1.3 Early Warning for All in Volcanology: Case Study Series, Part IV (Phlegrean Fields, Italy)

Introduction: The Role of the Italian Civil Protection Department and INGV

The Department of Civil Protection (DPC), under the Presidency of the Council of Ministers, coordinates the Italian National Civil Protection Service and is responsible for national emergency planning, risk coordination, preparedness activities, and response management during natural hazards and emergencies. For volcanic risk, DPC defines national emergency strategies, supports regional and local authorities, coordinates preparedness exercises, and ensures the integration of scientific information into operational decision-making.

A fundamental pillar of the Italian volcanic monitoring framework is the synergy between the DPC and the Istituto Nazionale di Geofisica e Vulcanologia (INGV). Specifically, the Osservatorio Vesuviano (INGV-OV), established in 1841 as the first volcano observatory globally, oversees the surveillance of active volcanic systems in southern Italy, including Campi Flegrei, Vesuvius, and Ischia. INGV conducts continuous monitoring of activity of volcanoes through sophisticated observational networks equipped with cutting-edge instrumentation. These systems are managed 24/7 by two operational centres, including the one located at the Naples (INGV-OV). As an operational branch of the National Civil Protection Service (under D.L. 381/1999 and D. Lgs.1/2018), INGV provides regular status updates to the DPC. This collaborative effort is primarily aimed at mitigating the natural risks inherent to the complex dynamics of volcanic systems.

At Campi Flegrei, INGV operates one of the world's most advanced volcanic monitoring systems, integrating:

- seismic monitoring,
- geodetic measurements (GNSS, tiltmeters, dilatometers, tide-gouges),
- satellite geodesy,
- geochemical monitoring of hydrothermal emissions and groundwater,
- gravimetric measurements,
- thermal monitoring,
- periodic field surveys.

These multidisciplinary observations are continuously analysed to analyse seismicity, detect changes in the hydrothermal-magmatic system, assess unrest evolution, and support forecasting activities. INGV provides routine bulletins, weekly and monthly reports, rapid communications during seismic swarms and other significant phenomena, and scientific assessments to DPC and local authorities. This operational scientific support constitutes the backbone of the volcanic early warning chain at Campi Flegrei.

The collaboration between DPC and INGV represents a long-established science–policy interface in which monitoring data, hazard scenarios, emergency planning, and public communication are continuously integrated. During the recent bradyseismic crisis, this coordination became particularly important as accelerating ground uplift, frequent felt earthquakes, and increased public concern required constant interaction between scientists, civil protection authorities, municipalities, emergency responders, and communities.



Figure 1 – View of Solfatara crater, site of intense hydrothermal activity.

