COMPOUNDING MULTI-HAZARD IMPACT ASSESSMENT OF VOLCANIC AND CYCLONE HAZARDS: A CASE STUDY FROM SAINT VINCENT

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June 2024

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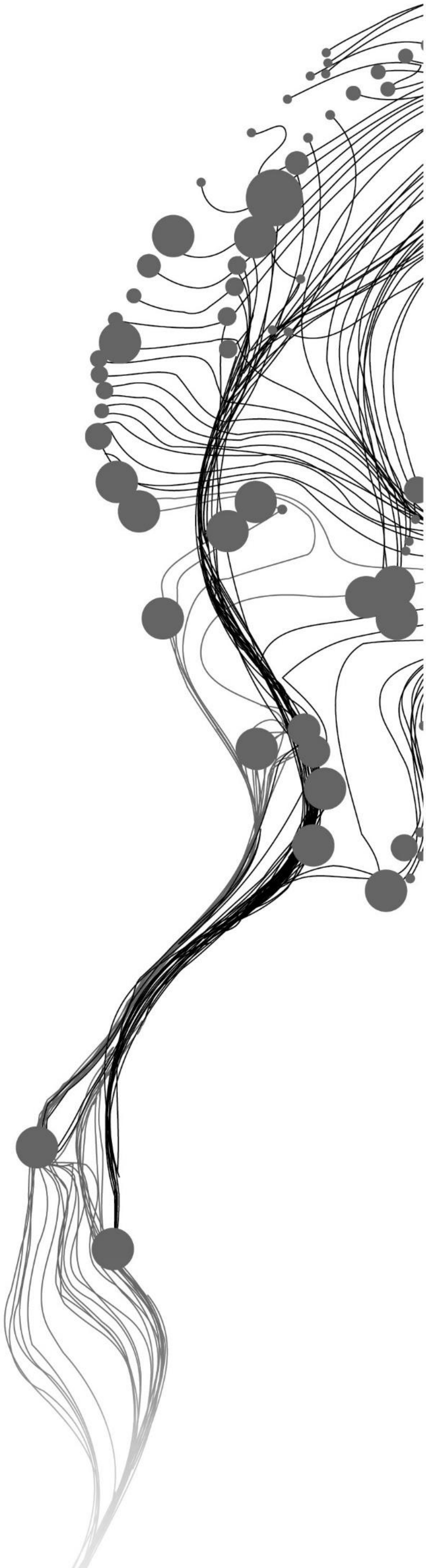

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Since the last decade, disaster risk management literature starts to acknowledge the connections between disaster events and multiple contributing hazards. When multiple hazards occur, they worsen each other's impact leading to the increase in the total impact. While there has been a massive improvement in assessing multi-hazards and their impacts, the hazard interaction itself is often neglected and not incorporated into the process. Identifying the interaction between hazard allows us to obtain comprehensive results by considering the sequence of events.

Using the case study of the 2021 compounding events in Saint Vincent, this thesis tries to overcome this gap. A low-probability high-impact combination of compounding cyclone and volcanic event happened in 2021 in Saint Vincent. La Soufrière, their volcano, erupted and was followed by a cyclone. This thesis uses this event as the study case for assessing the impact of compounding hazards between volcanic eruption and tropical cyclones. This event was chosen due to its recent occurrence that can portray the current situation of the area.

The proposed solution in this thesis is to use a retrospective approach and review historical events through impact chains. This assessment is then used as the basis for the development of future multi-hazard scenarios. The hazardous events of the scenarios of compounding volcanic eruption and tropical cyclones are then simulated with temporal and intensity variations. Considering the temporal sequence, the output of previous hazard simulations will be used as the input to simulate the next hazard events. This way, subsequent hazard interactions are incorporated.

The retrospective assessment shows that lahar and ashfall are the main significant hazards related to volcanic eruption, whereas strong wind and rainfall are the ones for cyclone event in Saint Vincent. Focusing on these hazards, the result shows that highest winds and minimum central pressure of a cyclone does not directly define the tephra ground load deposits if it occurs simultaneously with an eruption. However, they affect the tephra column mass dispersal that eventually will affect the ground load deposits. The impacts are found most severe in the scenarios which either the cyclone has a rapid intensification and widespread deposition that causes thicker ground deposition. For lahars, most runout difference for each scenario is noticeable in the north-east coast. From the impact assessment, some towns in the north-east coast might be trapped and therefore improvement in health facilities are needed for those towns.

Keywords: impact chains, scenarios, lahars, ashfall, impact assessment, compounding multi-hazard.

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I would not call this thesis 'mine', as this is also a tribute to the incredible support that has helped me navigate the challenges in my thesis endeavour. However, this thesis is indeed a part of me, my life, and my future. To everyone who has been a part of this journey, even if you're mentioned or not in this page, your support is beyond on what's written and you may not realize how meaningful it is.

Lastly, a special one.
Mbah Uti, I present this thesis for you.

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LIST OF ABBREVIATIONS

1. INTRODUCTION

1.1. Background

Since the Hyogo Framework for Action 2005-2015, understanding hazards and disaster impacts have evolved with the Sendai Framework for Disaster Risk Reduction 2015-2030. The wide hazard spectrum, with the interconnected, cascading, and complex nature of hazards, has led to a wider focus on the resilience of communities and countries within global discussions due to its potential cascading impacts (UNDRR, 2020). Since the last decade, disaster risk management literature starts to acknowledge the connections between disaster events and multiple contributing hazards. When multiple hazards compound, they worsen each other's impact leading to the increase in the total impact. This increase in the impact of several hazards is also referred to as a compounding event, where the effects are greater than when only one hazard would occur (Cegan et al., 2022). The combined impact of compounding hazards in time and space can oppress the community's ability to respond (M. Liu & Huang, 2015).

When vulnerable communities and livelihoods are exposed to a hazardous event of phenomenon, they may be impacted to a certain degree. Impact refers to the consequences of an extreme event on natural, social, and economy (Valles et al., 2020). Disaster impacts are mostly negative, although some positive impacts may also exist. Negative impacts include physical injuries, loss of life, property damage, displacement, and emotional trauma. The positive impacts, on the other hand, usually is more towards long-term impacts (e.g. more fertile soils around a volcano after an eruption due to the presence of volcanic material deposits). Disasters can provide sediments deposits that enriches the soil to increase agricultural yields (Popp, 2006). Disasters can also lead to increased resilience and preparedness for the future.

Loss and damage are often used to identify disaster impacts. It is important to note that there are different definition of loss and damage for the disaster and climate sector. In fact, the United Nations distinguishes loss and damage as the United Nations Framework Convention on Climate Change (UNFCCC)'s negotiations for Loss and Damage compensation, and loss and damage as the impacts themselves (IPCC, 2022; New et al., 2022). The UNFCCC defines loss and damage as, "the impacts of climate change that exceed households' and communities' ability to adapt" (UNFCCC, 2017). In climate sector loss refers to irreversible harm caused by climate change, such as complete destruction or submergence of islands due to sea-level rise, or extinction and permanent loss of species and cultural heritage sites caused by extreme weather events (Balzter et al., 2023). Damage is defined as harmful effects and costs due to climate change that are quantifiable, such as economic, social, and environmental losses. Damage can be temporary or partially reversible and often involves repair, restoration, or compensation (Balzter et al., 2023).

This thesis uses the definition of loss and damage (impact) for the disaster sector. Similar to the climate sector, damage is defined as the monetary value for destroyed assets, meanwhile losses are referred to changes in livelihood that will not be forthcoming until the economic recovery and reconstruction have been achieved (GFDRR, 2010). Although similar, the specific cause of impacts in the climate sector is not considered in this thesis.

After a disaster, rapid damage or loss assessments are usually carried out to better plan the recovery phase of the disaster. This assessment is often conducted in a harmonized and coordinated approached and published in Post Disaster Needs Assessment (PDNA) which provides an objective, comprehensive, and government-led assessment of damages, losses, and recovery needs after a disaster (GFDRR, 2013). However, these assessments can also be carried out during the prevention phase to assess past events impacts and be used for risk assessment. A comprehensive impact assessment which considers multiple spatial and temporal scales plays a role in providing empirical foundation for risk assessment (Valles et al., 2020). Meaning that it addresses a systemic approach, not restricted to only the hazard area, and considering indirect impacts.

Small Island-Developing States (SIDS) are susceptible to a broad range of risks coupled with a constrained capacity to manage them effectively. They are often exposed to hazards which impact both their sea section (such as tsunami, storm surges, coastal pollution, sea level rise), and their land section (such as landslides, earthquakes, storms, floods, and volcanic activity). The Caribbean consists of many SIDS with a combined exposure to hurricanes, earthquakes, and volcanic hazards as the main hazards in this region (Gibbs, 2001). According to the European Commission, the Caribbean is the second most disaster-prone region in the world with increased vulnerability to more frequent extreme climatic events (European Commission, 2022). Over the past 30 years, the Caribbean experienced a significant increase in the frequency and severity of compounding hazards (UNDRR & OCHA, 2023). Climate change is expected to increase the problem, and it is estimated that the region will be seven times more impacted by natural hazards than larger states and twice as likely as other small states (Otker & Srinivasan, 2018).

According to the Emergency-event Database (EM-DAT), tropical storms and hurricanes are the most frequent disastrous event in the Caribbean since 1900. It has also produced the highest total damage among other disaster events in the Caribbean. Tropical storm and hurricane differ in their wind speed. Both commence as a tropical depression, which is a low-pressure area that moves through the moisture-rich tropics and may rapidly increase in its intensity as evidenced by intensive rain showers, thunderstorms, clouds, and wind activity (NOAA, n.d.-a). Once the storms reach approximately 74 miles per hour, it is then categorized as a hurricane (NOAA, 2023b). According to National Oceanic and Atmospheric Administration (NOAA), we will refer both cases as tropical cyclone in this thesis (NOAA, n.d.-c). By nature, tropical cyclones already consist of multiple hazards which are strong wind, excessive rainfall. In some cases, cyclones can lead to storm surge as well due to the strong wind and differences in atmospheric pressure (Rutledge et al., 2023).

Additionally, the Caribbean is underlain by several active tectonic plates, making it a home to several active volcanoes in some of the Caribbean islands. There are approximately 21 active volcanoes across 11 volcanically islands which most of them have only erupted once with a possibility of erupting again in the future (UWI Seismic Research Centre, n.d.-a). For these islands, volcanoes have been a severe hazard, next to the tropical cyclones. Similar to tropical cyclones, when a volcanic eruption occurs, compounding hazard event especially for volcanic hazards cannot be avoided.

Even though volcanic eruptions have far less frequency as compared to other hazards in the Caribbean, they can be very destructive and lead to significant death tolls in the most severely affected areas (UNDRR & OCHA, 2023). In fact, there have been major eruptions that destroyed the capital of a Caribbean Island in the past, which are the 1902 eruption of Mount Pelée in Martinique and the 1997 eruption of Soufrière Hills in Montserrat (UWI Seismic Research Centre, n.d.-a). The eruption of Mount Pelée ejected ash plumes and pyroclastic surge, as well as resulted in mudflows which reached Saint Pierre city (Hawaiian Volcano Observatory, 2004). At that time, Saint Pierre was the cultural and economic capital in Martinique. The death toll was numerous as people from the neighbouring cities evacuated to Saint Pierre (Scarth, 2002). Similarly, the eruption in 1997 of Soufrière Hills has left more than half of the island uninhabitable, including its former capital, Plymouth (BBC, 2023). Due to the eruptions, Saint Pierre and Plymouth were completely destroyed and never restored to its former entirety.

1.2. Case Study Context

In 2021, the island of Saint Vincent, the main island of Saint Vincent and the Grenadines experienced a devastating period of compounding hazards event. Looking back to 2021, the world was still combatting Covid-19 pandemic, as well as Saint Vincent. Frequent reports of cases and deaths in Saint Vincent kept on going until early 2022 (Johns Hopkins University of Medicine, 2023). Other than that, approximately 1,790 dengue cases were confirmed with eight deaths and kept creasing since October 2020 (Government of Saint Vincent and the Grenadines, 2021). In addition, La Soufrière volcano which occupies one-third of the island erupted vigorously. Approximately three months after the eruption, Saint Vincent was exposed in Hurricane Elsa's track and affected by its strong wind and excessive rainfall. Among these compounding hazards occurring in 2021, this thesis will only focus on the volcanic eruption and Hurricane Elsa. The details of the event will be elaborated on Section 3.1.

