AN EXPERIMENTAL APPROACH TO MAPPING EXPOSURE IN CONTAMINATED SITES[1]

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Abstract. The management of Sites of National Interest (SIN) in Italy represents a major environmental, health, and social challenge, as these areas often face severe socio-economic problems and a high risk of social inequality. This paper proposes an experimental approach to map population exposure in contaminated areas, operating on two territorial levels: sub-municipal, through the aggregation of Istat enumeration areas, and supra-municipal, through clusters of municipalities, in order to represent different levels of pollutant exposure. By integrating GIS-based proximity analysis with census and environmental data, the approach allows exploration of spatial gradients of potential exposure beyond administrative boundaries. Applied to the Sulcis–Iglesiente–Guspinese SIN (Sardinia), it aims to support complex environmental and social issues, highlighting areas that may be more vulnerable. It is conceived as a replicable tool to support evidence-based governance at multiple territorial levels.

1. Introduction and literature review

The management of contaminated sites and the assessment of their environmental and social impacts represent a global challenge. Research on environmental justice, initially developed in the United States, has shown that exposure to contaminants is unevenly distributed among social groups, with the most severe impacts on vulnerable communities characterized by lower education levels, reduced income, or minority status (Bullard, 2000; Brulle and Pellow, 2006; Mohai and Saha, 2006). These studies introduced the concept of environmental inequality as a key consideration for planning remediation and mitigation policies.

At both European and national levels, epidemiological and risk assessment studies have documented similar dynamics. The European Environment Agency (2018) and the World Health Organization (WHO, 2010) emphasize the importance of integrating environmental and socio-demographic data to identify the populations most exposed. In Italy, the SENTIERI project provides systematic evidence on mortality and morbidity in proximity to Sites of National Interest (SIN, see §2),

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highlighting particularly severe impacts on socially disadvantaged communities (Pirastu *et al*., 2013; SENTIERI VI Working Group, 2023). In recent studies additionally highlight the relationship between environmental degradation and socio-territorial vulnerability, underlining the need for integrated approaches to spatial planning and contaminated site governance (Pasetto, 2022; Scognamiglio, 2023).

From a methodological perspective, the study relies on spatial analysis methods, using Geographic Information Systems (GIS) to integrate Istat census data and apply distance-based spatial models to estimate territorial risk and identify potentially exposed populations in contaminated sites (ATSDR, 2005). Specifically, proximity and buffer analyses are employed to represent spatial gradients of potential exposure, assuming that pollutant concentrations decrease with increasing distance from contamination sources (Anderton *et al*., 1994; Chakraborty *et al.*, 2011).

The two most common approaches to quantifying exposure are *spatial coincidence*, which identifies the exposure area to environmental risk with the boundaries of the territorial units where pollution sources are located and buffer analysis (Chakraborty and Armstrong, 2001; Mohai and Saha, 2006) which defines concentric zones around the source. Both approaches assume that proximity to the source corresponds to higher exposure (Anderton *et al.*, 1994; Chakraborty *et al.*, 2011).

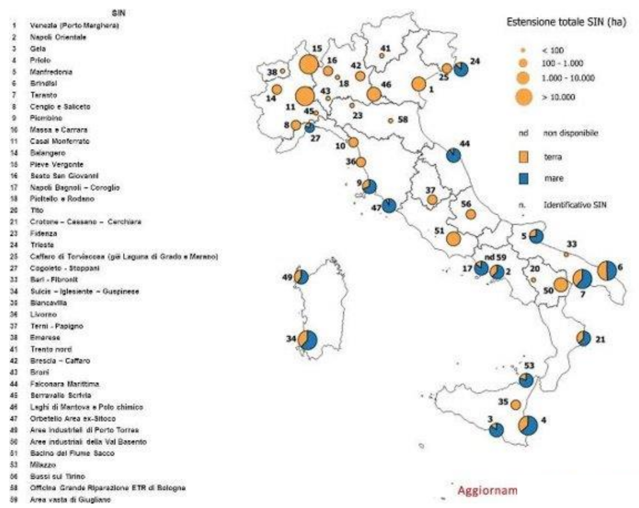
This study applies these methods across two territorial levels with the aim of identifying the influence areas of contamination sources and grading the risk of affected territories; the sub-municipal level which allows high-resolution mapping in areas close to contamination sources, and the supra-municipal level which aggregates municipalities into statistically robust units, supporting local governance, planning, and comparisons across different sites.

