication of Sediment Flow Connectivity Index (SCI) in flood monitoring*. Water, 12 (7), 1857. https://doi.org/10.3390/w12071857

Zingaro M., Refice A., Giachetta E., D'Addabbo A., Lovergine F., De Pasquale V., Pepe G., Brandolini P., Cevasco A., Capolongo D., 2019. *Sediment mobility and connectivity in a catchment: a new mapping approach*. Science of The Total Environment, 672, 763-775. https://doi.org/10.1016/j.scitotenv.2019.03.461

Zingaro M., Scicchitano G., Palmentola P., Piscitelli A., Refice A., Roseto R., Scardino G., Capolongo D., 2023. *Contribution of the Sediment Flow Connectivity Index (SfCI) in landscape archaeology investigations: test case of a new interdisciplinary approach*. Sustainability, 15 (20), 15042. https://doi.org/10.3390/su152015042

Zingaro M., Scicchitano G., Refice A., Marsico A., Kushabaha A., Elia M., Lafortezza R., Capolongo D., 2024. *Assessing the impact of vegetation cover changes and post-fire effects through an enhanced sediment flow connectivity index (SfCI)*. CATENA, 247, 108474. https://doi.org/10.1016/j.catena.2024.108474

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