This thesis uses the 2021 event in Saint Vincent as the study case for assessing the impact of compounding hazards between volcanic eruption and tropical cyclones. This event was chosen due to its recent occurrence that can portray the current situation of the area. Aside from that, this thesis will also support PARATUS project (https://www.paratus-project.eu/) that aims to increase preparedness and reducing risks related to impacts of multi-hazard events on various sectors.

1.3. Problem Statement

The compounding events of a volcanic eruption and a tropical cyclone could happen to many volcanic areas in tropical regions and may also become more severe with climate changes. This combination can also be considered as a high-impact, low-frequency event (Veeramany et al., 2015). However, the combination of these event has been reported elsewhere, for example in mount Pinatubo, the Philippines in 1991, mount Pacaya, Guatemala in 2010, and Kīlauea volcano, Hawaii in 2014 (Ching et al., 2020; Gill & Malamud, 2016). Therefore, assessing the impact and interaction of this combination is important in disaster risk management studies especially for mitigation and prevention under future climate scenarios (Hiroki, 2013). The 2021 compounding hazard sequence of volcanic eruption and Hurricane Elsa in Saint Vincent several lessons to be learned. In the 10th Symposium on Building a Weather-Ready Nation by American Meteorological Society in 2022, Jeffers et.al (2022) presented an abstract explaining this event and how this has affected Saint Vincent community and enhanced the government's awareness of this type of compounding hazards. One of the lessons learned is "the need of scenario assessment and planning prior to the occurrence of multiple hazards". Thus, this thesis is aimed to contribute to this reflection.

1.4. Research Gap

Many studies and reports have reported on the hazards and impact of the eruption as well as the hurricane of the 2021 event in Saint Vincent. Some of those studies are summarized in Table 1 and is explained further in Chapter 2. To summarize and make a point in this section, Among the studies that have been done and mentioned previously, the interaction between the hazards is still not yet considered in assessing the impact of compounding hazards. Therefore, this thesis will assess the impact of compounding hazards.

Using the 2021 compounding hazards event as the case study, this thesis will try to overcome the above gaps to assess the impact of compounding multi-hazards event in tropical-volcanic settings. The interaction between compounding volcanic and tropical cyclone hazards have not been studied extensively. Gill et.al (2016) reinforces that to obtain better disaster management priorities, hazard interaction should be incorporated into multi-hazard methodologies. Therefore, this thesis will assess the impact of compounding hazards and instead of using multi-layer single hazard as the input, the interaction between each hazard will also be considered. This thesis aims to provide a scenario-based impact assessment of compounding hazards even as the basis for mitigation planning in the future.

The proposed solution in this thesis is to use a retrospective approach and review historical events through impact chains and use these as the basis for the development of future multi-hazard scenarios. The hazardous events of the scenarios of compounding volcanic eruption and tropical cyclones are then simulated with temporal and intensity variations. Considering the temporal sequence, the simulations will consider 'what-if' scenarios with a different sequence as the real event.

1.5. Thesis Objectives and Questions

The main objective of this thesis is to assess the compounding effect of several multi-hazard impacts focusing on the interaction of volcanic and tropical cyclone hazards, based on the case study of the events in Saint Vincent in 2020-2021. This thesis will use a retrospective approach to assess the historical events in the form of impact chains and simulate the events of different scenarios based on the historical records. The main objective can be divided into several sub-objectives and research:

1.5.1. Investigate the historical volcanic and tropical cyclone events in Saint Vincent and determine and the historical scenarios.

a. What are the most significant hazards in volcanic and tropical cyclone events in Saint Vincent?
b. How was the interaction between the 2021 events of volcanic eruption and hurricane Elsa in Saint Vincent?

1.5.2. Model the simulations of the most impactful hazards according to the historical events investigation using the characteristics from the 2021 eruption and Hurricane Elsa.

a. Considering the characteristics of Hurricane Elsa, what would change in the hazard footprint if the eruption happened simultaneously with the hurricane?
b. How will the variation of hazard intensity affect the interaction between the significant hazards in eruptions and cyclones in Saint Vincent?

1.5.3. Identify and estimate the impacts of different hazard scenarios.

a. What will be the change in the impacts if the tropical cyclone and eruption occur at the same time or in sequence?
b. How does the hazard intensity variation affect the exposed elements-at-risks?

1.6. Relevance and Contribution of Thesis

The main contributions of this thesis include (1) retrospective analysis of historical volcanic and tropical cyclone events in Saint Vincent; (2) development of compounding hazards scenarios of which the components are then simulated; (3) compounding hazards and impact assessment for each scenario. Furthermore, this thesis will contribute to better understanding of impact assessment which incorporates the interaction between volcanic eruption and tropical cyclones as a basis for better mitigation planning in tropical volcanic islands. Additionally, each of the processes conducted in this thesis also contribute to the implementation of a certain modelling processes to simulate hazard scenarios. The scenarios will be modelled using different parameters which portrays the parameter affects the hazard interaction.

During the process of this thesis work, several presentations were conducted and summarized below:

a. The use of impact chains in this thesis was presented during the author's internship at the Center of Global Mountain Safeguard Research (GLOMOS), Eurac Research as the initial discussion to improve and determine the multiple use of impact chains.
b. The impact chains and retrospective assessment of this thesis is used to support the deliverable of the 2.1 deliverable of PARATUS project (https://www.paratus-project.eu/).
c. The preliminary results from this research were presented in a poster at the European Geoscience Union General Assembly held in Vienna on April 2024 under the title of 'Multi-hazard Impact Assessment for Volcanic and Storm Hazards: the Saint Vincent Case Study' (https://meetingorganizer.copernicus.org/EGU24/EGU24-9940.html).
d. To contribute to the advancement of open-source academia, the codes used in this thesis are uploaded on GitHub: https://github.com/salsablrp/thesis_itc/.

1.7. Thesis Structure

This thesis consists of 6 chapters. Chapter 1 explains the overall background and aim of this thesis. Continued with Chapter 2 is the literature review which provides information on the essential concepts of the work. Chapter 3 and 4 consecutively talks about the study area and methodology of this thesis. Results and discussions are explained in Chapter 5. Finally, the conclusion is elaborated in Chapter 6.

Table 1. Summary of literature and reports of hazards and impact assessments conducted for Saint Vincent, especially for the 2021 compounding volcanic and tropical cyclone hazards event.

Main Aspect	Topic	Author(s) and Year Published
Precursors and volcanological aspects	Thermal and seismic precursors	(Thompson et al., 2022)
	Eruption source parameters estimation	(Constantinescu et al., 2023)
	Assessing eruption states from limited volcano-seismic data	(Latchman & Aspinall, 2023)
	Magma petrology in the plumbing system	(Frey et al., 2023)
	Explosive eruption drivers and consequences	(Cole et al., 2023)
	Deformation monitoring	(Camejo-Harry et al., 2023)
Volcanic hazard	Ash fall-out and deposition during the 1979 eruption	(Brazier et al., 1982)
	Physicochemical hazard assessment of ash and dome rock	(Horwell et al., 2022)
	Satellite measurements of ash plumes	(Taylor et al., 2022)
	Pyroclastic Density Currents (PDCs) modelling of the 2021 eruption.	(Gueugneau et al., 2023)
	Lahar modelling of the 2021 eruption	(Miller et al., 2022; Phillips et al., 2023)
	Magma flux and eruption intensity analysis	(Sparks et al., 2023)
	Petrology of the 2021 explosive deposits	(Frey et al., 2023)
	Evolution and growth of lava dome and coulee during the 2021 eruption	(A. J. Stinton, 2023)
	SO2 emission during the 2021 eruption	(Esse et al., 2023)
	Magma rheology from lava	(A. Stinton et al., 2023)
Hurricane Elsa studies	Improving deterministic forecast using Weather Research and Forecasting (WRF) model	(Khaira & Astitha, 2023)
	Simulating initially weak, moderately sheared tropical cyclones using the Hurricane Analysis and Forecast System (HAFS)	(Alvey & Hazelton, 2022)
	Experiment methodology for storm mitigation by releasing environmentally friendly aerosol particles to weaken the intensities tropical cyclone forces	(Chaganti et al., 2022)
	Exploring intrinsic intensity-size relationship of tropical cyclones	(Sun et al., 2022)
2021 compounding hazards event	La Soufrière Volcanic Eruption, Heavy Rainfall, Hurricane Elsa, and the COVID-19 Pandemic: The Challenges of Multiple Hazards in St. Vincent and the Grenadines	(Jeffers et al., 2022)
Impact assessment from literature and reports	Macroeconomic impact assessment of disasters in the Caribbean	(Heger et al., 2008)
	Rapid damage and loss assessment of floods in Saint Vincent in 2013 and 2016	(Government of Saint Vincent and the Grenadines, 2014; Government of SVG, 2016)
	Vulnerability of critical infrastructure systems and the impacts towards multiple hazards (floods, coastal surge, hurricane, landslide, and earthquake) in 16 countries in the Caribbean region	(Schweikert et al., 2020)
	Rapid environmental impact assessment following the 2021 eruption	(Kelly, 2021)
	Multi-hazard (ash fall, PDCs, lava dome, pyroclastic surge, landslides, flash floods) map with elements-at-risk (roads, waterbodies, river streams, and transportation points) of Saint Vincent	(CDEMA & MapAction, 2021)
	Post disaster needs assessment of the La Soufrière 2021 eruption	(Government of Saint Vincent and the Grenadines, 2021)
	National Hurricane Center: tropical cyclone report for Hurricane Elsa	(Cangialosi et al., 2022)
	CCRIF[1] Tropical Cyclone Elsa wind and storm surge final event briefing for Windward Islands	(CCRIF, 2021)

[1] The Caribbean Catastrophe Risk Insurance Facility

2. LITERATURE REVIEW

This chapter provides information on the essential concepts of the research work. The overview of hazard interactions (Section 2.1), overview of volcanic and cyclone hazards (Section 2.2), investigating compounding hazards in volcanic and cyclones event (Section 2.3), and elaboration of impact chains (Section 2.4) are explained in this chapter.

2.1. Hazard Interactions

Hazard interactions occur when multiple hazards (multi-hazard) occur and overlap either spatially or temporally. There are different classifications of hazard interactions defined in literature. The United Nations Office for Disaster Risk Reduction (UNDRR) (UNDRR, n.d.-b) states that multi-hazard can occur simultaneously, cascading, or cumulatively over time according to the potential interrelated effects. Tilloy et al (2019) reviewed current research available for classifying hazard interactions from four different references; Gill and Malamud (2016), Decker and Crinkman (2015), Liu et al (2016), and Westen and Greiving (2017). Five classifications were concluded from the review: independence, triggering (cascading), change condition, compound hazard (association), and mutual exclusion). Another classification is defined by De Angeli et al (2022) through identifying hazard interaction classifications from six references, including Tilloy et al (2019) with addition Kappes et al (2010) and Garcia-Aristizabal and Marzocchi (2013). In conclusion, Angeli et al (2022) classified hazard interactions into parallel, cascading, disposition alteration, additional hazard potential, and coincident triggering.

Understanding hazard interaction is important as the basis for multi-hazard impact assessment since it will determine to what degree does one hazard affect a certain exposed element-at-risk. Despite the different classification among experts, each of the classification has similar definition. Therefore, the interactions between hazards can be summarized into several interaction types. Each of the hazard interaction type will be elaborated below.

2.1.1. Independent Hazard Interaction

In this interaction, the trigger factors between the hazards are unrelated. Tilloy et al (2019) and De Angeli et al (2022) define this interaction in their classification as independent and coincident triggering, consecutively. The cause and trigger factors of each hazard are independent one and another, as well as the occurrences. The hazards will overlap if the causes and triggers of each hazard occur at the same time (2016). Similarly, Hielkema et al (2021) call this interaction as "pure coincidence" because of the independency and no correlation between the triggering factors. One example of this interaction is when volcanic eruption and a hurricane, or a typhoon and an earthquake happen together.

2.1.2. Coupled Hazard Interaction

Coupled interactions occur when the different hazard types have the same triggering event. De Angeli et al (2022) describes this as the parallel interaction. Since the hazards have the same triggering mechanism, the temporal probability and probability of occurrence between the hazards are also the same (Westen & Greiving, 2017). One example of this category is tropical storm which can lead to flash floods or debris flows due to the strong wind and heavy rain that are coupled to the storm. Assessing the impact of these hazards are complicated not only because the hazard footprints cannot be done separately, but also the vulnerability assessment needs to be done simultaneously as well.

