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Assessment of the Environmental Risk in Seismic Area of "Phlegraean Fields" Italy. Note II: Risks Associated with Toxic Gas Emissions, Volcanic Ash, and Lava Flows

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Abstract

This study examines the geological and socio-economic risks associated with the "Phlegraean Fields" region, characterized by intense volcanic and geothermal activity. Key features of solfataras, including the emission of sulfurous gases (e.g., SO_2, H_2S, CO_2) and mineral deposits, highlight the area's geothermal potential and associated hazards. Risk matrices were developed to assess potential impacts from toxic gas emissions, volcanic ash, and socio-economic disruptions. The aim of the study is to develop risk matrices for risks associated with risks associated with explosive eruptions, earthquakes, and lava flows in seismic area of "Phlegraean Fields" Italy. The results emphasize the importance of continuous monitoring, early warning systems, and well-defined evacuation and emergency response plans to mitigate risks. Public education and investment in resilient infrastructure are crucial for reducing the long-term socio-economic and environmental impacts. The findings provide a framework for decision-makers to prioritize interventions and enhance community preparedness against volcanic hazards in the Campi Flegrei region.

Keywords: exposure, human health, hydrogen sulfide, infrastructure.

1. Introduction

Solfataras are specific forms of geothermal activity, which form under certain specific geological conditions. They are volcanic phenomena characterized by the emission of hot vapors and gases, mainly sulfurous, from cracks in the earth's crust [9, 12]. The emissions, in this case, are often associated with active or recent volcanic areas and are usually accompanied by deposits of sulfur and other minerals. The main characteristics of solfataras are represented by:

- gas emissions
- high temperatures
- mineral deposits
- geothermal activity.

The dominant gases emitted by solfataras are sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbon dioxide (CO_2) and water vapor (H_2O). The specific smell of "rotten eggs" is given by the presence of hydrogen sulfide (H_2S).

Emissions from solfataras have temperatures that can vary from a few tens of degrees Celsius to over 100°C. Around the cracks through which the gases escape, deposits of sulfur and other minerals often form, which can color the soil in shades of yellow, white and red. Solfataras are often indicators of geothermal activity, being associated with the presence of magma at relatively shallow depths below the earth's surface ([4, 5].

Although spectacular, solfataras can be dangerous due to toxic gases and high temperatures. Hydrogen sulfide (H_2S) is a toxic gas and can be lethal in high concentrations [3].

Examples of solfataras are those in "Phlegraean Fields", Italy, those in Iceland, or the Kawah Ijen volcano, Indonesia. The solfatara of "Phlegraean Fields", Italy is one of the best-known solfataras, located near Naples, is a major tourist attraction and geological research site ([3, 4, 5, 7]. Areas such as Hverir near Lake Myvatn [1] and other geothermal regions in Iceland have active solfataras. The Kawah Ijen volcano in Indonesia is known for its sulfur gas emissions and for the mining activity that extracts sulfur from its crater [2, 6]. Evaluating the potential impact of emissions on the environment, including air, water, soil and ecosystems, and assessing the impact on human health and material assets, such as housing, infrastructure and drinking water sources, is a valuable and particularly useful approach in risk analyses [11].The aim of the study is to develop risk matrices for risks associated with risks associated with explosive eruptions, earthquakes, and lava flows in seismic area of "Phlegraean Fields" Italy.

2. Material and Method

An useful tool in assessing the risks produced by the phenomena recorded at this level is the preparation of risk matrices. For this, it is necessary to identify and classify the risk sources, namely the identification of solfatares, fumaroles and other emission sources in the Campi Flegrei region, as well as classifying them according to their emission potential and impact on the environment and human health [10]. Probability assessment refers to the assessment of the probability of the occurrence of different emission scenarios, taking into account the frequency and intensity of geothermal and volcanic activity. It is useful to use historical data and models to estimate the probability of events such as small eruptions or massive gas releases. The preparation of a risk matrix that classifies the different emission sources according to the probability of the event and the severity of the impact is very useful. The use of an evaluation scale (e.g. from low to high) to illustrate the level of risk associated with each identified scenario is recommended [8, 10, 13].

