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Cascading hazards in volcanic environments: monitoring, modelling and impact analysis of tsunamigenic flows for risk reduction

Irene Manzella*[1,2], Symeon Makris[2,3], Daniele Casalbore[4], Paul Cole[2], Karim Kelfoun[5], Aggeliki Georgiopoulou[6], Anna Hicks[3], Cees van Westen[1]

(1) University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands
(2) University of Plymouth, School of Geography, Earth and Environmental Science, Plymouth, UK
(3) British Geological Survey (BGS), Edinburgh, UK
(4) Università La Sapienza, Dipartimento di Scienze della Terra, Roma, Italy
(5) Université Clermont Auvergne, Laboratoire Magmas et Volcans, Clermont-Ferrand, France
(6) Ternan Energy, Aberdeen, UK

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Abstract

Volcanic environments present complex multi-hazard scenarios where primary volcanic activity can trigger cascading hazards or where multiple hazards can occur simultaneously, leading to cascading and compounding impacts on communities and ecosystems. Stromboli, one of the most active volcanoes globally, exemplifies these challenges with its frequent eruptions, pyroclastic density currents, landslides, and tsunamis. In the present study, the mechanisms behind tsunamigenic flows at Stromboli are investigated by using extensive monitoring data from previous studies and numerical modelling. Key findings from simulations and parametric analysis are presented, showing the relationships between mass flow dynamics, morphological factors, and tsunami generation. A more comprehensive context is then considered by drawing the impact chain related to tsunamigenic flows during a volcanic eruption. This includes a broad evaluation of the exposure, vulnerability and possible mitigation measures. Starting from the study of the hazard and then following up with the evaluation of the impacts, this study emphasizes the necessity of a holistic approach in multi-hazards environment, where accurate hazards modelling and monitoring, interdisciplinary collaboration, and community engagement need to be considered to reduce risk.

Keywords: Cascading hazards; Volcanic Risk; Stromboli Volcano; Impact Chains; Tsunamigenic Flows

1. Introduction

Society today faces global challenges such as climate change, increasing disaster impacts, and population growth, that can have cascading effects across various sectors and can cause long-lasting socio-economic and environmental consequences. The systemic nature of risk and increasing global connectivity are key factors contributing to the rising impacts of natural hazards. Between 2000 and 2019 alone, over 7,000 recorded disaster events resulted in more than one million deaths, affected over four billion people, and caused nearly three trillion US dollars in losses worldwide (CRED and UNDRR, 2020). These impacts are unevenly distributed, disproportionately affecting low- and middle-income countries and significantly hindering their economic and social development (Clark et al., 2013; Kammerbauer and Wamsler, 2017).

The COVID-19 pandemic has further highlighted the interconnected nature of hazards and risks. It has demonstrated that an outbreak in one region can rapidly spread globally, acting both as a great equalizer – impacting everyone in some way – and as a magnifier of existing vulnerabilities (Nundy et al., 2021). The pandemic has challenged existing approaches to disaster risk reduction and underscored the need for new methods and partnerships to assess hazards and enhance resilience.

Geohazards do not recognize national borders, as evident in events like the 2010 Eyjafjallajökull eruption in Iceland, which disrupted aviation across the northern hemisphere (Mazzocchi et al., 2010), and the 2004 Indian Ocean tsunami, which resulted in over 250,000 deaths and massive displacement across 12 countries (Keys et al., 2006; Rodriguez et al., 2006). Even smaller-scale events, such as damage to seafloor internet cables from submarine sediment movements, can have global social and economic effects by interrupting international connectivity (Pope et al., 2017). Therefore, there is a need to direct efforts toward a deeper understanding of complex geological processes, and implementing accurate forecasting, and timely warnings to increase preparedness.

Significant technological advancements in recent decades aid these efforts, however, one of the main challenges for geoscientists is integrating these technologies to improve practices and effectively communicate science to inform decision-making processes, as advocated by frameworks like the Sendai Framework for Disaster Risk Reduction, the Paris Agreement on Climate Change, and the Sustainable Development Goals.

While geosciences are vital for hazard assessment, a multidisciplinary approach is essential to address the complexity of risk, in particular in multi-hazards context. Combining knowledge from fields like natural sciences, social sciences, engineering, and environmental sciences is needed to fully understand all risk elements such as hazard, vulnerability, exposure and capacity (De Angeli et al., 2022; Ward et al., 2022, White et al., 2024).

Impact chain analysis is an effective tool increasingly implemented in Disaster Risk Reduction contexts to facilitate the dialogue between experts from different disciplines and other interested parties, such as communities, scientists, local authorities, policy makers and first responders (e.g. Gallina et al., 2016; van Westen et al., 2024). Through the visualization of the possible connections between hazards, exposed elements, vulnerabilities, and existing capacities, this tool helps highlighting possible dependencies and area of effective intervention. This is often co-designed and co-created by the different interested parties as the visual representation fosters communication and cooperation among them. When applied as a research tool, as in the present work, it provides a more comprehensive view of the phenomena being studied, highlights areas where interdisciplinary input is crucial, and promotes effective collaboration.

Interdisciplinarity and holistic approaches are particularly relevant in volcanic environments which are characterized by complex interactions between geological, hydrological, atmospheric, and biological processes. Volcanoes can produce a range of hazards, including lava flows, pyroclastic density currents (PDCs), ash fall, gas emissions, subsidence, collapses and lateral explosion (Sigurdsson et al., 2015). These events can initiate cascading hazards such as landslides, lahars, and tsunamis (López-Saavedra and Martí, 2023), leading to compounded impacts (Papale and Marzocchi, 2019). The 2018 Anak Krakatau eruption and subsequent landslide-induced tsunami (Williams et al., 2019), is one of the recent most devastating events that illustrates the potential risk of such cascading events. In agreement with the definitions of Gill et al. (2022), volcanic multi-hazards are characterized by complex interrelationships which can be triggering, amplifying and compounding and for this reason they necessitate a comprehensive understanding of the system for effective risk reduction and resilience building.