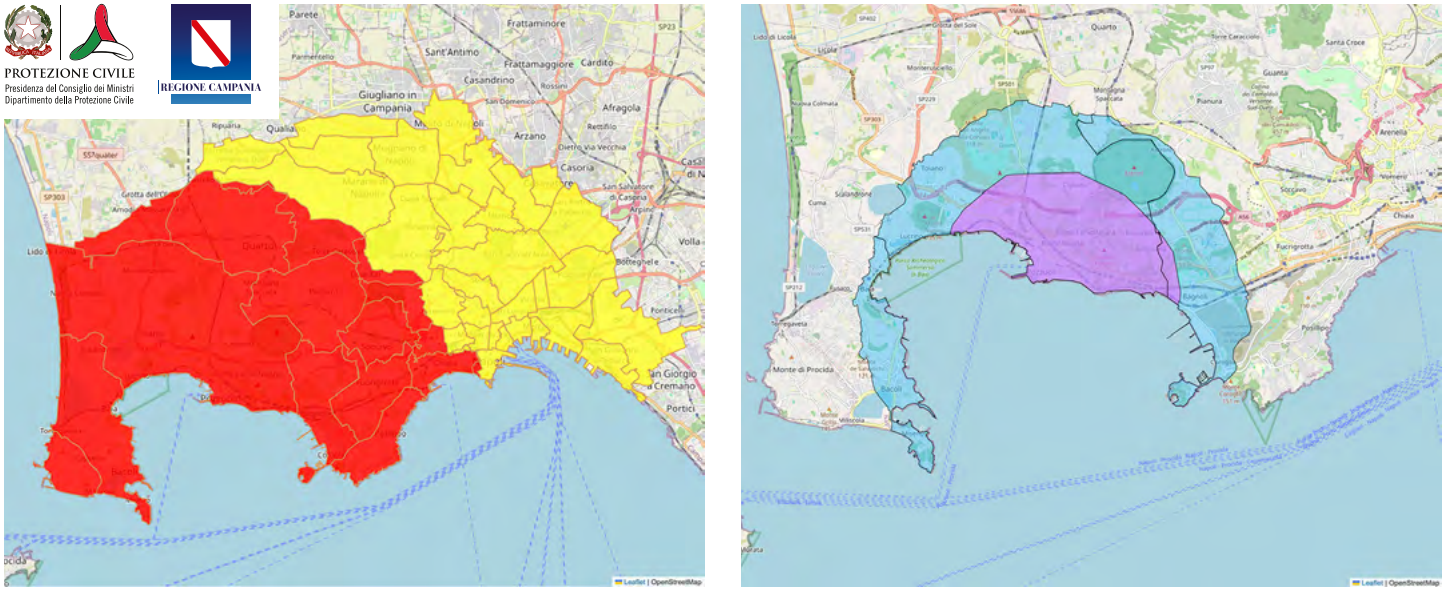

Figure 2 – On the left the red zone and the yellow zone of the National Emergency plan for volcanic risk. On the right the intervention areas for the bradyseism risk management.

The Campi Flegrei case therefore illustrates how scientific monitoring and civil protection governance must function together within a multi-hazard early warning framework, where monitoring alone is insufficient without effective communication, preparedness, and institutional coordination.

Volcanological and Risk Context

Campi Flegrei is a large active caldera located in Campania Region west of the city of Naples in southern Italy. The area hosts intense urbanization, critical infrastructure, cultural heritage sites, and a resident population of several hundred thousand people exposed to volcanic, seismic, and hydrothermal hazards (Figure 1).

The caldera is characterized by bradyseism, a phenomenon involving slow ground uplift and subsidence associated with the dynamics of the hydrothermal-magmatic systems. Bradyseismic crises are commonly accompanied by shallow earthquakes and ground deformation, which may damage buildings and infrastructure and generate significant societal impacts. Main historical crises occurred between 1969–1972 and 1982–1984, when approximately 40.000 residents were evacuated from the municipality of Pozzuoli due to intense uplift and seismic activity.

Since 2005, Campi Flegrei has entered a new unrest phase characterized by progressive uplift, increasing seismicity, and enhanced degassing. Recent studies indicate that uplift at Pozzuoli has exceeded 1.6 m since 2006 and that magma and magmatic gases likely contribute to the ongoing unrest.

The crisis intensified between 2023 and 2025, with frequent seismic swarms and earthquakes exceeding magnitude 4 affecting Pozzuoli and nearby municipalities. Although no eruption occurred, the unrest generated multi-hazard impacts including structural damage, temporary evacuations, disruption of daily life, and heightened public anxiety. The Campi Flegrei crisis therefore represents a complex example of volcanic risk where non-eruptive impacts can become a major emergency management issue.

Cross-Pillar EW4All in Practice

As highlighted in other IAVCEI EW4All case studies, effective volcanic early warning depends on the interaction of all four pillars rather than on monitoring alone.

Pillar 1: Disaster Risk Knowledge and Management
Long-term volcanic hazard assessment and emergency planning form the foundation of risk management at Campi Flegrei. The **National Emergency Plan for volcanic risk** defines hazard scenarios and identifies a **red zone**, where preventive evacuation of the population is the principal protective measure against pyroclastic density currents, and a **yellow zone**, potentially exposed to significant accumulations of volcanic ash. This planning provides the framework for preparedness for a possible future eruption (Figure 2).