3. Results and Discussions

Analysis of potential risks generated by toxic gas emissions. Toxic gas emissions from the seismic zone can generate potential risks related to human health and economic life, can have an impact on the environment and infrastructure, but can also create serious social problems. The risks to human health refer to respiratory problems caused by the specific nature of the gases emitted, taking into account the fact that sulfur dioxide, hydrogen sulfide and carbon dioxide predominate, as well as acute chronic poisoning. Sulfur dioxide (SO_2) is an irritating gas that can cause breathing difficulties, asthma and other lung diseases, especially among children, the elderly and people with pre-existing respiratory diseases. Carbon dioxide (CO_2) in high concentrations can lead to hypoxia (oxygen deficiency) which can be fatal. CO_2 can accumulate in low and closed areas, presenting an invisible and insidious danger. Hydrogen sulfide (H_2S) is a highly toxic gas that, even in low concentrations, can cause eye, respiratory, and skin irritation. At higher concentrations, it can lead to unconsciousness and death. Long-term exposure to toxic gases can lead to chronic adverse health effects, including cardiovascular, neurological, and cancer diseases. Environmental impacts include soil and water acidification and air pollution. Gases such as sulfur dioxide can lead to the formation of acid rain, which can acidify soil and corrode vegetation, negatively affecting agriculture and biodiversity. Acidification of water bodies can harm aquatic ecosystems, affecting local flora and fauna. Volcanic particles and gases can reduce air quality, affecting plant photosynthesis and the overall health of ecosystems. Economic risks mainly relate to agriculture and tourism. Soil acidification and water contamination can reduce soil fertility and agricultural productivity, affecting farmers' incomes and food supplies. The Phlegraean Fields and Naples are major tourist destinations. Toxic gas emissions can reduce the number of tourists, affecting the local economy, which is somewhat dependent on tourism. Temporary closure of tourist attractions due to risks of exposure to toxic gases can lead to economic losses.

The impact on infrastructure can result in corrosion of materials. Gases such as sulfur dioxide can accelerate the corrosion of metals and the degradation of construction materials, leading to additional maintenance and repair costs for buildings and public infrastructure. The social problems that may arise are related to possible evacuations and relocations. The risk of toxic emissions may require periodic evacuations or permanent relocations of the population, which can create stress and social dislocation. These evacuations can lead to economic losses for residents and considerable costs for authorities. Due to these potential risks, continuous

monitoring is recommended by installing monitoring systems to detect gas emissions and warn the population in a timely manner, as well as adopting emergency plans, by developing and testing evacuation and emergency response plans. To create a risk matrix for toxic gas emissions, the probability and severity of the different types of risks associated with these emissions are assessed. The risk matrix will include two dimensions: probability (from very low to very high) and severity of impact, from insignificant to catastrophic (Tables 1 and 2).

Table 1. Potential risk matrix for toxic gas emissions

Probability/ Impact	Not significant	Minor	Moderate	Major	Catastrophic
Very high	-	-	-	-	-
High	-	-	Affecting the health of the local population, Increase in hospitalizations	Mandatory evacuation, Severe long-term health impact	Loss of life, Major health crisis
Moderate	-	Respiratory irritation, mild symptoms of toxicity	-	-	-
Low	Minimal discomfort for the population	-	-	-	-
Very low	-	-	-		-

Loss of life and major health crisis have a high probability of occurrence given the volcanic activity and history of toxic gas emissions and catastrophic impact, as toxic gas emissions can cause death and a major health crisis in the region. Mandatory evacuation and long-term health impact have a major impact because prolonged exposure to toxic gases can lead to serious health problems, require evacuation of the population and affect the quality of life in the long term and high probability of occurrence due to the potential for eruptions and constant emissions.. Impact on the health of the local population, increased hospitalizations have a moderate impact, as emissions can cause health problems requiring medical treatment and hospitalization and high probability of occurrence due to continued volcanic activity.

Table 2. Probability, Impact and Potential Risk Level Values for Explosive Eruptions

Risk	Probability	Impact	Level
Loss of life	4	5	20
Major health crisis	4	5	20
Evacuarea obligatorie	4	4	16
Severe long-term health impact	4	4	16
Affecting the health of the local population	4	3	12
Increase in hospitalizations	4	3	12
Respiratory irritation, mild symptoms of toxicity	3	2	6
Minimal discomfort for the population	2	1	2

Respiratory irritation and mild toxicity symptoms have a minor impact because the effects are temporary and treatable, but can cause discomfort and affect daily activities, and a moderate probability of occurrence due to occasional gas emissions. Minimal discomfort to the population has a minor impact because the discomfort is minimal and does not affect long-term health. and a low probability of occurrence due to monitoring and prevention measures.