2.1.3. Domino (Triggering or Cascading) Hazard Interaction

This interaction takes place when the occurrence of a hazard changes or acts as the triggering factors of a hazard, resulting in the occurrence of another hazard (Angeli et al., 2022; Liu et al., 2016). The second hazard could be the same or different as the first one but occurs within a different time. There is also a possibility that more than one hazard can occur as the secondary hazards. An example of this interaction is when an earthquake could break a dam construction, resulting in a breach which then flooded the surrounding area, or landslide in a hilly area.

2.1.4. Conditional Hazard Interaction

This type of interaction occurs when a hazard influences environmental condition of an area, creating more susceptibility towards the second hazard (Westen & Greiving, 2017). Environmental condition can be influenced by many hazards hence it may change constantly. For example, heavy rain due to tropical storms might lead to flash flood and change in soil saturation, increased erosion, leading to debris flow or landslides. Identifying this type of interaction is difficult and needs a comprehensive and regular update of risk assessment once every major hazard event occurs.

These categories of hazard interaction are not limited to the provided examples. The provided categorizations mostly consider the temporal aspect of the event. Temporal aspects need to be considered thoroughly since hazard interactions might change depending on the timeline. Hence, the impact and risk might also differ according to the corresponding interaction. In-depth chronological study is also required in assessing the interaction between hazards. The chronological study determines to what extent the related hazards interact.

Although the temporal aspect is significant to assess the hazard interaction, the spatial consideration of an event is important as well. When assessing the impact and risk of interacting hazards, the spatial aspect provides information of the overlapping hazards and how the hazards spread from the source. Other literature also mentions hazard interaction according to spatial and temporal coincide (Gill & Malamud, 2016). However, this may not be focused on in this thesis as the case study has been decided and spatial-temporal aspect is evident in this case.

2.2. Volcanic and Cyclone Hazards

As mentioned in Section 1.3, compounding events of volcanic eruptions and tropical cyclones have happened throughout history in different parts of the world, often with different sequences of events and intensities. Due to the volcanic and geographic settings of the area, these differences also result in different impacts. Understanding the processes for each hazard is important to define the interactions when conducting impact assessment for compounding multi-hazard events. The processes and related hazards for each volcanic and cyclone are elaborated below.

2.2.1. Volcanic Hazards

A volcanic eruption occurs when the magma reaches or approaches the surface. The physical processes of magma plumbing systems is unique for each volcano and each eruption. The triggers are classified in general into internal (processes that build the magma pressure with the reservoir) and external (causing magma reservoir failure by changing the stress field and the strength of the host rock) triggers (Caricchi et al., 2021).

Volcanic hazards are multi-hazard by nature. When a volcano erupts, it produces several hazards which affect the neighbouring area around the volcano (British Geological Survey, n.d.). The presence of each hazard depends on the settings of the volcano. The most common volcanic hazards are lava flows, pyroclastic flows, volcanic gas, and tephra or ashfall. Lava flows are magma which extrudes onto the surface of the volcano and flows very slowly, yet destructs everything in its pathway due to its heat. If the lava has high viscosity, it cannot travel far from the volcano and builds up into lava domes. Pyroclastic flows, on the other hand, are hot density currents consisting of debris and gas which flows at high speed along the ground. When an eruption occurs, various gases are emitted which can cause various health hazards locally up to affecting global climate depending on the intensity of the eruption. Lastly, tephra or ash are volcanic material being ejected through the plumes and fall to the ground with proximity to the volcano depending on the size of the particle. The term tephra is used to describe all erupted particles, whereas the term ash is used for particles with less than two mm in size (British Geological Survey, n.d.).

Other hazards might also occur with interference of external processes such as hydrological and geological processes (British Geological Survey, n.d.). Lahar, which is a type of debris flow, occurs due to the mixture of volcanic debris with water, especially by heavy rainfall. In the Eastern Caribbean, the lahars occur because of intense rainfall especially during rainy seasons in the tropical climatic zone where they are located, including Saint Vincent (Miller et al., 2022; Phillips et al., 2023). In volcanoes with ice cover, lahars can occur as a result of a large amount of meltwater. *Jökulhlaups*, a glacial outburst flood might also happen to volcanoes beneath a glacier. Tsunamis can also be associated with volcanic eruptions for submarine eruptions or interaction between large volcanic materials (edifice, lahars, pyroclastic currents) into surrounding water. Additionally, landslides are also possible because of a volcanic explosion such as a dome collapse.

2.2.2. Cyclone Hazards

Cyclone is caused by atmospheric activity that results in a pressure difference and depression. The tracks and intensity are the main indicator that defines the tropical cyclone. The tropical cyclone track is dominated by the atmospheric motions on the outer circulation of the tropical cyclone, whereas the intensity is indicated by the minimum sea-level pressure and the peak winds (Pasch & Zelinsky, 2016; Rogers, 2021)

Similar to volcanic hazards, when occurs, cyclone consists of multiple hazards. It can bring destructive strong winds, torrential rain, storm surges, and sometimes tornadoes (World Meteorological Organization, 2023). Cyclone's winds can damage and destroy structures by lifting the roofs from dwellings, or as a result of the roofs being lifted up and crashing other structures (NOAA, 2023a). Depending on the intensity, the wind can cause storm surge to the coastal areas, even at large distances from the cyclone. Torrential rainfall can lead to inland flooding such as flash, urban, or river floodings. Tornado happens when the cyclone makes a landfall or onshore. Its presence adds destructive power to the cyclone and sometimes accompanied by hail or lightning (NOAA, 2023a). The occurrence remains after the cyclone passes if the remnants maintain an identifiable low-pressure circulation.

2.3. Compounding Events of Volcanic Eruption and Cyclone

2.3.1. Hazards Interaction between Volcanic Eruption and Cyclone

Globally, the attempts to understand the interaction between volcanic and tropical cyclone are focused on the atmospheric and landscape conditions. The interaction between eruptions and the earth systems can result in changes in the landscape, oceans, and the physical nature of the surface (Manga et al., 2017). Additionally, volcanic activities may respond to the slow surface deformation associated with seasonal and climatic cycles, such as the growth and melting of glaciers and ice sheets, and changes in sea level (Manga et al., 2017). Deglaciation and the associated loss of weight on the earth's surface contributes to decompression melting, resulted in liquid magma formation that fuelled the subsequent volcanic activity in Iceland (Blackett, 2023; Swindles et al., 2018). Volcanic responses to glacial cycles and sea level changes are likely the dominant climatic influence on volcanism. However, weather and climate can impact volcanism in other ways, such as rainfall-triggered volcanic activity and wetter climate increases the likelihood of volcanic flank collapse (Deeming et al., 2010; Matthews et al., 2009).

A study by Robock (2000) mentions that depending on the intensity, volcanic eruptions can influence climate. The emissions from volcanic eruptions injected into the upper troposphere and stratosphere can influence atmospheric chemistry and climate (Robock, 2000). It is also mentioned that the aerosol layer from large eruptions heats the stratosphere, especially larger in a tropical region. The eruption of Mount Pinatubo in 1991 (will be explained further in Section 2.3.2) caused the plasma density on the upper ionosphere near the equator decreased, leading to the increase in the cyclonic activity especially in the western Pacific (Kostin et al., 2019). Similarly, the aerosol cloud from the 2022 eruption of Hunga Tonga-Hunga Ha'apai strengthened the convection of Tropical Cyclone Cody. The cyclone occurred approximately 500 km from the volcano during the eruption and enhanced the precipitation and intensity of the cyclone (H. Liu & Tang, 2022).

While there are many interactions between volcanic eruptions and the earth systems, as well as cyclones and hydrological systems of the earth, this thesis particularly considers the interaction between the meteorological component of the earth system and volcanic eruptions that affects the population directly. Some volcanic and cyclone hazards depend on external factor(s) for it to behave in a certain way, which are explained below.

a. Not only depending on the material characteristics, volcanic gas and ash dispersal are also influenced by wind, pressure, environmental temperature, and humidity components (Durant, 2015; Graf et al., 1999; Vogel et al., 2017). Therefore, an influence of these components from cyclones when compounding directly with the ejection of volcanic gas and ash can be expected to occur.

b. Torrential rainfall resulted from a cyclone, if compounded with volcanic debris, might result in higher lahars intensity and frequency compared to daily rainfalls in an area (Bonasia et al., 2022; Capra et al., 2010).

c. (Heidarzadeh & Rabinovich, 2021)When an eruption results in tsunami, if compounded with storm surge resulted from a cyclone, coastal floodings might happen with increased intensity as compared to if only the tsunami or storm surge happens separately (Heidarzadeh & Rabinovich, 2021).

2.3.2. Historical Events of Compounding Volcanic Eruption and Cyclone

There have been several cases of compounding events between volcanic eruption and cyclones. Those are portrayed in the event of 1991 eruption of Mount Pinatubo in the Philippines, 2010 eruption of Pacaya volcano in Guatemala, and 2014 eruption of Mount Kīlauea in Hawaii. The detail of each event is explained in this section as follows.

The explosive eruption of Mount Pinatubo in 1991 was coincided with Typhoon Yunya, bringing intense rainfall that triggered lahars, structural failures, and potential for flooding and landslide events (Gill & Malamud, 2016). This eruption ended more than 400 years of the volcano's dormancy and resulted in 320 deaths. However, the warnings from a joint team between Philippines and the United States averted a much greater loss of life and property (Pinatubo Volcano Observatory Team, 1991). The eruption lasted on 12 to 15 June 1991 with over 19 separate eruptions penetrated the troposphere. The prevailing winds in the troposphere and stratosphere were from the east and the plume managed to propagate over 200 km upwind (Lynch, 1991). On 14 June, Typhoon Yunya moved westward and made landfall along the south coast of the Philippines. Most of the losses and damage were the results of ash, lahars, and building collapse due to the rain-soaked ash (Lynch, 1991). The aerosol particles of 17 megatons SO_2 produced by this eruption caused dramatic decreases in the amount of net radiation reaching the earth's surface and resulted in the cooling of the northern hemisphere (Self et al., 1993).

Eruption of Pacaya in 2010 occurred two days prior to the onset of Tropical Storm Agatha. Pacaya erupted on 27 May 2010, generating a plume directed towards the north. This took a surprise to the local communities and civil defence as previous tephra falls had been to the west and southwest, making the defence efforts had been focused on those areas (Wardman et al., 2012). Tephra deposits affected Guatemala City, and considerable quantities of tephra were washed into the city's underground network, making it difficult to be removed. Tropical Storm Agatha made landfall on the Pacific Coast, bringing more than 400 mm of rain and affected 21 out of 22 departments of the country (Villamar, 2010). This event created catastrophic secondary hazards of mass movements, ground collapse events, strong winds, torrential rains, and lahars which resulted in drainage systems blockage and increased the intensity of flooding (Gill & Malamud, 2016).

The impacts of Mount Kīlauea that erupted in 2014 were exacerbated by the swift Tropical Storm Iselle. The lava flows from the slow-onset eruption with lava flows, and brush fires was exacerbated by the swift impact of Tropical Storm Iselle with forceful rains, winds, storm surges, and ocean waves (Ching et al., 2020). In Hawaii, storms hardly happen, and this hazard combination was observed closely. A scientist from the USGS Hawaii Volcano Observatory mentioned that the storm had effect on the eruption. Steve Businger from the University of Hawaii also stated that the volcanic gases and particles could make aspects of the storm more intense (Jaggard, 2014). The fine particles from volcanic emissions caused water in storm clouds to divide into smaller droplets, which created more lightning in the storm (Pattantyus & Businger, 2014).

2.4. Retrospective Assessment

Pyle (2014) mentioned that we can learn valuable lessons from the records, reports, and testimonies of past events and their consequences. By definition, retrospective assessment is an observational review and/or a reassessment of database records to analyse events of interest that have already happened (de Sanctis et al., 2022). Observational review also includes obtaining historical information through interviews and field visit, and in earth observation field, database reassessment includes assessing remote sensing data. Though it has been used in health care settings, it has been implemented in disaster management studies as well. For an instance, PARATUS project applied the methodology of utilizing historical disaster events information and combined the approach with disaster history in their case studies (Cocuccioni et al., 2023). Additionally, Romagnoli et al (2024) proposed a structured risk analysis method in combining disaster forensic analysis with impact chains to link retrospective with the prospective risk analysis.