Among the diverse hazards associated with volcanic activity, tsunamis generated by volcanic mass flows, commonly referred to as tsunamigenic flows, are among the most complex and least understood. Although infrequent, these phenomena carry a significant potential for widespread and catastrophic impacts far from their source. One of the key challenges in studying tsunamigenic flows is the scarcity of well constrained historical data. These events are rare, and the available records are often incomplete, poorly documented, or inconsistent, which complicates efforts to understand their behavior and predict their occurrence (Paris et al., 2014). The lack of comprehensive data is a major obstacle to developing accurate predictive models, hindering preparedness and mitigation efforts . Moreover, the physical dynamics involved in the interaction between volcanic mass flows and water are inherently complex. The sudden entry of large volumes of rock, ash, or debris into the sea generates turbulent water displacements that are challenging to predict and model (Watts and Waythomas, 2003). The interaction between the mass flow and the water column involves a combination of hydrodynamic and gravitational processes that require advanced numerical modelling to comprehensively simulate, particularly given the various factors that influence wave formation, including flow volume, speed, density, and the bathymetric characteristics of the seabed.

The study of tsunamigenic flows is hence crucial for advancing scientific understanding, improving hazard assessments, and developing effective mitigation strategies in volcanic environments as they represent a significant risk. By improving our knowledge of these destructive phenomena, we can better prepare for future events, especially in vulnerable regions like volcanic islands and coastal areas. A deeper understanding of the dynamics of tsunamigenic flows can lead to more effective early warning systems, targeted land-use planning, and enhanced community resilience.

1.1 Tsunamigenic mass flows and advances in monitoring systems

Subaerial and submarine mass flows, such as landslides or PDCs entering the sea, are capable of displacing massive volumes of water, leading to powerful tsunami waves (Watts and Waythomas, 2003). The sudden nature and rapid propagation of local source tsunamis make them particularly hazardous to coastal communities, which can be severely impacted with little time for warning or evacuation as the wave generated can reach nearby coastlines within minutes, leaving populations highly exposed and with limited opportunities for response (Giachetti et al., 2012). Tsunamis are also capable of reaching far away coasts, even on the other side of oceans, and in these cases, there is greater potential to issue and respond to warnings. However, the perceived improbability of being impacted by events occurring hundreds or even thousands of kilometers away may result in inadequate preparedness. The 1883 Krakatoa eruption in Indonesia, for example, produced massive pyroclastic flows that entered the sea, generating tsunamis which caused over 36,000 fatalities (Simkin and Fiske, 1983) as far as 185 km (2 people died in Pakisjaya, northern Java) and even 3,000 km from the volcano (one person in Arugam, Sri Lanka) (Paris et al., 2014). Other example of devastating tsunamigenic flows is the 1792 Unzen landslide in Japan that triggered a tsunami that killed approximately 15,000 people (Siebert et al., 1987) and more recently, the 2018 volcanic flank collapse at Anak Krakatau which generated a tsunami and resulted in over 400 deaths (Grilli et al., 2019).

The development and integration of submarine and subaerial mapping techniques is particularly important in tsunamigenic flows. Accurate and up-to-date morphological data are essential inputs for numerical models that simulate mass movements and their potential to generate tsunamis. Understanding the current state of the volcano structure above and below sea level allows for better prediction of mass flow behavior, identification of areas at risk of failure, and assessment of the potential impact of tsunamigenic events on nearby or remote coastal areas. This comprehensive mapping facilitates improved hazard assessments, early warning systems, and the development of effective risk mitigation strategies. However, monitoring in marine and volcanic environments often requires specialized techniques, which can present challenges related to costs and accessibility.

Nevertheless, advancements in technology have transformed the ability to monitor hazard systems, making it more accurate and accessible. The digitalization of the environment through sensors, big data, social media, open-source data, and the IoT has revolutionized geohazard monitoring (e.g. Barclay et al., 2015; Dini et al., 2021; Kryvasheyeu et al., 2016; Sgarabotto et al., 2023; Shoyama et al., 2021). Satellite imagery allows for global mapping and monitoring over time, providing critical data for hazard assessment. Technologies like LiDAR, drone footage, and structure-from-motion photogrammetry have made accurate digital terrain models (DTMs) attainable (Cook, 2017), enhancing the understanding of geological features and potential hazard zones. Di Traglia et al. (2022) demonstrated the effectiveness of integrating satellite data and ground-based surveys to monitor morphological changes at active volcanoes. By generating high-resolution digital elevation models (DEMs), they were able to detect changes in the volcano surface, which are critical for assessing slope stability and the potential for mass movements.

Computational data analysis techniques and statistical analysis integrated with Geographic Information Systems (GIS) increase the efficiency of data sampling and protocol implementation in geo-environmental practice (e.g. Zaki et al., 2024). High-performance computing enables the development of sophisticated computational fluid dynamics models, allowing for more accurate simulations of hazardous processes (e.g. Mead et al., 2023, Tierz et al., 2024). Machine learning and data mining techniques applied to geoscientific data are revolutionizing geo-environmental analytics, improving predictive capabilities (e.g. Miller and Han, 2009).

In marine environments, monitoring geohazards presents unique challenges due to the limitations of optical and electromagnetic sensors underwater. However, technologies such as underwater acoustic sensors, pressure gauges, and cabled observatories are enhancing our ability to detect submarine events (Heesemann et al., 2014). High-resolution seafloor mapping and subsurface data acquisition have improved but are still insufficient for global coverage. It would take an estimated 350 years for one research ship to map all ocean floors beyond 200 meters depth at high resolution (Mayer et al., 2018).

Repeated seafloor bathymetric surveying has become more systematic in recent years, helping identify areas of seafloor change (Casalbore et al., 2022). Monitoring the water column provides information about sediment mobility, including turbidity currents and seafloor seepages, using moored sensor arrays gliders, and remotely operated vehicles (ROVs). However, these methods face challenges, such as the destructive nature of some processes that can damage equipment.