Loss of life and major health crisis, mandatory evacuation and severe long-term health impact have a major risk level. Affecting the health of the local population and increasing hospitalizations have a moderate risk level. Respiratory irritation and mild toxicity symptoms have a moderate risk level, and minimal discomfort to the population has a negligible risk level. Analysis of potential risks generated by volcanic ash. Volcanic ash emissions pose risks

that can affect human health, the environment and the local economy. These relate to human health and the economy, impact the environment and infrastructure, and can also create social problems. The impact on human health refers to potential respiratory problems through the inhalation of ash particles that can even lead to chronic lung diseases and/or eye and skin irritation. Volcanic ash is made up of fine particles of rock and minerals that can be inhaled. These particles can cause irritation of the respiratory tract, coughing, difficulty breathing, asthma and other lung conditions. Long-term exposure to fine particles can lead to chronic lung diseases, such as chronic bronchitis and silicosis.

Volcanic ash can irritate the eyes, causing tears, burning sensation and conjunctivitis. Contact with the skin can cause irritation, itching and rashes. The impact on the environment can mainly result in the destruction of vegetation and water pollution. The destruction of vegetation can be achieved through the deposition of ash and soil contamination. A thick layer of ash can cover vegetation, blocking sunlight and affecting photosynthesis, leading to plant death. Volcanic ash can alter soil pH and nutrient content, affecting soil fertility and, consequently, agriculture. Contamination of water sources can be achieved by considering that volcanic ash can contaminate rivers, lakes and drinking water reservoirs, affecting both aquatic fauna and the availability of clean water for human consumption. Economic risks can materialize through the impact on agriculture and tourism. This can lead to reduced productivity, additional costs, a decrease in the number of tourists and the temporary closure of tourist attractions.

Ash deposits can affect agricultural crops, reducing productivity and farmers' incomes. Farmers may incur additional costs for cleaning up land and rehabilitating affected soils.

Volcanic eruptions and ash emissions can discourage tourists from visiting the area, affecting local economies dependent on tourism. Tourist attractions may be temporarily closed due to the risks of exposure to ash, leading to significant economic losses.

Impacts on infrastructure can be seen in the damage to buildings and infrastructure due to the weight of ash and corrosion, and transportation problems due to reduced visibility, which can even lead to the closure of airports.

Ash deposits can accumulate significant loads on roofs and structures, leading to their collapse. Volcanic ash can be abrasive and corrosive, damaging building materials and industrial equipment. Ash in the atmosphere can reduce visibility, affecting air and road traffic and increasing the risk of accidents. Ash deposits on airport runways and the risk of damage to aircraft engines can lead to the temporary closure of airports.

Social problems can result in the need for evacuations and relocations, which can be temporary or permanent, but also in the stress and anxiety caused by the fear of eruptions

The population in the affected areas may be forced to evacuate temporarily, which can create stress and social dislocation. In severe cases, evacuations can become permanent, affecting local communities and the social structure.

The constant risk of volcanic eruptions and ash emissions can generate stress and anxiety among the population.

To reduce the risks associated with volcanic ash emissions, authorities can implement monitoring and early warning measures, along with the development and testing of evacuation and emergency response plans, information and education, or investments in infrastructure, by strengthening infrastructure to reduce the impact of ash deposits and improve the resilience of communities, or by investments in infrastructure modernization to reduce the impact of pollution and improve the resilience of communities. To create a risk matrix for volcanic ash, the probability and severity of the different types of risks associated with it are assessed.

The risk matrix includes two dimensions: probability (from very low to very high) and severity of impact, from insignificant to catastrophic (Tables 3 and 4).

Long-term economic devastation and habitat destruction have a catastrophic impact because volcanic ash can completely destroy the habitats and economic resources of the region and a very high probability of occurrence, given the history of volcanic activity and the potentially devastating impact.

Mandatory evacuation of the population and blocking of economic activities have a major impact because evacuation and blocking of economic activities can seriously affect community life and the local economy and have a very high probability of occurrence, given the history of volcanic activity and the potentially devastating impact.