According to our findings, there are two types of retrospective assessment implementation in disaster management studies. The first one is statistical techniques using historical data records, which have been applied in assessing probabilistic hazard forecasts, losses estimation, and risk analysis (Hincks et al., 2014; Velásquez et al., 2014; Villalta et al., 2014). Hincks et al (2014) uses evidence-based approach of historical eruption precursors to provide probabilistic volcanic hazard forecast using a statistical tool. Loss exceedance curve assessment was also applied using the existing disaster database (Velásquez et al., 2014). Additionally, risk analysis can also be conducted by taking the advantages of historical data model (Villalta et al., 2014).

The second one is literature review on historical reports and articles, as well as collecting testimonies related to hazard events for understanding past history of a hazard or current literature to identify the gaps and opportunities for mitigating future risks (Goldschmidt & Kumar, 2016; McCraine & Surminski, 2019; D. Pyle, 2014). Strengthening Resilience in Volcanic Areas (STREVA) project, initiated the project with a workshop to understand the past history and identify the lessons learned for mitigating future risks (Pyle, 2014). Another retrospective review was conducted to provide the needs in future research regarding humanitarian development in reducing future social and economic losses (Goldschmidt & Kumar, 2016). Similarly, retrospective analysis was also used to identify current gaps on disaster risk reduction, urban adaptation, and policymaking for exploring the dynamics in event-based decision-making (McCraine & Surminski, 2019).

2.5. Impact Chains for Exploring and Assessing Multi-hazards Impacts

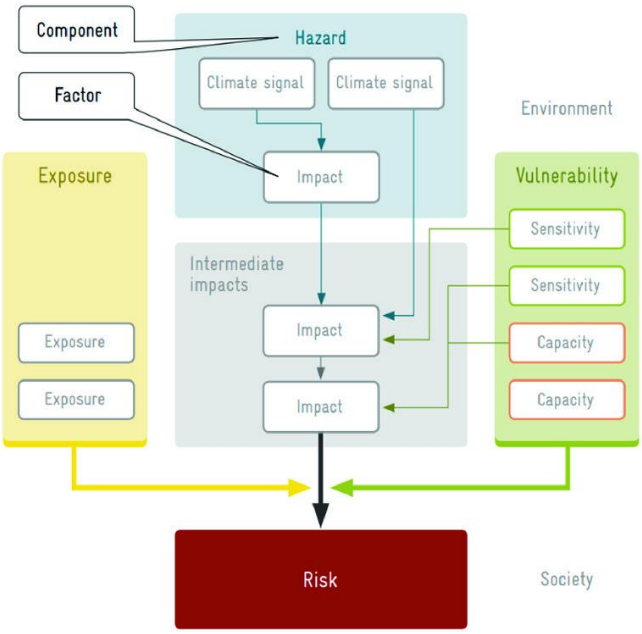


Figure 1. Generic impact chain example (Source: Zebisch et al., 2022).

Impact chains are conceptual models based on cause-effect chains (generic example in Figure 1. This model includes all major factors and processes assigned to hazard, vulnerability, and exposure components leading to specific climate risks in a specific context (Zebisch et al., 2022). Cascading effects in this model are considered as intermediate impacts. Impact chains are initially built for current climate-related risks through assessing the past events impacts and it has been extended to assess the impacts of potential future situation (PARATUS, 2022).

Impact chains can be generated through two manners. The first one is the most common way, which is through a participatory approach together with stakeholders and experts (Pittore et al., 2023). This way, a commonly agreed picture, integration of local data and knowledge, as well as learning from past disaster risk management actions can be obtained (Zebisch et al., 2022). The second one is through desktop analysis by empirical evidence from multiple data and information sources, including scientific literature and grey literature (Albulescu & Armaş, 2024).

Impact chains exploration revolves around the purpose of identifying multi-hazard impacts (Albulescu & Armaş, 2024). The impacts are defined as the intertwined effects of compounded hazards affecting the same area in the same period (Tilloy et al., 2019; Zscheischler et al., 2018). For this thesis, Impact Chains are advantageous to understand which are the significant hazards and exposed elements-at-risk in a complex hazard condition.

2.6. Hazard Simulation

As mentioned previously, prioritized hazards and elements-at-risk to focus on this thesis are chosen and considered according to the result of the retrospective assessment through the impact chains. In this chapter, two simulations are introduced for ashfall and lahars as those are the hazards component to be prioritized in this thesis according to the impact chains results. The readers are suggested to read Chapter 5.1 for detailed information regarding the result of the impact chains.

2.6.1. Ashfall Simulation

Ashfall occurs after an explosion with ash plumes, followed by rain-like situation with ash particles brought down by gravity and dispersed by the atmosphere. Volcanic ash is made of fragments of magmatic glass, country rocks, and minerals. Ash particles are produced by processes when brittle response accommodates local deformation stress that surpasses the capacity of the bulk material to respond through viscous flow. The dispersal of ash is influenced by volcanic and atmospheric processes over large distances and can distribute globally (Paredes-Mariño et al., 2022). Therefore, deciding the ash material characteristics and the meteorological conditions at the time as the inputs for the simulation are very important.

There are various methods to simulate ashfall. The most widely applied empirical methods for estimating ashfall using isopach maps which are contour maps of ash thicknesses. These maps are usually hand drawn but increasingly developed to use Geographic Information System (GIS) interpolation methods (Kawabata et al., 2013). Tephra dispersion and attenuation are also estimated using numerical models based on advection-diffusion equations. These models are used in several tools such as HAZMAP (Barberi et al., 1990), ASHFALL (Hurst & Turner, 1999), Tephra2 (Bonadonna et al., 2005), PlumeRise (https://www.plumerise.bristol.ac.uk/), or FALL3D (Costa et al., 2005).

This thesis uses FALL3D to conduct ashfall simulation. According to the four test cases of the newest version of FALL3D (Puyehu, Raikoke, Etna eruptions and Chernobyl nuclear accident) and the result for tephra modelling of the 1979 La Soufrière eruption, this tool is shown to result in a good agreement with the ground observation for each case (Poret et al., 2017; Prata et al., 2021).

FALL3D is a Eulerian model for atmospheric passive transport and deposition based on advection-diffusion-sedimentation (ADS) equation (Equation 1). This equation uses advective flux, sedimentation flux, diffusive flux, source, and sinks in the model. It also solves the model with consideration towards time, concentration, wind velocity vector, terminal settling velocity, and the diffusion tensor. Using this equation, the substances are grouped into particles, aerosols, and radionuclides. Each of this category are defined internally as data structures that inherit the parent category properties (Prata et al., 2021).

$$\partial c \partial t + \nabla \vec{F} + \nabla \vec{G} + \nabla \vec{H} = S - I$$

Equation 1. Advection-diffusion-sedimentation (ADS) equation for tephra model (Source: Prata et al., 2021).

FALL3D solution comprises of four phases: (1) Generating particle Total Grain Size Distribution (TGSD) for species of category particles, (2) Interpolating meteorological variables from the meteorological model grid to the FALL3D computational domain, (3) Generates emission source terms for the different species which can also perform a-priori particle aggregation and a TGSD cut-off, and (4) Running the model output of ground load, wet deposition, deposit thickness, concentration at ground level, column mass load, concentration at different flight levels, as well as total and class concentration at all model layers (https://fall3d-suite.gitlab.io/fall3d/chapters/overview.html). For all the phases, only one common configuration file is needed. In the file, the input parameters and files are defined under several blocks.

There are 13 blocks in the configuration file in which each of them solves a different step for the model. These blocks are elaborated here according to the article of Folch et al (2020): (1) Block Time: defines variable related to date and time of the modelled ashfall event. (2) Block Insertion Data: used if initial conditions are defined. (3) Block Meteo Data defines variable for meteorological data inputs. (4) Block Grid: defines grid variables for the model including the resolution of the model cells. (5) Block Species: defines the species either particles, aerosols, or radionuclides. (6) Block TGSD: defines the material characteristics including particle density and distribution models. (7) Block Particle Aggregation: specifies whether particle aggregation or cut-off is defined in the model. (8) Block Source: defines variables for generating the source term for the emission phases. The parameters include source heights above the vent and mass flow rate. (9) Block Ensemble and (10) Block Ensemble Post: define the parameters to generate ensemble models which are multiple probabilistic models are generated in one process. (11) Block Model Physics: defines the variables related to physics of the model such as turbulence model and deposition characteristics. (12) Block

Model Output: defines the variables for the output results such as file extension and result deposition types. (13) Block Model Validation: used to perform model validation with quantitative and categorical metrics of observation types and files.

2.6.2. Lahar Simulation

Lahars are generated from the interaction of intense, frequent rainfall and loosely consolidated volcanic material deposits (Phillips et al., 2023). The main physical parameters to assess lahars impact are the flow depth and the dynamic pressure (Gattuso et al., 2021). In order to obtain these parameters, simulation which considers the physical processes of lahars is needed.

There are a number of modelling approaches to simulate the runout and inundation. Some models identify inundation areas according to the elevation model and assigned material volumes, such as LAHARZ (Schilling, 1998). Other models use computational fluid dynamics model with velocity and thickness, such as LaharFlow (Darnell et al., 2013), Flo-2D (O'Brien et al., 1993), TITAN2D (Patra et al., 2020), VolcFlow (Kelfoun & Druitt, 2005), pyFlowGo (Harris & Rowland, 2015), or LISEM (Bout, Lombardo, van Westen, et al., 2018).

The tool Lisem Integrated Spatial Earth Modeler (LISEM) is used in this thesis for lahar simulations. LISEM is an open-source geospatial modelling tool focuses on simulation of physical processes on and in the Earth's surface which includes hydrology, flood, slope failure, landslide, and debris flow runout modelling (https://lisemmodel.com/docs/home/). This tool is suitable to investigate physical processes in a catchment leading to hazardous processes, as well as for simulating scenarios in risk and hazard assessment (Bout, Lombardo, van Westen, et al., 2018). These advantages are in line with the aims of this thesis, and therefore LISEM is used. This exercise can also contribute to LISEM application as so far there has not been any application for lahar simulation using LISEM.

Lahar is essentially a type of debris flow which contains water and solid particles originating from volcanoes (Thouret et al., 2020). Therefore, in this thesis the debris flow equation is used for the simulation. The debris flow equations in LISEM follows a two-phase equation as shown in Equation 2 for the solid phase and Equation 3 for the fluid phase (Pudasaini, 2012). This equation contains a physically based two-phase momentum balance (Bout, Lombardo, van Westen, et al., 2018). It also includes pressure and gravitational forces, viscous force, non-Newtonian viscosity, two-phase drag. For the solid phase, a Mohr-Coulomb type friction force is also included. With this equation, a smooth transition between non viscous flow, hyper concentrated streamflow, and debris flow can be obtained (Bout, Lombardo, van Westen, et al., 2018).

$$S_{y,s} = \alpha_s \left(g\left(\frac{\partial b}{\partial y}\right) - \frac{v_s}{|\vec{u}_s|}\tan\left(\partial P_{b_s}\right) - \varepsilon P_{b_s}\left(\frac{\partial b}{\partial y}\right)\right) - \varepsilon \alpha_s \gamma P_{b_f}\left(\frac{\partial h}{\partial y} + \frac{\partial b}{\partial y}\right) + C_{DG}(v_f - v_s)|\vec{u}_f - \vec{u}_s|^{j-1}$$

Equation 2. Debris flow equation for solid phase.

$$S_{y,f} = \alpha_f \left\{ g\left(\frac{\partial b}{\partial y}\right) - \varepsilon\left[\frac{1}{h}\frac{\partial}{\partial y}\left(\frac{h^2}{2}P_{b_f}\right) + P_{b_f}\frac{\partial b}{\partial y} - \frac{1}{\alpha_f N_R}\left(2\frac{\partial^2 v_f}{\partial y^2} + \frac{\partial^2 u_f}{\partial y \partial x} + \frac{\partial^2 v_f}{\partial y^2} - \frac{\chi v_f}{\varepsilon^2 h^2}\right) + \frac{1}{\alpha_f N_R}\left(2\frac{\partial}{\partial y}\left(\frac{\partial \alpha_s}{\partial y}(v_f - v_s)\right) + \frac{\partial}{\partial y}\left(\frac{\partial \alpha_s}{\partial y}(u_f - u_s) + \frac{\partial \alpha_s}{\partial x}(v_f - v_s)\right)\right) - \frac{\xi \alpha_s (u_f - u_s)}{\varepsilon^2 \alpha_f N_{R_{\mathcal{A}}} h^2}\right]\right\} - \frac{1}{\gamma}C_{DG}(u_f - u_s)|\vec{u}_f - \vec{u}_s|^{j-1}$$

Equation 3. Debris flow equation for fluid phase.