In the present study past tsunamigenic events at Stromboli Volcano are analysed. Stromboli, located in the Aeolian Islands of Italy, is one of the most active volcanoes in the world, while being also one of the most extensively monitored and studied in the last decades (Di Traglia et al., 2014). This setting provides a unique natural laboratory to study these complex phenomena. The volcano is characterized by consistent moderate eruptions, but it has the potential for more severe paroxysms and other hazards, including landslides and tsunamis. Thanks to the availability of data from previous studies and current collaborations of the authors, it was then possible to have access to accurate data of both the recent subaerial (Di Traglia et al., 2022) and submarine morphology (Casalbore et al., 2022) providing better constrains for the considered tsunamigenic flows events.

The present study thus aims to deepen the understanding of tsunamigenic volcanic flows by conducting dedicated numerical modeling of past events at Stromboli Volcano, assessing most important factors for the relative hazard assessment and utilizing impact chain analysis to consider also exposure, vulnerability and capacity for a more interdisciplinary and holistic view of the associated risk.

2. Tsunamigenic flows: the Case Study of Stromboli

Stromboli volcano is an ideal case study to explore the challenges and advancements in monitoring and understanding multi-hazard environments. Known for its persistent Strombolian activity, characterized by regular, mild explosive eruptions, Stromboli has been active for at least 2,000 years (Rosi et al., 2019; Rosi et al., 2013). The Volcano poses significant hazards due to its potential for more severe events, including major explosions and tsunamigenic mass flows. The volcano's steep flanks are prone to gravitational instabilities, leading to both subaerial and submarine landslides. These mass movements together with PDCs can generate tsunamis, as evidenced by at least seven events since the early 20th century (Di Traglia et al., 2022). In the Middle Ages, documented instances of tsunamigenic mass flows were caused by flank collapses (Rosi et al., 2019). The 30th of December 2002 eruption-triggered landslides and tsunamis caused property damage and necessitated evacuations (Bonaccorso et al., 2003; Tinti et al., 2006a; Tinti et al., 2006b). More recently, the paroxysmal eruptions of the 3rd of July 2019, resulted in pyroclastic density currents (PDCs), landslides and tsunamis, leading to one fatality and extensive damage (Corradino et al., 2021; Giordano and De Astis, 2021).

For recent events there is a large availability of data at Stromboli thanks to extensive monitoring networks (Bonilauri et al., 2024; Di Traglia et al., 2014; Ripepe et al., 2017) which include:

- Seismic Stations: Detect and analyze seismic activity associated with magma movement and eruptions.
- Thermal Cameras: Monitor surface temperatures to detect changes in volcanic activity.
- Gas Sensors: Measure gas emissions to identify changes in degassing patterns.
- Ground Deformation Instruments: Track changes in the volcano shape, indicating magma movement.
- Buoy Wave Gauge Networks: Monitor sea-level changes to detect tsunamis.

The availability of data pre- and post-event facilitates their back analysis, i.e. simulate past events using the pre-event data as input to calibrate the set of parameters and flow characteristics that best fit the event. This is important to characterize and understand complex processes which depend on multiple parameters and are difficult to model. Once these are assessed, it is then possible to carry out a broader study on the factors of influence on the tsunami characteristics, such as wave heights and velocity of propagation. For the present study, the 3rd of July 2019 event has been studied as data were available for the PDCs, landslide and the tsunami wave, allowing a better constraint of the tsunamigenic flows' characteristics and dynamics.

2.1 The 3rd of July 2019 Eruption and Simulation data

On the 3rd of July 2019, Stromboli experienced a sudden and violent paroxysmal eruption. The explosions caused extensive damage and resulted in one fatality. The eruption also produced two subaerial PDCs and a submarine landslide which traveled along the Sciara del Fuoco and entered the sea (Andronico et al., 2021). The Sciara del Fuoco, Stromboli's northwestern flank is the most active slope of the volcano where most of the lava flows, PDCs and landslides propagate, often reaching the sea because of its steepness. Tsunami waves were recorded at several locations, with heights reaching up to 1.5 meters near the Sciara del Fuoco and 0.2 meters near the village of Ginostra (Bonilauri et al., 2024; Di Traglia et al., 2022).

The present research aims at addressing critical questions about the primary source of the tsunami, the volumes and characteristics of the mass flow involved, and how the morphology of the area influenced the tsunami wave height and its propagation. These factors are critical for hazard assessment and impact analysis, as they offer insight into the potential extent of affected areas and the magnitude of impact on those regions in the event of a tsunami. To achieve this, a back analysis of the 3rd of July event was conducted using the numerical model VolcFlow (Kelfoun et al., 2009), which is based on the depth-averaged approximation of the Saint Venant equations, which means that the landslides or PDCs are considered as a fluid where the horizontal velocity field is constant throughout the depth of the flow. VolcFlow allows for different rheologies, i.e. changing the parameters defining the flow behavior, such as friction, viscosity etc. Volcflow is a continuum mechanics model that has been already extensively used to simulate large landslides, PDCs, lava flows and landslide induced tsunamis, (e.g. Giachetti et al., 2012; Giachetti et al., 2011; Kelfoun, 2017; Manzella et al., 2016; Nomikou et al., 2016; Paris et al., 2017; Salmanidou et al., 2017).

Input parameters included:

- Digital Elevation Models (DEMs): high-resolution representations of the terrain, including both subaerial and submarine topography (see Fig. 1). Two different bathymetries have been considered one carried out in July 2019, and one carried out in February 2020 (Casalbore et al., 2022; Di Traglia et al., 2022). This last bathymetry covered a larger area near the Sciara Del Fuoco coastline that was never accessed before because of the challenges posed by carrying submarine survey so close to such an active shore. Recent technological advancements and repeated surveys have allowed a better characterization of the submarine area, enabling a better constraint of the simulated events.
- Mass flow volumes and velocity: estimates were based on field observations, deposit measurements, and previous events (Giordano and De Astis, 2021).
- Rheological properties: parameters such as friction coefficients and cohesion values derived from previous studies (Dade and Huppert, 1998; Di Traglia et al., 2014).