Following the intensification of the unrest in 2023, the Italian Government therefore introduced specific measures for the prevention and management of seismic risk associated with bradyseism. These measures provided an important bridge between scientific knowledge of the evolving phenomenon and knowledge of the exposed and vulnerable elements of the territory.

A key outcome was the **Emergency Plan for the Campi Flegrei bradyseismic area**, developed by the DPC in coordination with the Campania Region, the Prefecture of Naples and the relevant territorial authorities, and based on municipal and national civil protection plans and hazard knowledge provided by the scientific community.

The resulting intervention area, covering parts of Pozzuoli, Bacoli and Naples municipalities, includes approximately 85.000 inhabitants and 15.500 residential buildings. Within it,

ALERT LEVEL	VOLCANO STATUS	EXPECTED CHANGES IN MAIN MONITORING PARAMETERS	PROBABILITY OF EVOLUTION TOWARDS AN ERUPTION	EXPECTED DURATION AT THIS LEVEL (DEGREE OF UNCERTAINTY)	POSSIBLE HAZARDS
GREEN	QUIESCENT	**Monitoring parameters within baseline values:** • Absence of medium-to-long term ground uplift or subsidence • Seismicity mostly absent • Fumarolic gases mainly hydrothermal in origin; hydrothermal system pressure and temperature stable over time	VERY LOW	NOT DEFINED	- CO_2 concentrations occasionally at potentially hazardous levels to human health near emission sites, in downwind sectors, morphologically depressed zones, or enclosed spaces
YELLOW	LOW UNREST	**One or more monitoring parameters above baseline values, slowly progressing and/or prolonged over time:** • Uplift of the caldera center at slow speed with radial geometry • Sporadic, low-energy volcano-tectonic seismicity • Slight increase in magmatic component in fumarolic gases; increase of CO_2 and degassing areas. Minor changes in the hydrothermal system equilibrium pressure and temperature	LOW	NOT DEFINED	- CO_2 concentrations occasionally at potentially hazardous levels to human health near emission sites (also diffusive), in downwind sectors, morphologically depressed zones, or enclosed spaces - Occasionally felt seismic shaking
	MEDIUM UNREST	**Monitoring parameters above baseline values, showing progression over time:** • Uplift of the caldera center at moderate speed with general radial geometry • Frequent volcano-tectonic seismicity with maximum magnitude (Md) sporadically between 4 and 4.5 • Moderate increase of the magmatic component in fumarolic gases; increase in CO_2 flux and extension of degassing areas. Further variations in the hydrothermal system equilibrium pressure and temperature	LOW-TO-MEDIUM	NOT DEFINED	- Potentially hazardous concentrations of CO_2 and H_2S to human health near emission areas (including diffusive), in downwind sectors, morphologically depressed zones or enclosed spaces - Light to occasionally strong seismic shaking near epicentral areas - Localized phreatic explosions in areas with intense hydrothermal activity - Seismic induced landslides near epicentral areas
ORANGE	HIGH UNREST	**Monitoring parameters significantly above baseline values, with an ongoing progression:** • Uplift of the caldera center at moderate-to-high speed with general radial geometry • Very frequent volcano-tectonic seismicity with repeated events of magnitude (Md) between 4 and 4.5 • Significant increase of the magmatic component in fumarolic gases and of the hydrothermal system equilibrium pressure and temperature values; further expansion of degassing areas	MEDIUM	WEEKS/MONTHS/YEARS (VERY HIGH)	- High concentrations of CO_2 and H_2S, potentially hazardous to human health, near emission areas (including diffusive), in downwind sectors, morphologically depressed zones or enclosed spaces - Strong seismic shaking near epicentral areas - Localized phreatic explosions in areas with intense hydrothermal activity - Seismic induced landslides near epicentral areas
	VERY HIGH UNREST	**Monitoring parameters well above baseline values, with further progression:** • High-speed ground uplift with radial geometry, eventually not centered in the caldera. Surface fractures may open. • Very frequent volcano-tectonic seismicity with general increase in maximum magnitude (eventually up to Md = 5). Possible appearance of long-period (LP) seismicity • Further geochemical variations with expansion of degassing areas and new emission points. • Sudden changes in groundwater level, temperature, and salinity. Possible appearance of SO_2 in fumarolic fluids	MEDIUM-TO-HIGH	WEEKS/MONTHS/YEARS (VERY HIGH)	- High concentrations of CO_2 and H_2S, potentially hazardous to human health, near emission areas (including diffusive), in downwind sectors, morphologically depressed zones or enclosed space - Intensification of hydrothermal activity and expansion of high-emission areas with increased likelihood of phreatic explosions - Strong and frequent seismic shaking near epicentral areas - Seismic induced landslides near epicentral areas - Surface fracturing in areas experiencing the greatest uplift
RED	PRE-ERUPTIVE	**Monitoring parameters at very high levels and rapidly evolving:** • Very high-speed uplift with non-radial geometry. Deformation maxima may localize in association with surface fracturing and/or faulting, sometimes associated with water or fumarolic fluid emission • Extremely frequent volcano-tectonic seismicity eventually migrating towards the surface. Possible increase of the maximum Md also over 5 and occurrence of LP seismicity. • Strong increase in gas flux, significant rise of the temperatures, rapid changes (days/hours) in gas chemistry, appearance and/or increase of SO_2, and possible presence of other acidic gases (HF, HCl) Possible identification of the area with the highest probability of eruptive vent opening.	VERY HIGH	HOURS/DAYS (LOW)	- CO_2-SO_2 gas emissions from areas of maximum uplift and surface fracturing - Further intensification of hydrothermal activity with expansion of the emission zones and higher probability of hydrothermal and/or phreatic explosions - Very frequent and intense seismic shaking - Seismic induced landslides near epicentral areas - Rapid and localized uplift with surface faulting/fracturing - Opening of new degassing areas associated with possible phreatic explosions