The input parameters used to simulate lahar (debris flow) in LISEM are derived from these equations. The input parameters needed for the debris flow model are digital elevation model (DEM), surface roughness, solid height, water height, material density, rock size, internal friction angle, and drag force coefficient. Before simulating debris flows, it is important to calculate the shear stress of the terrain to identify the area that is likely to initiate slope failure which will result in a debris flow. Slope failure occurs when the driving shear stress along the sliding block is greater than the resisting shear stress subjected to a saturated soil mass

(Hairani & Rahardjo, 2021). Driving shear stress is caused by weight force, while resisting shear stress is caused by frictional resistance at the base of sliding block (Hairani & Rahardjo, 2021). The shear stress can be calculated using the equation in Equation 4 (Bout, Lombardo, van Westen, et al., 2018).

$$t = c + N \tan(\emptyset)$$

Equation 4. Shear stress equation with Manning's approach.

Additionally, when aimed to simulate lahar runout due to a certain rainfall parameter, precipitation rate associated with the simulated event should be incorporated into the model. One way to incorporate rainfall into the model is through storm hyetograph, or triangular-shaped design storm. This method is expected to fit rainfall time distribution in arid and semi-arid regions, which is suitable for the Caribbean state (Ellouze et al., 2009). Total rainfall depth is given by the area under the hyetograph (Figure 2). This approach can also reduce the smoothing effect of averaging precipitation rate (Ellouze et al., 2009).

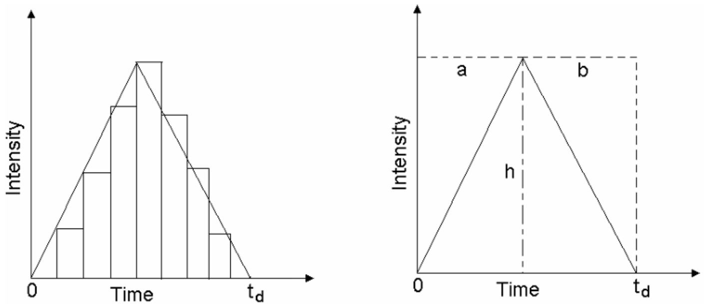


Figure 2. Triangular representation of a hyetograph (Source: Ellouze et al., 2009).

2.7. Impact Assessment from Multi-hazard Interactions

Impacts arise when a hazard exposes vulnerable communities and livelihoods. Impact refers to the consequences of an extreme event or climate change on natural, social, and economy (Valles et al., 2020). Disaster impacts can be classified into several categories according to the focus of the study. Some classify impacts into tangible-intangible, direct-indirect, and negative-positive impacts (Laugé et al., 2013; Valles et al., 2020). This thesis will only consider tangible and direct impacts.

Assessing impacts for multiple hazards requires a different approach as compared to single hazard especially regarding the interaction and dynamics of the impacts and vulnerability of the exposed systems. Angeli et al (2022) reviewed the existing multi-hazard risk approaches and came up with a conceptual framework to analyse impacts from multi-hazard interactions. This framework consists of the following steps: (1) Identification of hazards and their interactions (2) Multi-hazard modelling (3) Analysis of spatial and temporal evolution of the impacts from the hazards (4) Identification of the impact interaction types and (5) The multi-hazard risk or impact assessment. While steps (1) and (2) are already explained in this chapter in Section 2.1 and 2.6, this section will only explain steps (3) to (5).

A. Analysis of spatial and temporal evolution of the impacts from the hazards: this step focuses on the interactions between the hazards and the other components of the risk equation (vulnerability, exposure, and impacts from hazard interaction).

B. Identification of the impact interaction types: four cases of impact interactions are identified in this step. (1) Spatial-temporal overlapping impact. (2) Temporal but not spatial overlapping impact. (3)

Spatial overlapping impact (with residual and subsequent damage). And (4) independent single hazard impacts.

C. The multi-hazard risk or impact assessment: assessment is conducted by taking into account the hazard interaction that was assessed previously (Section 2.1).

As explained in Chapter 1, damage and losses are often used to identify disaster impacts. Assessing damage can be done in many ways, such as based on social media, crowdsourcing, remote sensing data, deep learning, or vulnerability (fragility) curve (Irwansyah et al., 2023; Khajwal & Noshadravan, 2021; Lagomarsino et al., 2019; Shan et al., 2019; Yamazaki & Matsuoka, 2012). Yamazaki and Matsuoka (2012) assessed the damage from the 2004 Indian Ocean tsunami and the 2006 Central Java earthquake using high-resolution before-after optical satellite images. They extracted the damaged building based on land cover classifications. Satellite imagery can also be combined with deep learning to assess the level of damage through segmentation and classification (Irwansyah et al., 2023). Social media and crowdsourcing data can also be used to assess real-time damage (Khajwal & Noshadravan, 2021; Shan et al., 2019). Additionally, assessing damage from a disaster by identifying the vulnerability through vulnerability curves or also called fragility curve, or damage curve (Porter, 2021). This thesis will use vulnerability curve to assess the impact of the scenarios. Vulnerability curves make use of empirical data that shows the relationship between the process intensity and the degree of damage on the focused elements (Papathoma-Köhle et al., 2022; Porter, 2021).

3. STUDY AREA

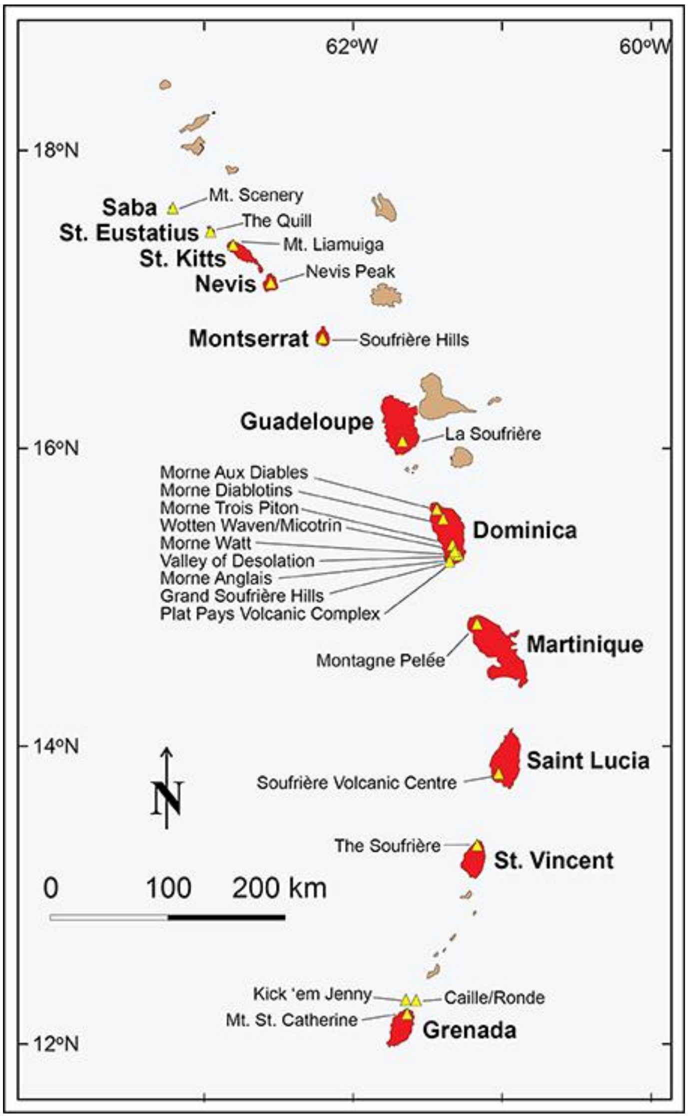


Figure 3. Potentially active volcanoes in the Lesser Antilles (Source: Lindsay & Robertson, 2018).

The Caribbean consists of many Small Island-Developing States which are exposed to multiple hazard threats such as hurricane, earthquakes, and volcanic hazards (Gibbs, 2001) (explained in Section 1.1). The Caribbean is grouped into Greater Antilles, which consists of large islands on the west of the Caribbean, and Lesser Antilles, consisting of smaller islands to the east (Britannica, 2024). Across 11 volcanically active islands in the Lesser Antilles, there are 21 potentially active volcanoes, as shown in Figure 3 (Lindsay & Robertson, 2018). Given the focus of this thesis is to assess multi-hazard of volcanic eruption and cyclones, the case of 2021 compounding event in Saint Vincent is chosen in for this thesis (explained in Section 1.2). In this chapter, Saint Vincent will be described thoroughly.

Saint Vincent and the Grenadines (SVG) is an archipelagic state in the Eastern Caribbean with Saint Vincent as its main island. It is located in the north part of the country, while the Grenadines islands lie to the south as can be seen in Figure 4. Saint Vincent was under the colonization of France and England until 1834 when the British abolished slavery. Autonomy was granted for Saint Vincent and the Grenadines in 1969 followed by independence in 1979 (CIA, 2024). Seven-tenths of the inhabitants are descended from Africans who were enslaved, nearly one-fourth of the population is of mixed African, European, and Carib ancestry, and small minorities are descended from South Asian, European, and Carib (Britannica, 2024). Saint Vincent once had the highest birth rates in West Indies but has declined in late 20th century due as a result of family planning efforts from the government (Britannica, 2024).

As a Small Island Developing State, this country is strongly dependent on tourism and investment for the economy development, as well as vulnerable to natural hazards (European Union, 2019). The economy of Saint Vincent mainly comes from the agricultural sector with the main crops are arrowroot, banana, and used to be cotton and sugarcane (Britannica, 2024). Due to the dynamic geomorphology and climatic conditions in Saint Vincent, the main crops often change and shift. Therefore, the government intends to grow the agriculture sector with diversifying the economy through tourism (Scott, 2022).

Figure 4. Map of Saint Vincent (Data source: Government of Saint Vincent and the Grenadines).

The country is characterized by a humid tropical climate with the annual average rainfall is 2800 mm inland and 2000 mm on the coast (Government of Saint Vincent and the Grenadines, n.d.). The landscape, dominated by steep slopes and volcanic layers, combined with high temperatures and abundant rainfall will lead to slope instabilities and a high landslide potential (Government of Saint Vincent and the Grenadines & World Bank, 2014). The main island, Saint Vincent, which is also the largest island in SVG is occupied by an active volcano (La Soufrière) on its northern end (Government of Saint Vincent and the Grenadines, 2021). La Soufrière has a long-recorded eruption history of more than three centuries. According to the records, the common volcanic hazards to occur for La Soufrière are lava flows, pyroclastic density currents (PDCs), lahars, volcanic ash and gas.

Tropical storms, hurricanes, and volcanic eruptions have been responsible for most of the disaster devastation in SVG. Other hazards also happen in SVG in which most of them are associated with the disasters mentioned previously, such as floods, landslides, and lahars (Murray, 2014). These hazards have created damage in SVG, especially towards agriculture, transportation, public facilities, telecommunication, and electricity. From the early 1900s, it is recorded that the damage caused by volcanic activity ranged from US$100 million to US$200 million. Meanwhile, the damage caused by hurricane corresponds with flood and landslide ranged from US$5 million to US$300 million (van Westen, 2016), as shown in Table 2.

Table 2. Damage of volcanic eruptions and cyclones in Saint Vincent (Source: Westen, 2016).