From the back analysis of the 3rd of July event, the best fitting parameters for the flows which caused the tsunami wave during the eruption is assessed and the parameters to simulate those flows are determined. Once the flow and the rheology are determined, a parametric study assessed how variations in mass flow volumes and rheological properties affect tsunami generation. Eruption time is also varied, this is relevant only for PDCs and it determines a change in the discharge rate when the volume and rheology are constant. Wave height is measured at different points where the buoys are located, called wave gauges in Fig.1. Three locations are thus considered: wave gauge 1 is located in front of the Ginostra village; 2 Punta dei Corvi is directly in front of the Sciara del Fuoco on the west side of the slope; 3 Punta Labronzo is located on the east side of the front of the Sciara del Fuoco. Series input parameters of the parametrical study and results of maximum wave height at Gauge 2 are shown in Table 1. Data, full results and videos of the simulations (see Fig. 2 for 4 snapshots of one of the simulation videos) can be downloaded at the link provided in the dedicated section below.

2.2 Key Findings from the Simulations

The results suggest that the tsunami was primarily caused by the subaerial PDCs of a volume of around 1 million cubic meters (Di Traglia et al., 2022). The simulations using the rheology model with constant retaining stress, also called cohesion, based on Dade and Huppert (1998), provided the best fit for the observed events. The best fitting cohesion value was that of 7,000 Pa. Based on these findings from the back analysis we could carry out the parametrical study which considered PDCs of different volumes, eruption time and cohesion values.

The results of the parametrical study showed that the PDC volume and discharge rates were critical factors in tsunami generation with an increase of tsunami waves height with volume (see Fig. 3a) and a decrease with an increase of eruption time (see Fig. 3b), i.e. a decrease of the eruption discharge rate when the other parameters are kept constant. This highlights the importance of accurate volume estimation and discharge rate of the flows in hazard assessment.

The study integrates field observations, remote sensing data from previous studies, and numerical modelling to enhance the understanding of the complex processes at Stromboli. High-resolution bathymetric surveys conducted in February 2020 revealed changes in the seafloor morphology, which were critical for refining the models but show no significant changes in the maximum wave heights (see results of s1 and s16 in Table 1).

Series	Bathymetry (July 2019/ February 2020)	Volume [m^3]	Eruption Time [s]	Cohesion [Pa]	Maximum wave height at Gauge 2 [m]
s1	July 2019	1000000	20	7000	1,49
s2	July 2019	800000	20	7000	1,25
s3	July 2019	600000	20	7000	1,01
s4	July 2019	1200000	20	7000	1,74
s5	July 2019	1400000	20	7000	2,01
s6	July 2019	1000000	40	7000	0,89
s7	July 2019	1000000	60	7000	0,53
s8	July 2019	1000000	80	7000	0,36
s9	July 2019	1000000	10	7000	2,46
s10	July 2019	1000000	2	7000	2,20
s11	July 2019	1000000	20	3000	1,51
s12	July 2019	1000000	20	5000	1,50
s13	July 2019	1000000	20	9000	1,47
s14	July 2019	5000000	20	7000	7,01
s15	July 2019	1000000	20	60000	Flow did not reach the sea
s16	February 2020	1000000	20	7000	1,56
s17	February 2020	800000	20	7000	1,37
s18	February 2020	600000	20	7000	1,13
s19	February 2020	1200000	20	7000	1,79
s20	February 2020	1400000	20	7000	2,03

Table 1. Numerical experiment conditions considered for the parametrical study and maximum wave height measured at Gauge 2.