2. Sites of National Interest (SIN): characteristics, risks and governance

Sites of National Interest (SIN) are officially designated areas recognized for their high levels of environmental contamination and the associated risks to human health and ecosystems (Figure 1). SINs are characterized by complex contamination profiles affecting multiple environmental matrices—soil, groundwater, surface water, and air—which interact to generate cumulative risk processes (Briggs, 2003; Landrigan *et al.*, 2018).

Contamination in these territories primarily stems from past and/or ongoing human activities, including industrial, mining, port and maritime activities, and waste disposal operations, often persisting over long periods. The situation is further exacerbated by delayed remediation, insufficient environmental controls, and inadequate land-use planning (Comba *et al.*, 2014; ISPRA, 2024).

Figure 1 – *Italian Sites of National Interest (SIN).*



Source: Ministry of Environment and Energy Security

The main sources of contamination include former metallurgical and petrochemical plants, mining districts, decommissioned industrial zones, and poorly managed or illegal landfills. Such activities have produced complex exposure scenarios affecting both environmental quality and public health.

Scientific literature identifies three main analytical dimensions of SINs for assessment: (i) multi-matrix contamination, where pollutants interact across different environmental components (Briggs, 2003; Landrigan *et al.*, 2018); (ii) documented health impacts, supported by epidemiological and mortality evidence (Comba *et al.*, 2014; SENTIERI VI Working Group, 2023); (iii) socio-territorial inequalities, stemming from processes of marginalization and unequal exposure (Bullard, 2000; Mohai and Saha, 2006).

From an institutional perspective, the coordination of SIN management is assigned by Italian law[2] to the Ministry of Environment and Energy Security (MASE), in collaboration with the Ministry of Health. Management decisions follow integrated criteria combining environmental and health risk assessments (ISPRA, 2024). The primary policy goal is the sustainable remediation and reuse of contaminated areas. However, high costs, technical complexity, and long implementation times continue to challenge remediation efforts, underlining the need for robust analytical tools to support planning and governance.

[2] Legislative Decree n. 152 of 3 April 2006, the so-called "Consolidated Environmental Act".

In line with European policy directions, the European Commission (2022) emphasizes integrated, multisectoral, and participatory governance approaches for contaminated site management, incorporating ecological, social, and health dimensions. This perspective aligns with the environmental justice literature, highlighting that SIN management should focus not only on physical remediation but also on reducing territorial and social inequalities.

The Sulcis–Iglesiente–Guspinese SIN provides a paradigmatic example of such complex contamination profiles and socio-environmental challenges, as discussed in the following section.

3. The case study

The Sulcis–Iglesiente–Guspinese SIN, located in South-western Sardinia, exemplifies the intersection between historical industrialisation[3], socio-economic fragility, and environmental risk (Figure 2). The coexistence of legacy mining and metallurgical activities with more recent petrochemical complexes illustrates how cumulative industrial legacies can amplify territorial vulnerability. Long-term demographic decline, population ageing, and limited economic diversification further reduce the area's adaptive capacity.

For over a century, the territory has been subjected to intensive mining and industrial operations that have produced widespread multi-source contamination across environmental matrices such as soil, groundwater, surface water, and air. The persistence of heavy metals, hydrocarbons and other industrial pollutants reflects the complexity of cumulative risk processes that continue to affect both ecosystems and human health (Comba *et al.*, 2014).

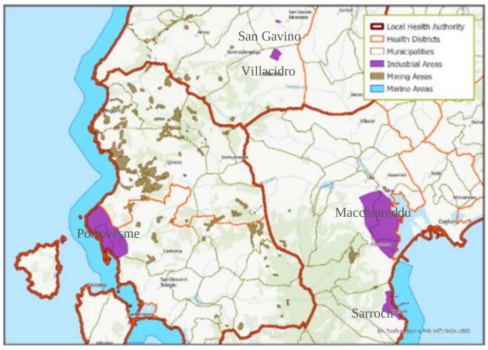
Environmental degradation is closely mirrored by adverse health outcomes, including excess mortality and higher hospitalisation rates for cancer, respiratory, and cardiovascular diseases, consistent with chronic exposure to industrial contaminants (SENTIERI VI Working Group, 2023). Combined with socio-economic vulnerability, these patterns point to a cumulative condition of environmental and social fragility.