Year	Event	Name	Damage (US$ mil)	Year	Event	Name	Damage (US$ mil)
1902	Eruption	La Soufrière	200	**2004**	Cyclone	Ivan	1.85
1967	Cyclone	Behulah	4.5	**2008**	Cyclone	Omar	1.85
1979	Eruption	La Soufrière	100	**2010**	Cyclone	Tomas	48.1
1980	Cyclone	Allen	16.3	**2013**	Cyclone	-	108.4
1987	Cyclone	Emily	5.3	**2021**	Eruption	La Soufrière	153

3.1. The 2021 Event

In 2021, La Soufrière erupted for the first time in the 20s century. This eruption was a unique one in La Soufrière history because it was started as an effusive eruption, then became an explosive one in the last three weeks of the event. The eruption occurred between 27 December 2020 and 22 April 2021. Throughout the eruption, effusive (27 December 2020 to 8 April 2021) and explosive (9 to 22 April 2021) phase happened in between (Robertson et al., 2023). The effusive eruption began with a viscous lava dome extraction in which later was destroyed upon the transition to the major explosive phase (as shown in Figure

5). The eruption was fed by magma with no evidence for chemical interaction or mixing of mafic and evolved melts (Weber et al., 2024). The initial explosive activity had high near-surface overpressures, resulting in excavation of the 2021 crater and conduit system (Cole et al., 2023). The shift in the eruption style is likely due to the efficiency of outgassing during magma ascent at different rates throughout the eruption, which may be in response to changes in buoyancy forces in the deep source region (Weber et al., 2024). Weber et al (2024) also mentioned that the eruptive products are similar to previous activity, indicating that La Soufrière is currently in a steady-state regime. From these observations, it can be concluded that the triggers for La Soufrière eruption come from internal factors.

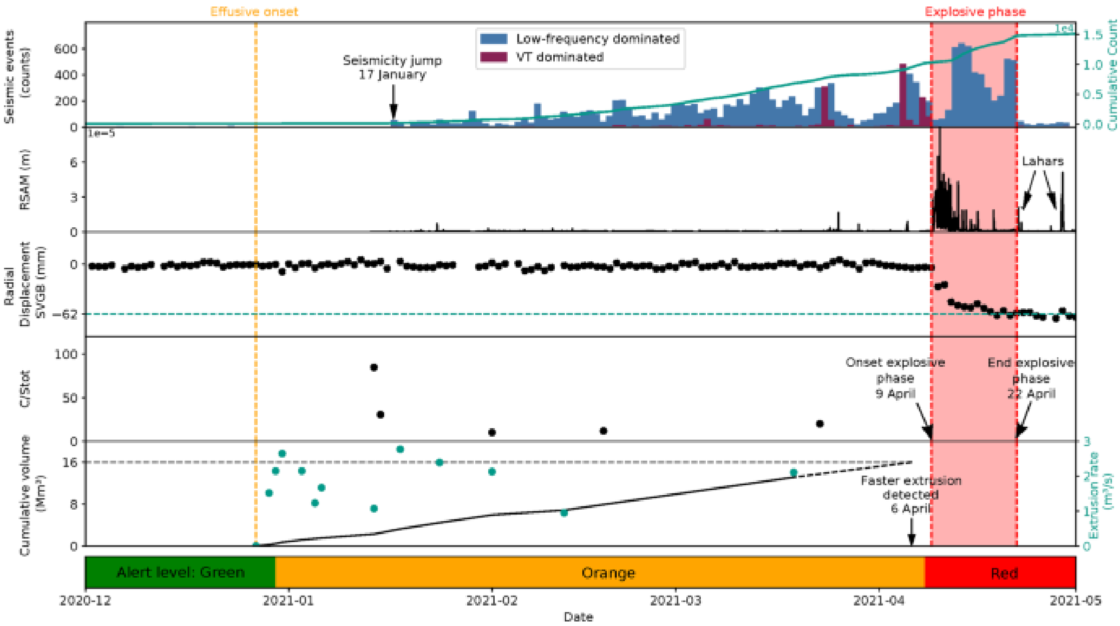


Figure 5. Timeline of monitoring for the 2021 La Soufrière eruption (Source: Joseph et al., 2022). The seismicity data is shown as bars and teal lines for daily and cumulative data consecutively. RSAM represents Real-time Seismic Amplitude Measurement. SVGB is a continuous GPS station. C/Stot is CO2/H2s concentration ratios in the plume.

3.1.1. Timeline of the 2021 Event

La Soufrière started to show activities since November 2020 continued in December 2020 with increasing seismicity. This marks the beginning of the effusive phase of the eruption. The Volcanic Alert Level (VAL) was increased to Orange. Lava flow began to appear and formed a lava dome in the crater. Localized earthquakes, gas-and-steam and sulphur dioxide emission were also present during the effusive activity. The effusive activity lasted for four months until March 2021 with the lava dome, volcanic-tectonic earthquakes, and gas-and-plume continued to occur.

These conditions were confined around the crater only. Therefore, there is no direct impact on the society since the settlements are all located along the coastline. However, the vegetation around the crater were all damaged with some of them are destroyed to the root so they do not grow back. According to information from some residents, the damage for vegetation was up to the town of Chateaubelair in the west side of the island (Leeward), approximately 10 km from the volcano.

The seismicity of La Soufrière increased rapidly in late March 2021 and the beginning of April 2021. The shift from effusive to explosive eruption is noticed from ash plume ejected into the atmosphere on 9 April 2021 in the morning. The VAL was raised to Red and evacuation order was issued. The explosive eruption lasted until 22 April 2021 with 32 explosions in total The last plume is noted to be on 24 April 2021 with steam plume ejected.

Ash plumes from the explosion resulted in ashfall dispersal across the main island Saint Vincent (Figure 6). The plume that went with east-northeast direction, also made landfall in some parts of Barbados and Saint Lucia, the neighbouring countries of Saint Vincent and the Grenadines. The ash is considered to consist of sufficient material of respiratory concern due to the abundance of respirable particles in the ash (Horwell et al., 2022). This particle will continue to be remobilized through various conditions and human activity, until the ash is completely removed or reworked into the soil which could take decades.

Figure 6. Ash cover in Saint Vincent (Source: Caribbean Disaster Emergency management Agency, 2021)

Following the explosive eruption, reports start to acknowledge lahars presence since 11 April 2021, two days since the first explosion was recorded. There were approximately 25 lahar events throughout the 2021 eruption until November 2021. These events were recorded with the associated rainfall that came with or before the lahars. A minimum rainfall of 20 mm is sufficient to result in a lahar and the average rainfall in rainy season of Saint Vincent is around 200 mm per month (Caribbean Institute of Meteorology and Hydrology et al., 2018; Phillips et al., 2023). Therefore, we can expect more frequent lahar occurrences during rainy season.

In May 2021, the seismicity started to decrease and remained low. The VAL was also lowered back to Orange and the residents from Yellow and Orange zones were allowed to return home. Despite the lower seismic activity shown, the island is still under the threat of lahars due to the volcanic deposits and rainfall especially with the approaching rainfall season (June-November).

As obtained from the retrospective assessment, heavy rainfall often comes with tropical cyclone events. This was also the case for Hurricane Elsa which hit Saint Vincent on 2nd July 2021. It was recorded that on 2nd July 2021, the rainfall was the highest since April 2021. However, the impacts from Hurricane Elsa are mainly caused by the wind with damage to houses and fallen power poles which affected other infrastructure such as roads (CCRIF, 2021).

The seismic activity of La Soufrière remained low until March 2022 when the VAL level was lowered to Green. This marked the end of the eruption event of La Soufrière in 2021. However, the volcano trail remained closed until several months later due to the instability of the terrain. The public was also reminded that there is still lahar threat especially during heavy rains.

3.1.2. Impacts and Response

Both eruption and the hurricane impacted Saint Vincent severely. The eruption initially started as an effusive one in late 2020, then in April 2021 it became an explosive eruption. It was estimated that approximately 16,000 to 20,000 persons have been affected and around 30 villages were evacuated (Government of Saint Vincent and the Grenadines, 2021). This event resulted in the evacuation of approximately 22,000 people, 88 shelters were activated, and clean-up operations which costed over US$6.7 million (UWI Seismic Research Centre, n.d.-c). The hurricane caused flash floods, landslides, and strong winds impacting around 200 houses being damaged (Cangialosi et al., 2022). When the hurricane hit, most of the shelters were already used for the evacuees from the eruption. Therefore, several emergency shelters were activated during the hurricane (Searchlight, 2021). Damage to the crops was worsened by the hurricane because they were already severely damaged after the eruption (Cooke, 2021). Some of the vegetation are owned by the farmers which created disruption in income leading to losses in the economy.

Figure 7. Damage to river crossing.
(Courtesy: Antonia Marks, 2021)

Lahar destructs everything in its pathways. The terrain of La Soufrière and damage to vegetation on the upper flank due to the previous explosions resulted in lahars occurring on all flanks of the volcano. This caused the primary roads, river fords, and bridges that connect communities on the northern part of the island were most vulnerable to lahar inundation (Phillips et al., 2023). The physical impacts of lahars were most visible at river crossings that caused damage to houses, roads, bridges, fords, and electrical infrastructures (Government of Saint Vincent and the Grenadines, 2021). However, lahar pathways are constrained physically and temporally due to most of the impacts are concentrated on the flanks of the volcano and most significant soon after the eruption when the tephra thickness was highest (Phillips et al., 2023). Fortunately, as mentioned in the Post-disaster Damage Assessment (PDNA) report (2021), the majority of bridges and road were not physically damaged heavily. Most damage occurs for the river crossings (Figure 7). Additionally, there were also no housing damaged by the lahars since none of them are located on the lahars route.

Due to the ash plumes, the ash covers the whole island up to the neighbouring island such as Barbados and some of the Grenadines such as Bequia. The ash required extensive works of removal and could be done after the residents are back to their homes after the evacuation. Meanwhile, ash could also potentially affect the residents' respiratory and eyesight. The massive load of ashfall can also damage the infrastructure such as building due to its load on the roof or ash particles escape through the hole in the building which can impact the people inside. These impacts are resulted from the lack of quality of the buildings. Approximately 91% of the buildings have metal sheet as their roof material (Government of Saint Vincent and the Grenadines, 2021). This material is the most vulnerable material to ash, yet the residents still use it because of the affordability. After the event, only some people did not change the roof material if their house was not damaged or if they were not compensated.

According to the field work conducted for this thesis, the sediments from La Soufrière eruptions still pile up especially on the northern part of the island. Therefore, lahars threat exists even without an eruption occurring at the moment. Additionally, reports and news of the 2021 eruption mentioned that the ashfall covered the entire island with different thickness linear to the proximity from the volcano, as far as the neighbouring islands such as Barbados and Saint Lucia (IFRC, 2021; Martin, 2021). This makes ashfall is one of the main hazards in Saint Vincent related to volcanic activity.

The government, together with other local, regional, and international organization conducted response and recovery actions during and after the eruption. For example, during the effusive activity, a project collaboration between National Emergency Management Organisation (NEMO) and Seismic Research Centre of University of West Indies (UWI-SRC), the Volcano Ready Communities Project distributed their volcano hazard map for potential evacuation preparation. Extensive monitoring was also conducted throughout the eruption for preparedness (Joseph et al., 2022). According to the interview during the field trip, the evacuation at the starting phase of explosive activity went fast and most of the residents were already evacuated later that day. According to the PDNA report (2021), the government of Saint Vincent and the Grenadines developed a recovery strategy by allocating funds for disaster risk management and climate change adaptation. The World Bank also provided an Eruption Emergency Project for Saint Vincent and the Grenadines to provide short-term income support, improve the government capacity, and support build back better critical services after the eruption (Shenfeld, 2021). For preventing future economic losses especially on tourism and agriculture as their main income, efforts to diversify the economy have been made (UNDP, 2020). According to interview, they have also tried to map springs as additional water resources, especially considering that currently almost all water supply comes from pipe ground water.

3.1.3. Studies Related to the Event

Responding to the latest eruption of La Soufrière in 2021, the government of SVG published a report on PDNA representing the background, context, effects, impacts, recovery needs and strategy of the event (Government of Saint Vincent and the Grenadines, 2021). This report relates to this thesis objective because it contains effects and impact assessment of the eruption. Since this report focuses on the 2021 eruption of La Soufrière which compounded with Hurricane Elsa and COVID-19, the result of this report is used as the baseline on impact assessment in this thesis.

Additionally, the World Wildlife Fund conducted rapid environmental impact assessment following the 2021 eruption. The assessment was intended for a quick issues identification for rapid response management (Kelly, 2021). In the report, several indicators influencing environmental impacts and its relation to certain hazards are presented. This information can help this thesis for impact assessment.