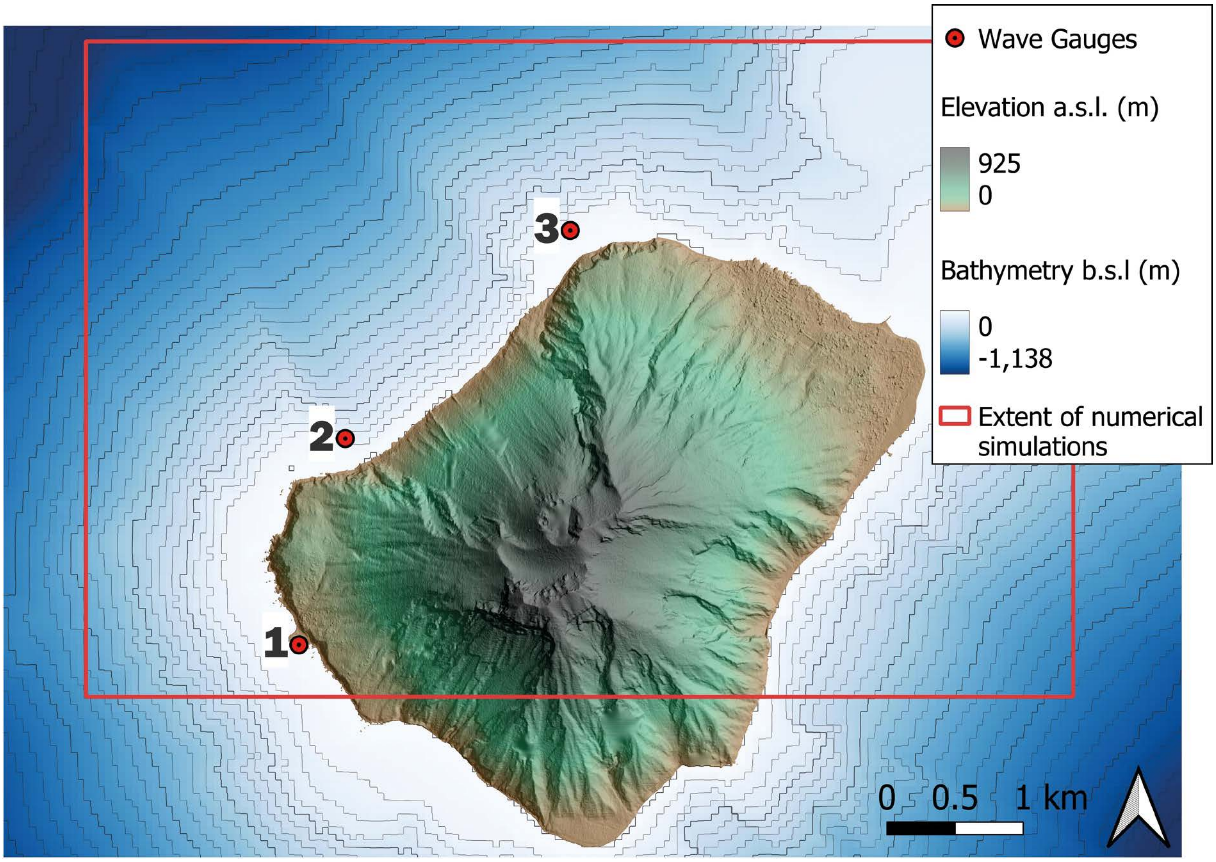

Figure 1. Topography used for the simulation including location of the gauge points 1, 2, 3 where the wave height was measured. Bathymetry contour spacing 50 m.

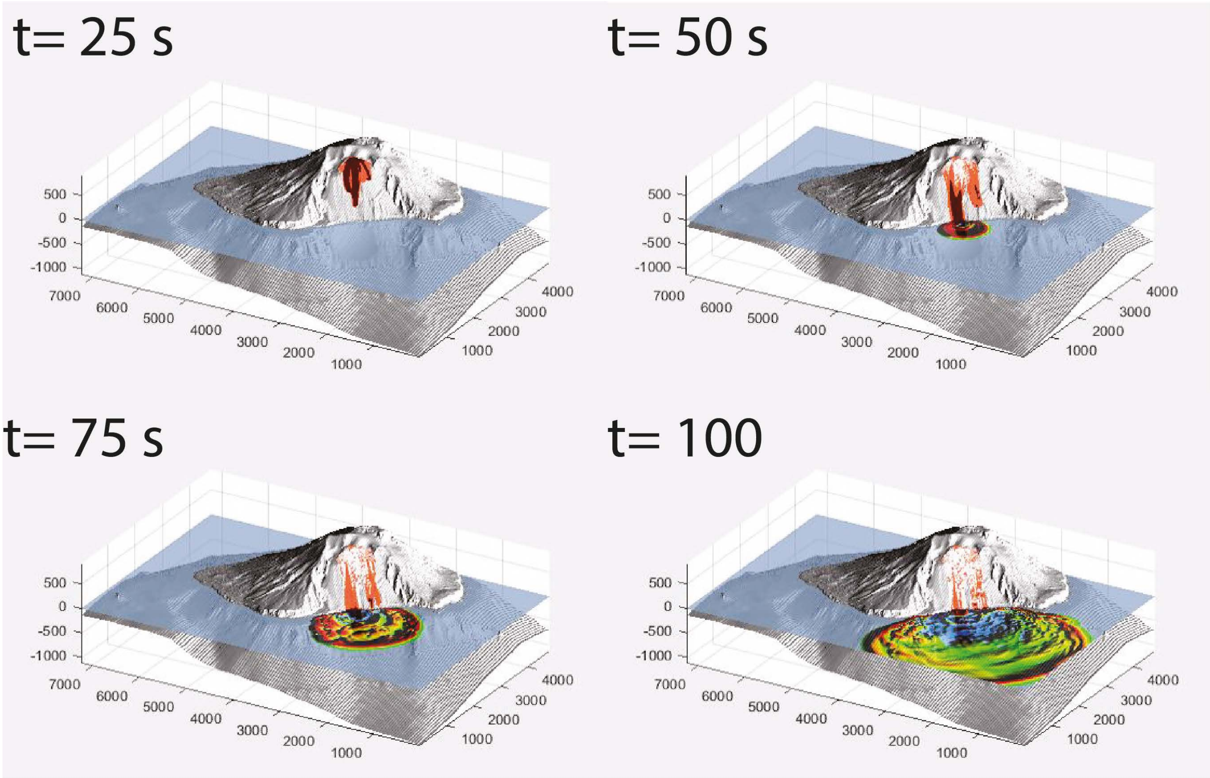

Figure 2. Simulation video showing the propagation of pyroclastic density currents into the sea and the generation of tsunami waves for numerical simulation s6 of Table 1, Volume=10^6 m^3, eruption time=40 s, cohesion=7000 Pa.