Figure 3 – New alert level scheme for Campi Flegrei.

a more restricted intervention area – where the most significant widespread effects could occur should bradyseism continue or intensify – includes approximately 34.000 inhabitants and 6.900 residential buildings.

Because the evolution of bradyseism cannot be predicted deterministically, the Emergency Plan does not rely on predefined alert-level transitions. Instead, it identifies **three operational scenarios based on the observed impacts of seismicity and deformation on buildings, infrastructure and essential services**, ranging from limited and localized damage to a situation involving significant structural damage and disruption of essential services. This impact-based approach provides a particularly relevant example of the connection between Pillar 1 and Pillar 4: risk knowledge is explicitly designed to support operational decisions.

Following major advances in volcano science and monitoring capability, the Commission for Forecasting and Preventing Major Risks—Volcanic Risk Sector recommended in May 2024 a prompt revision of the alert-level scheme within the National Emergency Plan for volcanic risk to align operational guidance with the current state of scientific knowledge.

The revised alert-level scheme (Figure 3) adopts a structure consistent with other Italian volcanic systems and is organized around five core fields: volcano state, expected variations in key monitoring parameters, probability of evolution toward eruption, expected persistence time at each level, and possible hazardous phenomena. The scheme distinguishes between quiescent conditions (green), weak and moderate disequilibrium (yellow), strong and very strong disequilibrium (orange), and pre-eruptive conditions (red).

In parallel, the DPC, in agreement with the Campania Region, developed a preliminary set of operational phases linked to the updated alert levels.

The Alarm phase entails full evacuation of the Campi Flegrei red zone, transfer and reception of the population in paired Regions and Autonomous Provinces.