The Sulcis–Iglesiente–Guspinese SIN also serves as a pilot site within the One Health Citizen Science (OHCS), initiative promoted by the Italian Ministry of Health. The project integrates environmental and health data to apply the One Health

[3] In particular, the Portovesme industrial complex, historically linked to non-ferrous metal processing, exemplifies persistent soil and groundwater contamination, sometimes accompanied by polycyclic aromatic hydrocarbons (PAHs) and fluorides. Other sites, including Sarroch and Macchiareddu, dominated respectively by petrochemical and chemical production, show contamination associated with hydrocarbons and organochlorine compounds (BTEX, dichloroethane). Additional areas, such as Portoscuso, San Gavino Monreale, and Villacidro, illustrate the diffuse and multi-source nature of contamination across the territory.

approach to contaminated sites, strengthening monitoring and prevention strategies while fostering interdisciplinary and participatory models of environmental governance. This pilot context provides an ideal setting for testing the dual-level analytical approach proposed in this study.

Figure 2 – *Sulcis-Iglesiente-Guspinese SIN.*



Source: our elaboration on MASE and Istat data

4. Methods

4.1 Methodological design

This methodological framework is applied to the Sulcis–Iglesiente–Guspinese SIN, providing a concrete example of how sub-municipal and supra-municipal territorial level can capture environmental exposure.

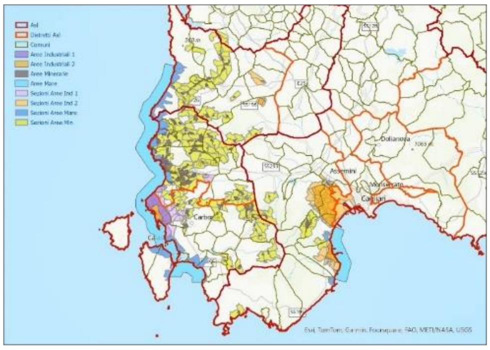
Building on the methodological considerations outlined in Section 1, the study adopts a two-tier territorial framework to assess exposure and vulnerability in contaminated sites. While spatial coincidence and buffer analysis define exposure metrics, the sub-municipal and supra-municipal levels represent complementary dimensions tailored for SINs.

The sub-municipal level allows high- resolution mapping of areas near contamination sources, supporting identification of potentially exposed populations and delineation of high-risk zones. The supra-municipal level aggregates municipalities into statistically coherent units, facilitating the integration of demographic, environmental, and epidemiological data to support broader planning and governance. By combining these two levels, the framework provides a two-tiered perspective on environmental vulnerability, capturing local specificity while linking it to wider socio-territorial dynamics. This approach is designed to be transferable to other SINs, allowing comparative analyses across different contaminated contexts (Chakraborty *et al.*, 2011).

4.2 GIS-based spatial modelling

Geographic Information Systems (GIS) provided the analytical environment for integrating and visualising spatial data from heterogeneous sources. ArcGIS software was used to model the potential influence zones around contaminated sites through the creation of distance-based buffers. This spatial modelling follows the distance–decay principle, according to which pollutant concentrations tend to decrease with increasing distance from the source (Zandbergen and Chakraborty, 2006).

Figure 3 – *SIN Sulcis Iglesiente Guspinese - overlay of Istat enumeration areas.*