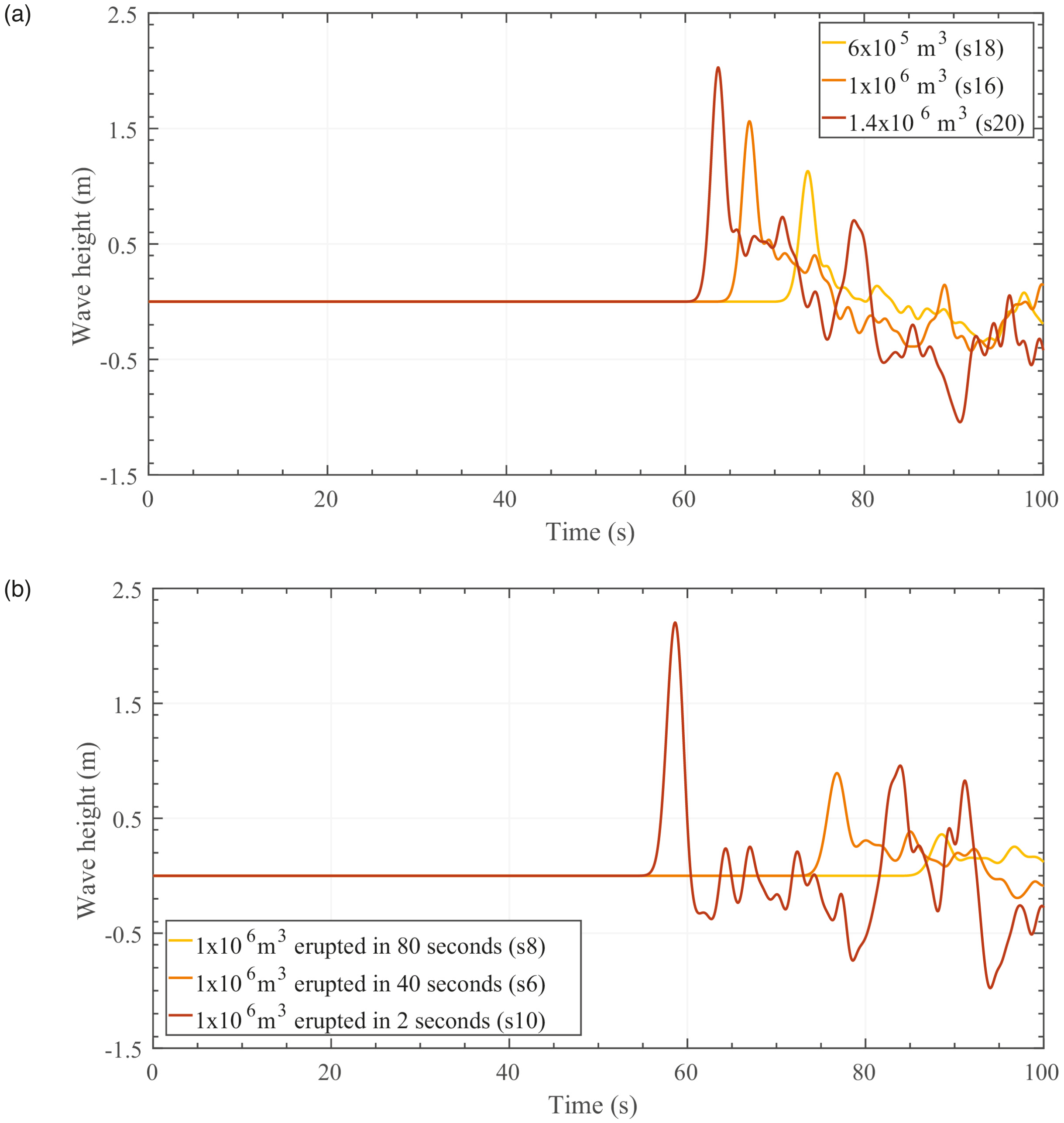

Figure 3. Graphs from the parametric study showing the relationship between (a) volume and maximum wave heights for series s16, s18, s20 measured in front of the Sciara del Fuoco (Gauge 2) and (b) eruption duration and maximum tsunami wave heights for series s6, s8, s10.

2.3 Impact Chain study

Impact chain analysis is a valuable tool for understanding and visualizing the interactions between hazards, vulnerabilities, exposures, and resulting impacts (Gallina et al., 2016; van Westen et al., 2024). It provides a structured approach to identify and analyze the causal relationships that lead from a natural hazard event to its socio-economic and environmental consequences and they are used to identify how impacts propagate through a system. They can be used to highlight risk factors such as exposed elements and systemic vulnerabilities, to which risk reduction measures may be applied.

Impact chains help break down risk scenarios into understandable components, facilitating communication among interested parties and identifying entry points for interventions (Hagenlocher et al., 2018). In volcanic environments, impact chain analysis is particularly useful due to the multi-hazard nature of volcanic activity, where multiple hazards can happen at the same time and when some hazards like eruptions can trigger other hazards such as landslides and tsunamis, leading to compound or cascading effects (Prasetya et al., 2024).

In the present study, the impact chain is used to broaden the context of the hazard assessment given by the parametrical study and it does not consider a specific event. At Stromboli, where the threat of tsunamis generated by landslides and PDCs is ever-present, such an analysis could be effective for identifying vulnerabilities and identifying/implementing risk reduction measures. The impact chain presented here is an example of how an impact chain can be developed and drawn. It highlights the sequential processes and interconnected factors that contribute to tsunamigenic flow generation and impact at Stromboli, but this could be generalized to similar volcanic environments. Understanding the complexities of tsunamigenic flows in those environments requires a comprehensive examination of the sequential processes and interconnected factors that contribute to the generation and impact of these hazardous events (Galderisi et al., 2013). The impact chain methodology serves as a vital tool in this endeavor, allowing us to delineate the cause-and-effect relationships from the initial volcanic activity to the far-reaching socio-economic and environmental consequences.

2.3.1 Impact Chain for Stromboli Volcano

The genesis of a tsunamigenic flow at Stromboli begins with landslides and/or volcanic activity, particularly during explosive eruptions that generate eruptive columns, which collapse into PDCs, or destabilize the volcanic edifice. The steep slopes of the Sciara del Fuoco are especially susceptible to gravitational failures even when the volcanic activity is low. These mass flows, laden with volcanic debris and, especially in the case of PDCs, gases at elevated temperature, possess significant kinetic energy as they approach the shoreline.

Upon entering the sea, these mass flows displace substantial volumes of water, initiating tsunami waves. As shown by the results of the present modelling study, the characteristics of the resulting tsunami – such as wave height, velocity, and propagation direction – are intrinsically linked to the properties of the mass flow, including its volume, speed, and density. The abrupt displacement of water sets off a series of oscillations that can travel rapidly across the sea surface (see Fig. 2), posing immediate risks to coastal communities both near and far from the source.

As the tsunami waves reach the shoreline, they interact with the coastal environment, leading to direct physical impacts (Turchi et al., 2022). The inundation of coastal areas can result in the destruction of infrastructures, such as residences, roads, and utilities. The force of the waves can demolish homes, disrupt transportation networks, and compromise critical facilities like hospitals and communication systems. Human casualties may occur due to drowning, physical trauma from debris, or the collapse of structures, emphasizing the severe threat to life that tsunamis represent.