The multi-hazard map from the Caribbean Disaster Emergency Management Agency (CDEMA) and MapAction provides possible hazard footprints of volcanic and geological hazards in Saint Vincent. The hazard maps (lahars and landslide) are based on the modelling conducted in 2021 before the eruption. However, the impacts of the rainfall might coincide with the modelled hazards. Additionally, ashfall, pyroclastic flows, and lava dome are also presented on the map according to observations from the event (CDEMA & MapAction, 2021). Nonetheless, this map also did not incorporate the hazard interaction and no further impact assessment was conducted. Tropical cyclone hazard was also not considered in the map.

Several studies of related tephra phenomena have been conducted after the 2021 La Soufrière eruption, and several ashfall thickness maps were published. However, most of them do not have detailed explanation on how those maps are generated. The maps of volcanic ash and gas modelling by the Caribbean Institute for Meteorology and Hydrology that are presented in an abstract of Jeffers et al. (2022) do not have a detailed information of the methodology used. An estimated ashfall accumulation map is also shown in the PDNA report with a source to the GRADE report of the 2021 La Soufrière eruption from the World Bank (Government of Saint Vincent and the Grenadines, 2021). However, no further explanation could be found in these reports on how the map was derived. Other tephra mapping was also done especially for the purpose of monitoring the explosion activity. Jeffers et al. (2022) also shows ash cloud monitored by GOES-East which was requested from NOAA/NESDIS by the Barbados Meteorological Service along with the Caribbean Meteorological Organization (CMO) Headquarters. A map was also produced by NASA that tracked the ash plume as well as the plume height (NASA, 2021).

Tephra modelling has been conducted previously for Saint Vincent. There is an ashfall simulation for La Soufrière eruption in 1979 reported by Poret et al. (2017). The study estimated the optimal Eruption Source Parameters for simulating tephra transport and deposition using the advection-diffusion-sedimentation equation (explained in Section 2.6.2), as well as performing comparative study of different modelling schemes. The optimal results from this study were selected through a goodness-of-fit method. Nevertheless, the simulation for tephra dispersal has not been done for the 2021 eruption. Along with complementing this gap, this thesis tries to also simulate tephra dispersal variation under different meteorological conditions.

The latest hazard map by the government of Saint Vincent and the Grenadines incorporates a simplified method to determine lahar footprints which does not cover the wider extent in low-lying areas (Lindsay & Robertson, 2018). Due to funding and time limitations, Lindsay et al (2018) took systemic approach to generate volcanic hazard map with basis on only previous studies and existing data. They first generated a phenomena-based hazard map for general scenario of most likely future volcanic activity. Then, they georeferenced volcanic hazard zonation maps from each scenario-based hazard map into user-friendly colour-coded maps.

The more recent lahar simulation is done using a semi-empirical lahar modelling approach to obtain the lahar footprints using a range input of lahar volumes. This simulation can assess the inundation of potential lahars runout through major drainages which affect downstream settlements (Miller et al., 2022). The result of this simulation was then improved by incorporating the runoff coefficient of a rainfall rate for Overland catchment (see Figure 4) on the east side of Saint Vincent (Phillips et al., 2023). However, to the best of our knowledge, lahar simulation incorporating rainfall in Saint Vincent has not been produced yet. Therefore, this thesis tries to cover this gap while also simulate lahars behaviours under different rainfall rates.

3.2. Historical Volcanic Events in Saint Vincent

During the recorded historical period, Saint Vincent has experienced five major volcanic eruptions of La Soufrière. The summary of those eruptions is shown in Table 3. This section is part of retrospective assessment to develop impact chains. The detailed explanation of impact chains is provided in Section 5.1.

Table 3. Summary of eruptions in Saint Vincent.

Year	Eruption Type	Main Characteristics
1718	Explosive	Saint Vincent was formally ceded by France to Britain.
1812	Explosive	Losses were concentrated in two northern coastal regions closest to the volcano.
1902	Explosive	Rapid onset, most casualties were from the Windward side.
1971	Effusive	Extrusion of lava for ~5 months.
1979	Explosive	Abrupt change from effusive to explosive. No direct loss of life.

3.2.1. 1718 Eruption

The first known eruption was in March 1718, which was noted as a major eruption. During this period, Saint Vincent was formally ceded by France to Britain at the end of the Seven Years' War (1756-1763) (Smith, 2011). Pyle (2014) mentioned that there are no known first-hand descriptions of this eruption. However, an article was published in a journal known as Mist's Journal by Daniel Defoe describing the explosive eruption of 1718 obtained from the reports from the passing ships (Pyle, 2014). These reports stated that a large volume of pyro clasts was produced during the three days of the eruption.

3.2.2. 1812 Eruption

Almost a century later, in 1812, the next major eruption of La Soufrière occurred. At about noon on 27th April 1812, La Soufrière produced thunderous cracks in the air, earthquakes, a massive column of ash plumes, and volumes of red-hot molten lava were spat into the atmosphere. The island was covered with ash, lahars were present on the northern parts of the island, two of the rivers were completely dried up, the crops were ruined, and food had to be imported from neighbouring islands (Pyle et al., 2018). Approximately 80 people died, and many were injured with most of them were enslaved people working in sugar fields and killed by the pumice (Clifford, 2017). Smith (2011) mentions that the losses of this eruption were concentrated in two northern coastal regions closest to the volcano, specifically towards long-established plantations and estates in the Leeward (western) side and recently established estates in Windward (eastern) side of the island (see Figure 4 for study area map). Insufficient evidence is available for intangible impacts, while most of the evidence explains the losses in economy for plantation and estates.

The information for response actions to this event is obtained from the analysis of Smith (2011). The colonial government petitioned relief and distributed emergency supplies through a committee, as well as grant to relieve sufferers. Meanwhile, the response coordinator to the disaster was undertaken by the government of Saint Vincent. This eruption, together with the 1898 hurricane contribute to the expansion of arrowroot sectors while sacrificing the declining of sugar economy. Although the decision for future planning were left to individual estate owners, their resilience was shown by the speedy restoration of production with a significant regional difference between Leeward and Windward sides. However, due to the regional differences, no discernible changes were made to the economy of the island or social system for mitigation purposes of future risk.

3.2.3. 1902-1903 Eruption

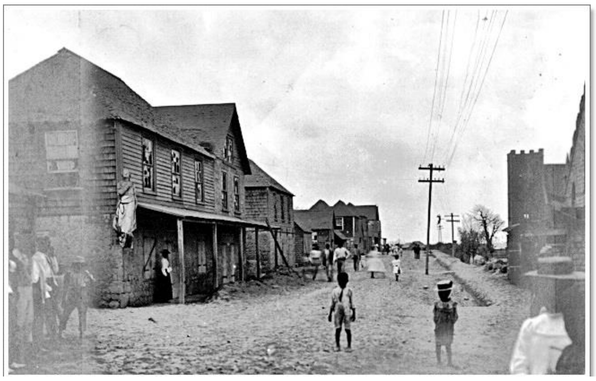


Figure 8. Georgetown covered in ash in 1902.

La Soufrière eruption which resulted in the greatest loss of life is the 1902-03 eruption, which is the next eruption after the 1812 event. Started with precursors activities in 1902, a violent eruption took place in May 1903 sending ash into the atmosphere (Figure 8 showing Georgetown on the Windward side of Saint Vincent, covered in ash in 1902), PDCs and lahars down the volcano flanks into the drainages that dissect the northern parts of the island (Pyle et al., 2018). The rapid onset caught people unaware and resulted in high death toll up to 1,500 people. Following the precursory activities, people in the Leeward side had responded to it and moved out from the so-called 'the harm way'. However, the people in Windward (eastern) side did not heed the precursory activities as they had the assumption of the dark clouds being a meteorological event rather than volcanological. Pyle et.al (2018) noticed that the people in Leeward could see the summit of the volcano, whereas it is not visible from the Windward side. Approximately 700 houses were built for the displaced communities and a total of £77,000 relief fund was set up in response for the people and impact towards the agricultural crops.

Efforts for longer term responses and recovery were made as well according to an article from Pyle et al (2018). Long-term investment recovering aid was distributed imperatively not to compensate individual landowners. A focus on community welfare by applying modern community-based disaster risk management with doles which benefit malnourished islanders. This attempt contributed to decreasing number of reported criminal offences. Although decision making was slow with some relief fund remaining, several attempts were successful and achieved good results. These are the attempt to focus on agricultural production which lead to improvement of crops diversity, recovery process wrapped into longer term of land re-distribution program, and improved communication protocols.

3.2.4. 1979 Eruption

After 10 months of mild premonitory and a short period of unrest, La Soufrière began to erupt again on 13th April 1979. For approximately 13 days, a series of strong vertical explosions generated ash falls, PDCs, and lahars (Shepherd et al., 1979). After the series of explosions, basaltic-andesite lava accumulated in the summit crater until October 1979. During the eruption, first aid and rescue supplies were provided by several countries and entities. The United States and Britain provided supplies such as fund, costs, and cooking utensils (Daily Press, 1979). This eruption is noted to have an abrupt change from effusive to explosive, making the residents did not have much time for evacuation (Shepherd & Sigurdsson, 1982). However, this eruption did not have direct loss of life, despite the disruption with 20,000 people evacuated to shelters. It was also reported that even though there were no serious injuries, the people could not see the sky due to the ash, and the sulphur flumes were choking (The Miami Herald, 1979). By mid-June 1979, revegetation of the areas affected by the eruption begun (Global Volcanism Program, 1979).

According to a documentary video by Streva Project (2014), the evacuation process was not well coordinated. Shelter management was also not well, not enough food and space, leading to chaos and thievery (UWI Seismic Research Centre, 2021). Cultural condition also contributed to the behaviour of people during that time. There was a dispute and stereotypes between community that made the people were uncomfortable in shelters (Edelman, 2021). Additionally, the government also took a role in recovery after people are back from shelters. They brought in some cattle such as sheep and cows. The soil was more fertile after the eruption; therefore, the agriculture could recover speedily (Streva Project, 2014).

3.2.5. Historical Effusive Eruptions

Aside from the explosive activities mentioned above, La Soufrière also experienced several effusive eruptions. These activities happened in 1780, 1880, and 1971. In contrasts with explosive ones, these eruptions only affected the inside part of the crater. Effusive eruptions in La Soufrière generally consists of steaming and discoloured lake with sulphurous smell and lava dome growth because of the extrusion of lava (Aspinall et al., 1973). Therefore, these eruptions cannot be considered as disaster events (UNDRR, n.d.-a) because they are not affecting the people. Rather, they affected the environment and ecosystems around the crater rim.

3.2.6. Mitigation and Recovery Efforts

Due to the infrequent occurrence of volcanic activity of La Soufrière, there has been a massive work in mitigation and recovery efforts as well as building people awareness and resilience towards these hazards. With the same reason, some agencies were not yet established in the beginning of the known activity of the volcano. UWI-SRC is one of the oldest bodies which has done extensive work, research, and monitoring towards volcanic activity in the Lesser Antilles to be able to react quickly to volcanic emergencies, including Saint Vincent (UWI Seismic Research Centre, n.d.-b). They were established in 1953 and have been continuously working towards resilient volcano communities. CDEMA was established in 1991 with the aim to reduce risk and loss associated with natural and technological hazards and the effects of climate change in the Caribbean through coordinated disaster response to member countries (CDEMA, n.d.). In 2002, NEMO was established with aims to coordinate local, regional, and international resources for better mitigation, preparedness, and response in Saint Vincent and the Grenadines (NEMO, n.d.). Each of these agencies have a role in disaster management towards volcanic emergencies in Saint Vincent.

3.3. Historical Cyclone Events in Saint Vincent

According to EM-DAT, there have been approximately 12 tropical cyclone events in Saint Vincent since 1900. The summary of those events is presented in Table 4. However, in this only five latest cyclone events are assessed for the impact chains. Therefore, detailed explanations are focused on these five events which are: Tropical Storm Bret in 2023, Hurricane Elsa in 2021, Tropical Storm Harvey in 2017, Tropical Storm Matthew in 2016, and Hurricane Tomas in 2010. More explanation on the choice of for these events are explained in Section 5.1.2.

Table 4. Summary of historical cyclones in Saint Vincent.

Year	Name	Type	Tracks
1955	Janet	Hurricane	Levels Saint Vincent with 115 mph winds.
1967	Beulah	Storm	Moved westward and passed Saint Vincent with storm-forced winds.