Source: our elaboration on MASE and Istat data

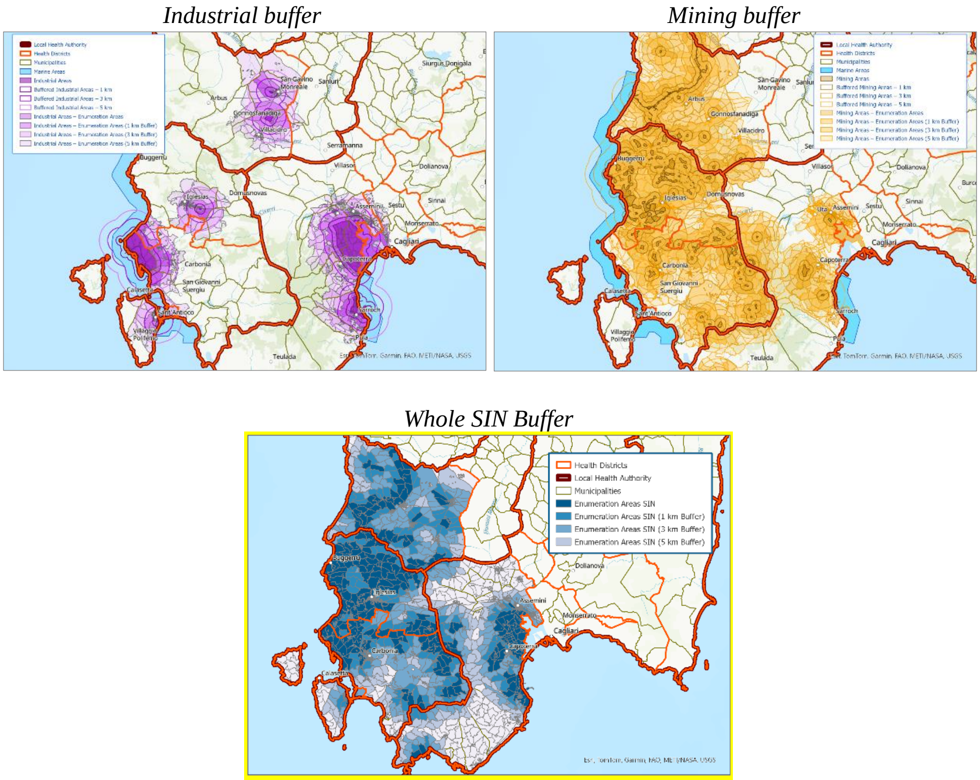
Boundaries of contaminated areas, provided by the Ministry of Environment and Energy Security (MASE), were intersected with 2021 Istat enumeration areas to identify local exposure patterns (Figure 3). Resulting polygons were overlaid with administrative boundaries to ensure spatial coherence across governance levels.

The delineation of influence zones provides the spatial foundation for subsequent multi-thematic analyses of exposure and vulnerability, ensuring consistency with epidemiological frameworks and supporting various levels of local governance, including Health Districts (HD) and Local Health Authorities (LHA).

4.3 Sub-municipal analysis

At the sub-municipal level, Istat enumeration areas serve as the basic spatial unit. All sections intersecting the boundaries of the contaminated site (buffer 0) were included. From the boundary of each section, concentric zones with radii of 1 km, 3 km, and 5 km were drawn (APAT, 2004), which allowed additional sections to be included and classified according to potential exposure, assuming a gradual decrease in risk with distance (Figure 4, Table 1).

Figure 4 – *Influence buffers of Mining, Industrial, and Whole SIN – Sub-municipal level.*



Source: our elaboration on MASE and Istat data

Table 1 - *Mining, Industrial and Whole SIN sub-municipal areas by buffer - Year 2021.*

	Mining		Industrial		Whole Sin	
buffer	**n. en_areas**	**area (km^2)**	**n. en_areas**	**area (km^2)**	**n. en_areas**	**area (km^2)**
0	339	796,1	167	217,7	503	1.006,7
1	613	548,8	254	125,0	832	606,1
3	1.068	797,1	762	319,0	1.233	885,8
5	641	581,6	582	372,0	591	558,8
9	1.420	1.102,3	2.316	2.792,3	922	769,0
Total	4.081	3.826,0	4.081	3.826,0	4.081	3.826,4

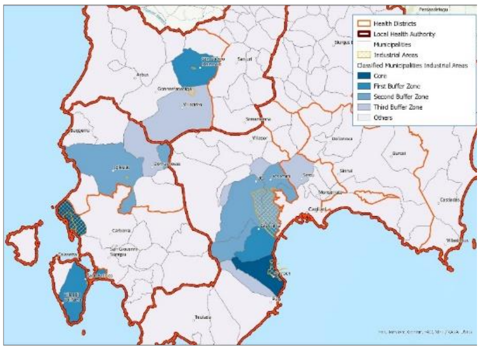
Industrial and mining sites were initially analyzed separately and then combined, assigning each section the highest corresponding risk class. This approach provides a continuous representation of exposure gradients and highlights inhabited areas most directly affected by contamination. The sub-municipal framework supports detailed population-based exposure assessment and informs local planning and targeted interventions.