Beyond these immediate effects, the impact chain extends to encompass secondary consequences that exacerbate the initial losses. The loss of infrastructure and services can hamper emergency response efforts, delaying aid and medical assistance. Displacement of residents can lead to overcrowding in shelters, strain on resources, and potential public health crises due to inadequate sanitation and the spread of disease. The psychological toll on affected individuals and communities can manifest as trauma, anxiety, and long-term mental health issues (Barclay et al., 2015; Malas and Tolsá, 2024).

Economically, the ramifications can be profound. The destruction of property and disruption of businesses can result in significant financial losses. Sectors vital to the economy of Stromboli, such as tourism and fishing, can suffer immediate setbacks due to damaged assets and the loss of revenue. In the longer term, the perception of risk associated with the area can deter visitors and investors, impeding economic recovery and growth.

Environmental impacts further compound the situation. The tsunami can alter coastal landscapes, erode shorelines, and deposit sediments and pollutants inland. Marine ecosystems may be disturbed by the influx of debris and changes in water quality, affecting biodiversity and fisheries. Terrestrial habitats can also be damaged, leading to loss of flora and fauna unique to the region (Turchi et al., 2020).

Critical to the impact chain analysis is the identification of risk factors that influence each stage of the chain (van Westen et al., 2024). Stromboli's geographical features, such as its steep slopes and proximity of settlements to the coast, inherently increase exposure to hazards. Socio-economic factors, including the reliance on tourism and limited economic diversification, heighten the community vulnerability to disruptions. Preparedness levels, determined by the availability of early warning systems, public awareness, and emergency planning, play a pivotal role in either amplifying or reducing the risks.

The connections between these elements highlight opportunities for intervention to break or attenuate the impact chain. Enhancing volcanic and tsunami monitoring systems enables the timely detection of precursory signs of mass movements and the rapid dissemination of warnings. Implementing land-use planning measures can reduce exposure by restricting development in high-risk zones and enforcing building codes that increase structural resilience. Infrastructure adaptations, such as the construction of elevated structures, provide physical barriers against inundation.

Community engagement is a fundamental component of effective mitigation (Hicks et al., 2014; Moreschini et al., 2024; Stewart, 2024). Informing residents and tourists about the risks, evacuation routes, and emergency procedures empowers them to act in the face of a tsunami threat. Incorporating traditional knowledge and practices can enhance the relevance and acceptance of preparedness measures. Moreover, involving the community in decision-making processes fosters a sense of ownership and cooperation that strengthens overall resilience.

The impact chain developed here for Stromboli volcano thus provides a holistic tool for understanding the multifaceted nature of the hazard and its consequences. By mapping out the sequential and interconnected factors – from volcanic eruption to mass movement, tsunami generation, direct and indirect impacts, and the role of vulnerabilities – valuable insights are gained into where and how to implement effective risk reduction strategies. This comprehensive approach underscores the necessity of interdisciplinary collaboration, integrating geological, engineering, environmental, and social perspectives to address the challenges posed by tsunamigenic hazards in volcanic environments. Applying impact chain analysis to Stromboli involves mapping out the sequence of hazards and their associated impacts, as well as the vulnerabilities and exposure of the local communities as shown in Fig. 4. The impact chain elements can be structured as follows:

Hazard Events:
- Volcanic eruptions
- Pyroclastic density currents
- Landslides (subaerial and submarine)
- Tsunamis
- Tephra fall
- Volcanic gas emissions

Direct Physical Impacts:
- Damage to infrastructure (buildings, roads, communication systems)
- Injury and loss of life
- Environmental degradation (loss of vegetation, marine ecosystem disruption)
- Air and water pollution (contamination from ash and gas emissions)

Secondary Impacts:
- Evacuation and displacement (need for temporary shelters)
- Economic losses (decline in tourism, loss of livelihoods)
- Health issues (respiratory problems, waterborne diseases)
- Psychological trauma (stress among affected populations)

Tertiary Impacts:
- Long-term economic decline (decreased investment, outmigration)
- Societal changes (altered land use patterns, changes in community cohesion)
- Environnmental changes (landscape alteration, soil degradation)

Risk Factors and Vulnerabilities:
- Geographic exposure (proximity to volcano and coastline)
- Socio-economic factors (limited resources, inadequate infrastructure)
- Preparedness levels (lack of awareness, insufficient early warning systems)

Mitigation and Adaptation Measures:
- Monitoring systems (seismic monitoring, early warning buoys)
- Emergency preparedness (evacuation plans, community education)

- Infrastructure planning (building codes, land-use regulations)
- Environmental management (slope stabilization, reforestation)
- Community engagement (involving local populations in decision-making)

This visual representation facilitates all the interested parties in the understanding of the intricate interactions and cascading effects associated with volcanic hazards and for this reason they are often co-created in community workshops (van Westen et al., 2024). By mapping these relationships, it becomes possible to identify critical points where interventions can be most effective in reducing risk and enhancing resilience. The diagram serves as a tool for communication, planning, and interdisciplinary collaboration in developing comprehensive disaster risk reduction strategies. Through this analysis, it becomes evident that mitigating the risks associated with tsunamigenic flows is not solely a technical endeavor but also a societal one. Building resilience requires a concerted effort that combines scientific understanding with community participation and supportive policies. By addressing each link in the impact chain, we can reduce the likelihood of catastrophic outcomes and enhance the capacity of the community to withstand and recover from such events.