Pillar 2: Detection, Observation, Monitoring, Analysis and Forecasting

INGV operates one of the world's most advanced volcanic monitoring systems at Campi Flegrei. Continuous multidisciplinary monitoring allowed scientists to track significant variations in the dynamics of the volcano throughout the unrest phase.

Scientific bulletins, weekly reports, and regular coordination meetings between INGV and DPC ensured that monitoring information was continuously translated into operational assessments supporting civil protection decision-making.

Pillar 3: Warning Dissemination and Communication

The prolonged Campi Flegrei unrest demonstrated the importance of transparent, sustained, and people-centred communication. DPC, INGV, the Campania Region, and local authorities coordinated communication through institutional websites, media briefings, social media, public meetings, educational campaigns, and dedicated information portals.

Effort was devoted to explaining the meaning of bradyseism, the role of monitoring systems, and the uncertainty associated with volcanic forecasting. Maintaining public trust became essential as repeated earthquakes and media attention amplified concern among local communities.

The communication strategy increasingly emphasized preparedness rather than imminent eruption scenarios. Authorities sought to avoid both alarmism and complacency while ensuring that communities understood emergency procedures and the evolving risk conditions.

The national communication campaign *Io Non Rischio* ("I Don't Take Risks") also contributed to improving public awareness regarding volcanic and bradyseismic risk at Campi Flegrei.

Pillar 4: Preparedness and Response Capabilities

Preparedness and operational response were progressively strengthened during the unrest phase. DPC coordinated updates to emergency plans, evacuation procedures, inter-agency coordination mechanisms, and operational exercises.

National exercises were organized to test emergency planning for both bradyseismic and volcanic risk scenarios (1 in 2019, 4 in 2024 and 2 in 2025). The exercises included tabletop and full-scale phases involving civil protection authorities, municipalities, emergency services, scientific institutions, and cultural heritage stakeholders.

Operational measures during periods of intense seismicity included:

- rapid damage assessments,
- temporary school closures,
- assistance to affected residents,
- strengthening of local emergency coordination centres,
- and verification of evacuation routes and critical infrastructure.

These actions demonstrated that preparedness for volcanic unrest in Campi Flegrei must address both eruptive and non-eruptive emergency scenarios.

Challenges, Successes and Lessons Learned

The principal challenge at Campi Flegrei is managing a long-lasting and evolving crisis under substantial scientific uncertainty. Monitoring can identify changes in the volcanic system but cannot deterministically forecast whether or when unrest will culminate in eruption. At the same time, recurring earthquakes can generate immediate impacts requiring civil protection action. Sustaining monitoring, preparedness, communication and public trust over years rather than days or weeks places considerable demands on both scientific and civil protection institutions.

A major strength of the response has been the continuous interaction between DPC, INGV and local civil protection authorities, allowing monitoring information to feed into risk assessment and operational decision-making while preparedness and communication are adjusted as conditions evolve.

The Campi Flegrei experience highlights a broader lesson for EW4All: effective early warning during volcanic unrest does not depend on predicting an eruption. It depends on maintaining a functioning chain between observations, risk and impact assessment, communication, preparedness and action. When forecasting the evolution of unrest is intrinsically uncertain, observed and expected impacts provide an additional basis for proportionate operational decisions.

Campi Flegrei therefore shows how the four EW4All pillars can function as an adaptive system throughout a prolonged crisis – turning monitoring into knowledge, knowledge into decisions, and decisions into preparedness and action, even in the absence of an eruption.

Mauro A. Di Vito, *Istituto Nazionale di Geofisica e Vulcanologia [National Institute of Geophysics and Volcanology] (INGV)*
Luigi D'Angelo, *Dipartimento della Protezione Civile [Italian Civil Protection] (DPC)*
Antonella Scalzo, *DPC*
Domenico Mangione, *DPC*
Antonio Ricciardi, *DPC*
Lucia Pappalardo, *INGV*



Solfatara