4.4 Supra-municipal analysis

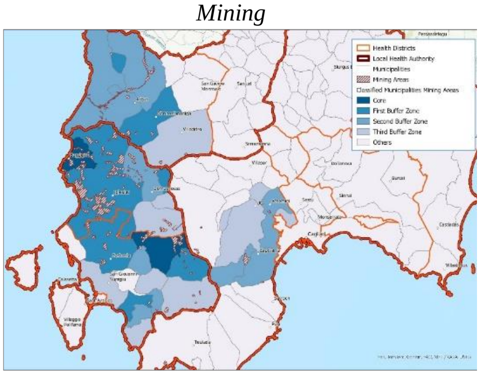
At the supra-municipal level, municipalities are aggregated into statistically coherent territorial units based on spatial proximity and the proportion of residents within exposure buffers. This procedure generated five territorial risk bands - Core, Buffer 1 (0–1 km), Buffer 2 (1–3 km), Buffer 3 (3–5 km), and Outer Zone (>5 km) - ensuring statistical robustness and comparability (Figure 5, Table 2).

Figure 5 - *Municipalities by environmental risk zone – Supra-municipal level.*

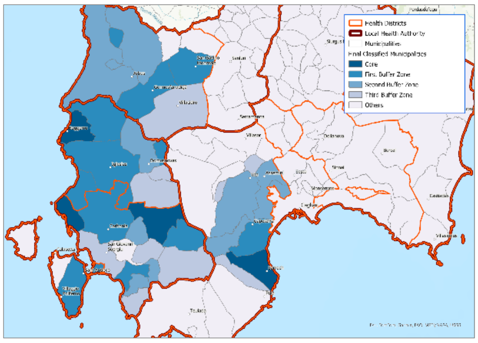
Industrial



Mining



Whole SIN



Source: our elaboration on MASE and Istat data

Table 2 - *Mining Industrial and Whole SIN Municipalities and areas by buffer(a)–Year 2021.*

	Mining		**Industrial**		**Whole SIN**	
Areas	**n. municipalities**	**area (km^2)**	**n. municipalities**	**area (km^2)**	**n. municipalities**	**area (km^2)**
Core	2	134,2	2	105,9	4	240,1
First buffer zone	7	727,2	3	243,8	10	971,0
Second buffer zone	8	781,1	4	475,2	9	861,4
Third buffer zone	10	733,6	4	331,7	9	624,7
Others	19	1.446,7	33	2.666,3	14	1.125,6
Total	46	3.822,9	46	3.822,9	46	3.822,9

(a) The difference in area compared to Figure 4 is due to different rounding methods used at the municipal and section levels

Together, the two scales of analysis offer a complementary perspective on environmental vulnerability: the sub-municipal level captures the spatial specificity of exposure, while the supra-municipal level translates these insights into actionable knowledge for health management and territorial policy (Chakraborty *et al.*, 2011; SENTIERI VI Working Group, 2023).

5. Preliminary results and discussion

This section presents preliminary findings for the Sulcis Local Health Authority (LHA), a subset of the Sulcis–Iglesiente–Guspinese SIN encompassing three Health Districts (HD): Carbonia, Iglesias, and Isole Minori. The study area includes 1,842 Istat enumeration areas covering 1,342.8 km², with a total population of 119,086 in 2021, nearly half residing in the Carbonia HD (Table 3). Marked spatial heterogeneity emerges across the HDs.