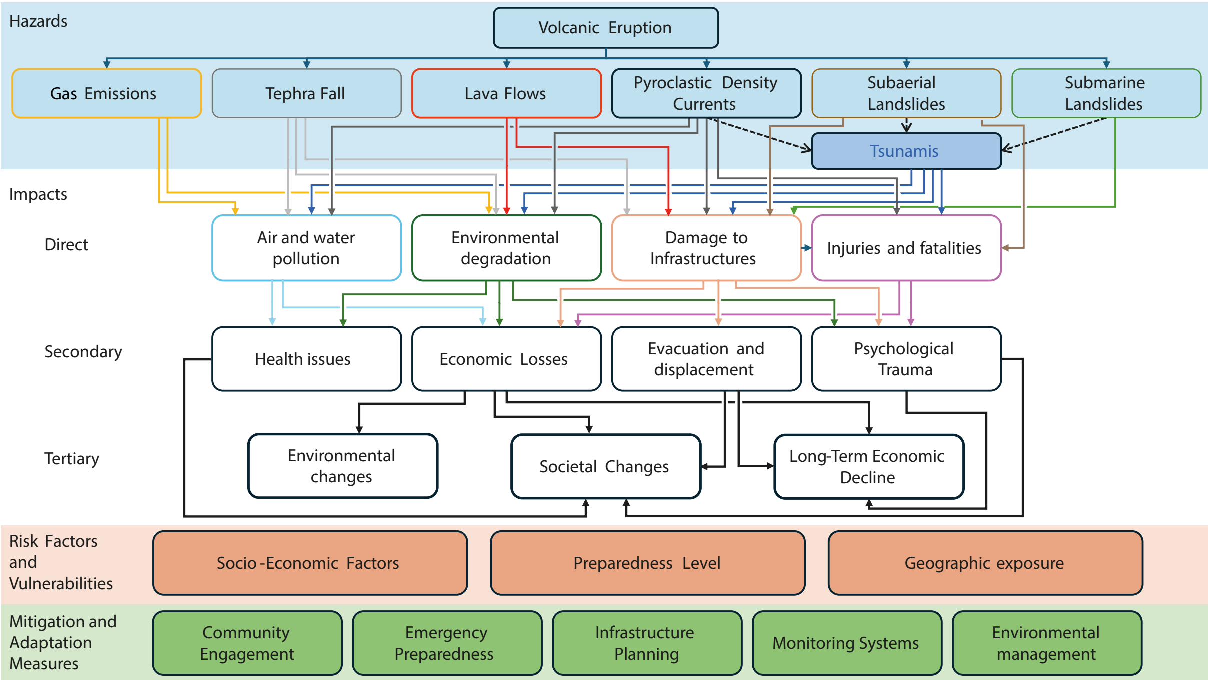

Figure 4. Example of impact chain in case of an eruption at Stromboli volcano with focus on tsunamigenic flows as cascading hazard, depicting the sequence of events from hazard initiation to final impacts and highlighting areas for intervention.

3. Conclusions

The study of tsunamigenic PDCs and landslides at Stromboli reveals the complexities inherent in volcanic hazard environments and underscores the importance of a multifaceted approach to risk assessment and management. Modeling tsunamis generated by volcanic mass flows, such as PDCs and landslides, offers valuable insights into the dynamic interactions between volcanic activity and coastal hazards. However, it also exposes significant challenges, particularly in the accurate representation of these processes and in the limitations of available data. There also remain notable challenges in accurately capturing submarine processes and mass movement dynamics. The destructive nature of some of these events, such as submarine landslides, complicates data acquisition by potentially damaging monitoring equipment. The difficulties in underwater mapping and real-time monitoring of the submarine environment introduce uncertainties into model predictions, underlining the need for ongoing technological development. Differently, satellite remote sensing, GB-INSAR and UAV technologies have markedly improved our understanding of subaerial volcanic morphology, allowing for the identification of changes that may indicate increased instability. These advances and repeated surveys, both subaerial and submarine, at Stromboli volcano have allowed us to acquire accurate data of recent events and to perform well constrained backward analysis and parametrical study of tsunamigenic flows. Numerical simulations, such as those performed with the VolcFlow model, have demonstrated that PDCs entering the sea are potential contributors to tsunami generation. The present study confirms that the speed, volume, and rheology of these flows directly affect the resulting tsunami's characteristics, such as wave height, speed of travel and propagation distance, allowing us to assess magnitude and extent of possible events. Understanding the dynamics of these mass flows through numerical modelling hence contributes to identifying key parameters for monitoring and developing early warning systems.

In addition, the Stromboli multi-hazard environment exemplifies the challenges faced in volcanic risk management, where complex processes and cascading events necessitate sophisticated approaches to hazard assessment and mitigation. The case study presented in this research demonstrates that addressing tsunamigenic flows requires a combination of advanced numerical modeling, continuous monitoring and impact analysis. By focusing specifically on the dynamics of volcanic mass flows entering the sea and their capacity to generate tsunamis, this study provides valuable insights into the mechanisms behind such events. The importance of the use of tools such as the impact chain, is also emphasized as it allows us to broaden our understanding of the interrelationships between the hazards, the possible short and long term impacts, vulnerabilities and possible mitigation and adaptation measures. The results confirm that enhancing resilience against tsunamigenic hazards will require sustained efforts not only in monitoring, modeling, but also in public engagement, ensuring that communities are not only protected but also actively involved in their own risk reduction processes.

In conclusion, interdisciplinary collaborations, such as the present one, prove essential in broaden our understanding of complex hazards. Geologists, geophysicists, engineers, and social scientists each bring a unique perspective to the problem, contributing to a comprehensive understanding that combines hazard analysis, engineering solutions, and community-level interventions. This integrated approach can ensure that hazard assessments are scientifically sound, that mitigation measures are technically robust, and that community needs and capacities are effectively addressed to enhance resilience.

Data availability statement. Data and videos of the simulations can be downloaded at: https://www.data.gov.uk/dataset/f629faec-68ce-48e0-90df-db26cee02612/mass-flow-and-tsunami-modelling-results-for-potential-events-in-the-sciara-del-fuoco-of-stromboli-nerc-ne-t009438-1#licence-info.

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***CORRESPONDING AUTHOR: Irene MANZELLA**,

Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

e-mail: i.manzella@utwente.nl