Severe damage to local agriculture and infrastructure has a moderate impact because damage to agriculture and infrastructure can have a significant economic impact in the short and medium term and a very high probability of

occurrence, as volcanic ash can cover a large part of the region, and temporary damage to daily activities has a minor impact, but still a very high probability of occurrence. Significant reduction in economic resources and severe disruption to daily life have a catastrophic impact and a high probability of occurrence. Significant impact on the health of the local population has a major impact because volcanic ash can cause serious health problems such as respiratory and dermatological conditions and a high probability of occurrence in the case of prolonged exposure to volcanic ash. Moderate damage to agricultural crops and infrastructure has a moderate impact and a high probability of occurrence, and moderate discomfort to the population has a minor impact because the discomfort may be manageable and temporary and a high probability of occurrence in the case of smaller volcanic events or limited ash deposition.

Table 3. Potential risk matrix for volcanic ash

Probability/ Impact	Not significant	Minor	Moderate	Major	Catastrophic
Very high	-	Temporary impairment of daily activities	Severe damage to local agriculture and infrastructure	Mandatory evacuation of the population, Blocking economic activities	Long-term economic devastation, Habitat destruction
High	-	Moderate discomfort for the population	Moderate damage to crops and infrastructure	Significant impact on the health of the local population	Significant reduction in economic resources, Serious disruption of daily life
Moderate	-	Minimal discomfort for the population	Minimal damage to crops and infrastructure	-	-
Low	-	-	-	-	-
Very low	-	-	-		-

Table 4. Probability, Impact and Potential Risk Level Values for Volcanic Ash

Risk	Probability	Impact	Level
Long-term economic devastation	5	5	25
Habitat destruction	5	5	25
Mandatory evacuation of the population	5	4	20
Blocking economic activities	5	4	20
Severe damage to local agriculture and infrastructure	5	3	15
Temporary impairment of daily activities	5	2	10
Significant reduction in economic resources	4	5	20
Serious disruption of daily life	4	5	20
Significant impact on the health of the local population	4	4	16
Moderate damage to crops and infrastructure	4	3	12
Moderate discomfort for the population	4	2	8
Minimal damage to crops and infrastructure	3	3	9
Minimal discomfort for the population	3	2	6

Minimal damage to crops and infrastructure has a moderate impact and a moderate probability of occurrence, and minimal discomfort to the population has a minor impact and a moderate probability of occurrence.

Analysis of the Potential Socio-Economic Risks generated by the Phlegraean Fields seismic area. The active volcanic caldera in the Phlegraean Fields area presents significant risks, both geologically and socio-economically. These can be

risks to the population and infrastructure, can have economic and environmental impacts, can create public health problems, as well as social costs. The risks to the population and infrastructure can result in loss of life, structural damage and/or emergency evacuations. Intense volcanic activity could lead to major eruptions, endangering the lives of residents in the Naples area and the surrounding area. Earthquakes and lava flows can cause significant damage to buildings, roads and other critical infrastructure. Mass evacuations could be necessary, which would create chaos and require considerable logistical and financial resources. The economic impact could manifest itself either as direct financial losses or through impacts on tourism and/or disruption to local businesses. Damage to buildings and infrastructure would entail enormous costs for repairs and reconstruction. Naples and the surrounding region are major tourist destinations. Seismic and volcanic activity could reduce tourist numbers, negatively affecting the local economy. Local businesses, especially small and medium-sized ones, could suffer significant losses due to disruptions to economic activities. Volcanic gas emissions, such as sulfur dioxide and carbon monoxide, can have serious effects on the health of the population. Air pollution resulting from volcanic activity can aggravate respiratory and cardiovascular diseases among residents.

Environmental impact can refer to the destruction of habitats and contamination of water. Eruptions and lava flows can destroy local ecosystems and the habitat of fauna and flora. Volcanic gases and particles can contaminate water resources, affecting both humans and animals. Social costs refer to the possible displacement of the population, usually accompanied by stress and trauma. Forced evacuations and relocations can lead to the uprooting of communities, with long-term social impacts. Fear and uncertainty related to potential eruptions can generate stress and anxiety among the population. To reduce these risks, authorities can adopt several measures, from monitoring and early warning, by implementing an effective system for monitoring seismic and volcanic activity to provide early warnings, to evacuation plans, raising awareness and educating the population about the risks and protective measures, but also by investing in infrastructure, namely strengthening infrastructures to better withstand earthquakes and other volcanic phenomena caused by the situation in the area.

To create a risk matrix for socio-economic impact, the probability and severity of different types of impacts on society and the local economy are assessed. The risk matrix includes two dimensions, probability (from very low to very high) and severity of impact, from insignificant to catastrophic (Tables 5 and 6).