Table 3 – *Enumeration areas and population within buffers –Sulcis LHA.*

HD Buffer	**Carbonia HD**				**Iglesias HD**				**Isole minori HD**				**LHA**			
	pop	**n. en_areas**	**area (km^2)**	**en_areas with pop**	**pop**	**n. en_areas**	**area (km^2)**	**en_areas with pop**	**pop**	**n. en_areas**	**area (km^2)**	**en_areas with pop**	**pop**	**n. en_areas**	**area (km^2)**	**en_areas with pop**
HD	54.858	923	668,3	548	44.687	693	605,0	333	19.541	226	69,6	126	119.086	1.842	1.343	1.007
0	6.992	146	226,8	68	3.666	187	389,8	50	961	6	3,5	4	11.619	339	620	122
1	15.996	225	137,2	147	22.905	259	132,7	150	4.296	36	9,1	24	43.197	520	279	321
3	18.095	268	218,7	180	12.695	175	55,4	106	5.287	55	26,4	29	36.077	498	301	315
5	10.353	151	85,6	92	5.418	66	27,1	26	130	14	30,6	7	15.901	231	143	125
9	3.422	133	-	61	3	6	-	1	8.867	115	-	62	12.292	254	-	124

Source: our elaboration on MASE and Istat data

Within the Carbonia HD, about one-quarter of enumeration areas lie within one kilometer of a contaminated site, involving roughly 16,000 inhabitants.

In the Iglesias HD, more than half of the population (51.3%) lives within this proximity range, reflecting the historical persistence of mining and metallurgical activities that produced the highest density of contaminated areas in the region. The Isole Minori HD, though smaller, also shows a high proportion of residents in the first buffer zone, accounting for more than half of its total population.

At the supra-municipal scale, the 23 municipalities of the Sulcis LHA were classified into five environmental risk zones (Table 4). The Core zone, corresponding to the areas of highest contamination, hosts around 9,000 residents, while the first buffer includes more than 60% of the LHA population (around 73,000 inhabitants). Population density is therefore highest in areas under territorial pressure, particularly in the Carbonia HD, where industrial and residential functions have historically coexisted.

These results show that industrial legacies continue to shape the spatial overlap between environmental pressure and population concentration. The persistence of this alignment suggests cumulative vulnerability within specific territorial clusters, reinforcing the need for place-based approaches to health surveillance, remediation, and environmental governance.

Table 4 – *Municipalities and population by environmental risk zone – Sulcis LHA.*

Areas	Carbonia HD			Iglesias HD			Isole minori HD			LHA Sulcis		
	n. municipalities	area (km^2)	pop	n. municipalities	area (km^2)	pop	n. municipalities	area (km^2)	pop	n. municipalities	area (km^2)	pop
Core	2	124,0	7.974	1	48,0	1.053				3	172,0	9.027
First buffer zone	3	238,0	29.939	3	364,0	32.760	1	87,9	10.756	7	689,9	73.455
Second buffer zone	3	70,0	3.369	1	81,0	5.922				4	151,0	9.291
Third buffer zone	4	262,0	12.556	2	112,0	4.952				6	374,0	17.508
Others	1	31,0	1.020				2	82,0	8.785	3	113,0	9.805
Total	13	725,0	54.858	7	605,0	44.687	3	169,9	19.541	23	1.499,9	119.086

Source: our elaboration on MASE and Istat data

6. Conclusions and perspectives

This study proposes a two-tier territorial framework for assessing population exposure and environmental risk in contaminated sites. By integrating environmental, demographic, and health data at both sub-municipal and supra-municipal levels, the approach provides a conceptual and operational basis for more detailed analyses of exposure gradients and socio-environmental vulnerability. The Sulcis–Iglesiente–Guspinese SIN serves as an initial application of this framework, aimed at testing its spatial coherence and potential usefulness for environmental planning and governance.

Preliminary results highlight spatial and demographic patterns that may reflect the lasting influence of historical industrial activities, but further investigation is required to validate these patterns through the integration of environmental, health, and socio-economic indicators. The integration of environmental, demographic, and health data within these new territorial divisions enables the construction of more robust and representative indicators, helping to overcome the limitations of formal administrative boundaries.

Future developments will extend the application of this methodology to other SINs to test its robustness and adaptability across different contexts, ultimately supporting more equitable and spatially informed environmental health governance. Overall, the proposed framework offers a replicable approach to integrate environmental, demographic, and health data, strengthening governance and decision-making at multiple territorial levels.

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