Table 5. Potential socio-economic impact risk matrix

Probability/ Impact	Not significant	Minor	Moderate	Major	Catastrophic
Very high	-	-	-	Temporary evacuations, Significant economic losses	Destruction of critical infrastructure
High	-	Temporary discomfort for the local population	Temporary impact on local tourism	Significant impact on the tourism sector, agriculture and fishing	Extensive impact on the local economy, Long-term losses
Moderate	-	-	Impact on local transport	Reduction of local economic activities, access restrictions	Severe impact on local livelihoods, Economic losses
Low	-	-	-	-	-
Very low	-	-	-	-	-

Critical infrastructure destruction and significant economic losses have a catastrophic impact, as the destruction of critical infrastructure (such as ports, airports, main roads) can severely

affect the economy and daily life and are very likely to occur in the event of a major eruption directly affecting the area.

Temporary evacuations and significant economic disruption have a major impact and are very likely to occur. Extensive damage to the local economy, long-term losses have a catastrophic impact and are very likely to occur.

Significant impact on the tourism, agriculture and fisheries sectors is catastrophic because the tourism, agriculture and fisheries sectors are essential to the local economy and could be significantly affected by an eruption and are likely to occur in the event of an eruptive event affecting these sensitive economic areas. Temporary significant local tourism disruption has a moderate impact and are likely to occur, and temporary inconvenience to the local population has a minor impact and are likely to occur.

Table 6. Probability, Impact and Potential Risk Level Values for Socio-Economic Impact

Risk	Probability	Impact	Level
Destruction of critical infrastructure	5	5	25
Significant economic losses	5	5	25
Temporary evacuations	5	4	20
Significant economic disruptions	5	4	20
Extensive impact on the local economy	4	5	20
Long-term losses	4	5	20
Significant impact on the tourism sector, agriculture and fishing	4	4	16
Temporary impact on local tourism	4	3	12
Temporary discomfort for the local population	4	2	8
Severe impact on local livelihoods	3	5	15
Economic losses	3	5	15
Reduction of local economic activities, access restrictions	3	4	12
Impact on local transport	3	3	9

The significant impact on tourism, agriculture and fisheries is catastrophic, as tourism, agriculture and fisheries are essential to the local economy and could be significantly affected by an eruption and a high probability of occurrence, in the event of an event affecting these sensitive economic areas. Reduction of local economic activities and access restrictions have a major impact, as access restrictions and reduction of economic activities can have a significant impact on local residents and businesses and a moderate probability of occurrence, in the event of an eruption involving temporary or moderate restrictions on access to the affected areas. Extensive damage to the local economy and long-term losses has a catastrophic impact, as extensive damage to the local economy could have long-term repercussions on the standard of living of the population and a high probability of occurrence, in the event of an eruption with a major and widespread impact on the area under consideration.

The risk level presents different degrees for socio-economic impact, as follows: very high for destruction of critical infrastructure and significant economic losses, high for temporary evacuations, significant economic disruption, widespread impact on the local economy, long-term losses and significant impact on the tourism sector, agriculture and fisheries moderate for temporary impact on local tourism, severe impact on local livelihoods, impact on local livelihoods and reduction of local economic activities, minor access restrictions for temporary inconvenience to the local population and impact on local transport.

4. Conclusions

The critical risks associated with toxic gas emissions from the Phlegraean Fields include loss of life and major health crises, followed by severe long-term health impacts and the need for mandatory evacuation. The likelihood of these risks is high, given the active volcanic context of the region. Response measures should include well-defined evacuation plans, toxic gas emission monitoring systems and public education on safety measures. Collaboration with health authorities is also essential to ensure a rapid and effective response in the event of a major health crisis. Planning and implementing early warning systems and robust public health infrastructure

will help minimize the impact of these risks on the population and the environment.

The major risks associated with volcanic ash are long-term economic devastation, mandatory population evacuations and significant public health impacts. It is essential to implement risk management plans and early warning systems to minimize the negative impact of these events on the community and the environment.

The major socio-economic risks associated with an eruption in Campi Flegrei, Naples, are related to the destruction of critical infrastructure, significant economic losses and severe impact on the tourism and agriculture sectors. It is important to develop and implement risk management plans and take preventive measures to minimize the negative impact on the community and the economy in the event of such devastating natural events.

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