1980	Allen	Hurricane	Moved westward, Saint Vincent experienced the outer southern fringes of the storm.
1987	Emily	Storm	Moved westward, the center passed directly over Saint Vincent with 50 mph winds.
1999	Lenny	Hurricane	Mowed westward around Saint Martin, approximately 600 km north-west of Saint Vincent.
2002	Lili	Storm	Reached tropical storm strength as it passed through the Windward Islands. Moved westward and continued to intensify as it moved west through the Caribbean Sea.
2004	Ivan	Storm	Large waves and high storm surge battered the coastline of Saint Vincent. Moved westward, passed over several Windward Islands with tropical storm strength.
2005	Emily	Storm	Moved westward, mainly affected the Grenadines islands.
2010	Tomas	Hurricane	Center passing over northern Saint Vincent, moving westward. Attained hurricane status right before passing Saint Vincent.
2016	Matthew	Hurricane	Moved westward, strengthening, and battered in Eastern Caribbean for about 12 hours.
2017	Harvey	Hurricane	Attained storm when entering Saint Vincent with slightly strengthened system, weakened when leaving Saint Vincent.
2021	Elsa	Hurricane	Move westward with rapid intensification and fast forward motion.
2023	Bret	Storm	Center passing over northern Saint Vincent, moving westward. Losing organization due to increasing vertical wind shear, with minimal convection near the center.

3.3.1. 2010 Hurricane Tomas

Around late October 2010, Tomas began to impact the Caribbean islands as a strong tropical wave. It was not more than one day that it developed to a Tropical Strom and was quickly upgraded to Hurricane. The Hurricane status was attained when Tomas was approximately 56 km (35 miles) east of Saint Vincent with surface winds of 75 mph (121 km/h) and 56-74 km (35-46 miles) of eye diameter (Stewart, 2010). When passing Saint Vincent, this hurricane produced wind gusts and damaged houses, power lines, water supply, road, and agricultural sector (CDEMA, 2010). The agriculture industry in the northern side of the island experienced major disruption in their income and jobs (Julien, 2010). Approximately 98% of bananas and plantains in this area were damaged (CDEMA, 2010). After the Tropical Storm Warning was issued, the National Emergency Operations centres were activated, and shelters were opened across the island. Regional Response Mechanism, regional and international supports, as well as search and rescue activities were taken place after the status was issued with Hurricane Warning (CDEMA, 2010).

3.3.2. 2016 Tropical Storm Matthew

In September 2016, over a period of 24 hours, Tropical Storm Matthew hit Barbados, Dominica, Saint Lucia, and Saint Vincent and the Grenadines. Heavy rains and strong winds were experienced which resulted in flooding, landslides, and some damage to infrastructure. When reaching 35 km (20 miles) north-northwest of Saint Vincent, Matthew the storm reached maximum sustained winds of 60 mph (95 km/h) (CCRIF, 2016b). In the Eastern Caribbean, specifically in the Lesser Antilles, Matthew battered and was strengthening around the area for approximately 12 hours (CCRIF, 2016b). Matthew was later become a hurricane, but it had passed Saint Vincent at that moment. Due to the wind, Matthew destroyed some buildings in Saint Vincent and Bequia. The excessive rainfall resulted in landslides and flooding which blocked some roads and damaged banana crops (CCRIF, 2016a). Approximately 290 people were accommodated in shelters across the island due to Tropical Storm Matthew.

3.3.3. 2017 Tropical Storm Harvey

National Hurricane Centre of NOAA identified slow-pressure area on the east of the Lesser Antilles as Tropical Storm Harvey in August 2017. It then passed over the Windward Islands with maximum sustained wind speed of 40 mph and entered the eastern Caribbean Sea (Ehrlich, 2017). Tropical-storm-force winds extended outward up to 110 km (70 miles) from the centre with minimum central pressure is around 1005 mb (IFRC, 2017). Flooding and landslides were reported due to the rainfall total which reached 1-3 inches in Saint Vincent. Some houses were damaged and flooded, which resulted in 15 people were provided with shelters. No injuries or casualties were reported from the event and the main roads were still passable (CDEMA, 2017). It was not more than one day that it weakened to a tropical depression, then a tropical wave, and the remnants moved across Yucatan Peninsula (Wurman & Kosiba, 2018). After the Tropical Storm Warning was issued, the government activated national plan and started internal briefing, monitoring, and coordination, and disseminated the information to public.

3.3.4. 2021 Hurricane Elsa

Hurricane Elsa came to the picture in 2021. This is the hurricane that was compounded by the eruption of La Soufrière. On late June 2021, it developed as Potential Tropical Cyclone Five and then upgraded to Tropical Storm Elsa. It was not more than 2 days later that it intensified and turned into Hurricane Elsa. It passed near Barbados, Saint Lucia, and Saint Vincent and the Grenadines and spread hurricane-force winds and tropical-storm-force winds over these countries (CCRIF, 2021). The rainfall rate in Saint Vincent increased during the passage of Elsa and triggered a number of lahar and flood events. However, there was no significant damage as a result of rainfall and rather there were more damages caused by wind. Several buildings were damages, as well as electricity poles, water supply, and agricultural land (Silva, n.d.). After the Tropical Storm Warning was issued, the government shut all water service as a precautionary measure against mudflows.

3.3.5. 2023 Tropical Storm Bret

The latest tropical cyclone event in Saint Vincent is Bret in June 2023. Over a period of 3 days, it started as a Tropical Depression Three over the Atlantic. It then strengthened into Tropical Storm Bret, moved towards the Lesser Antilles, Windward Islands, with its centre passing over northern of Saint Vincent and the Grenadines (CDEMA, 2023). It had maximum sustained winds of 60 mph (95 km/h) and minimum central pressure of 1,004 mb when approaching Saint Vincent with an estimated forward velocity of 18 mph (30 km/h) (CCRIF, 2023). Bret brought gusty winds, heavy rains, and storm surge to the Windward Islands, also damaged and destroyed several houses and electricity in Saint Vincent. The government of Saint Vincent and the Grenadines ordered a full shutdown of the country and 150 people where sheltered (CDEMA, 2023).

There is a similarity in response and recovery in all tropical cyclone events especially in the Caribbean. There are several watches and warnings issued by the government after receiving tropical disturbance forecast from the United States National Hurricane Center (NHC). Watches are issued when there is a possibility of a tropical cyclone event or danger in the area within the next 48 hours, whereas warning are issued when these possibilities are expected within 36 hours. Each of those arise according to the intensity of the disturbance and each warning type consists of different procedures. First, there is tropical storm watch/warning, and then hurricane watch/warning, and storm surge watch/warning if there is a possibility of life-threatening inundation from rising water inland from the shoreline (NOAA, n.d.). Evacuation and response actions are started from the issuance of tropical storm warnings. For CCRIF member countries, compensation will be given according to the modelled losses of wind and storm surge if calculated above 10% of the minimum payment of the policy for the Aggregated Deductible Cover (ADC) (CCRIF, 2021). As for rainfall excess compensation, CCRIF member countries have a separate policy according to the calculated Rainfall Index Loss against the Attachment Point of the country's excess rainfall policy (CCRIF, 2016a, 2016b).

4. METHODOLOGY

4.1. Research Workflow

The workflow of this thesis consists of three stages, representing the three sub-objectives mentioned in Section 1.5. The research started with a retrospective assessment, followed by hazard scenario modelling, which was followed by an impact assessment. The framework is presented in Figure 9.

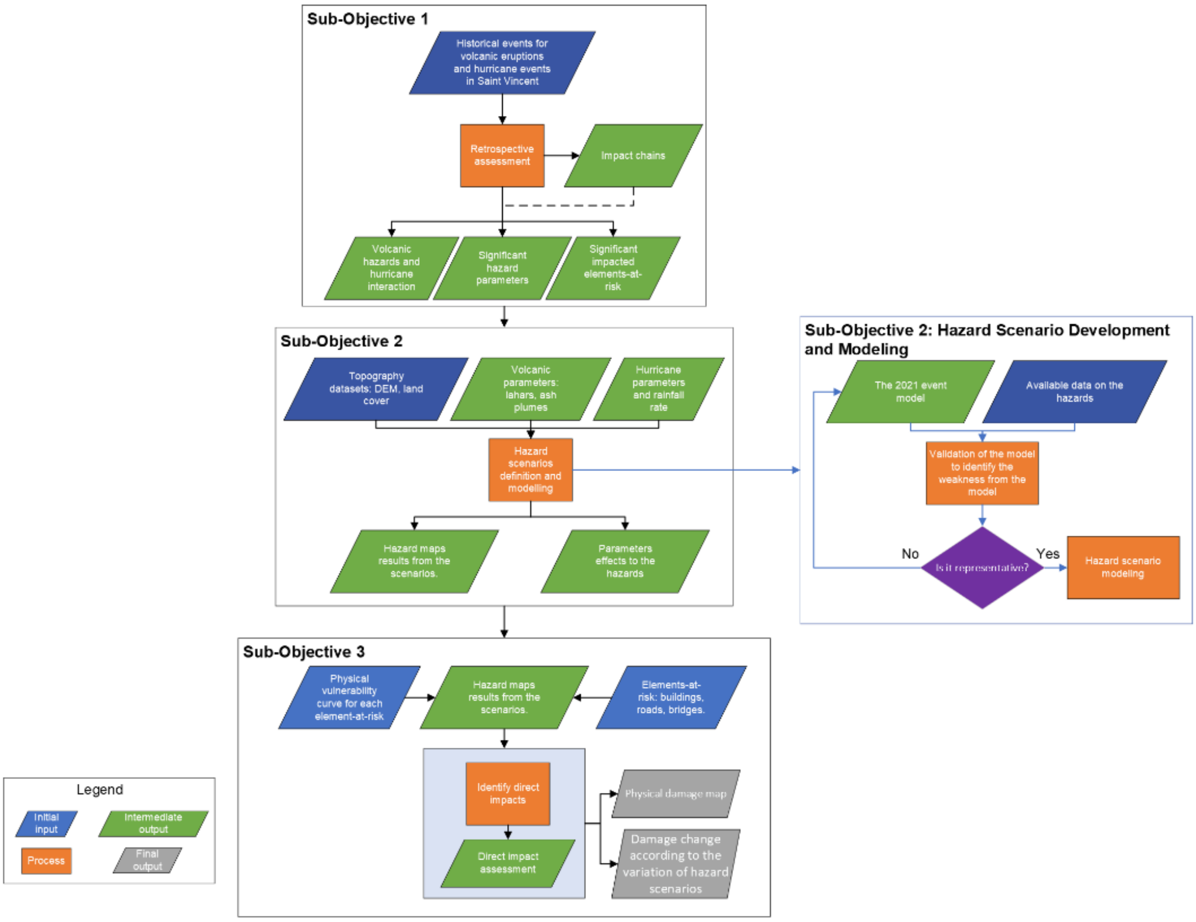


Figure 9. Research framework of this thesis.

The first objective of this thesis aims to investigate historical events of volcanic and tropical cyclones in Saint Vincent in order to determine the parameters for scenario development in the second objective. Literatures, reports, news articles, encyclopaedias, were collected and assessed to have better understanding of what happened in the past. Additionally, field work was conducted to understand the terrain after the eruption, as well as interview with stakeholders.

For better understanding of the impacts, impact chains were developed based for each assessed event. Impact chains are useful for identifying risk aspects and the most significant risk components to be prioritized, especially due to the limited timeframe of this thesis. In order to answer the research question of interaction between the hazards in the 2021 event, a timeline based on the 2021 event was assessed. Hazard interaction(s) is/are identified by understanding the timeline in detail for each prioritized hazard. This information is useful for further impact assessment which includes the sequence of events perspectives.

After understanding the processes and impacts of the prioritized hazards, hazard scenarios are developed. The results from the scenarios are aimed to see the change in impacts under different scenarios and the effects of the variations of a particular hazard parameter to the interactions between the compounding hazards. The parameter used to simulate the hazards depend on the prioritized hazards identified from the impact chains.

Before modelling the scenarios, the hazard model is validated with ground data from literature of an actual event to assess the efficacy and identify deficiencies of the model. Following the validation process is the scenario development and modelling. The scenarios are developed also by looking at the historical events and characteristics of hazards that have happened previously. The results of this process are hazard maps for each scenario. These maps will be used afterwards to assess the impacts of the scenario.

The third objective was to assess and estimate the impacts for different scenarios. Answering to the lesson learned of Jeffers et al. (2022) from the 2021 compounding event, the third objective of this thesis aimed to be the assessment of impacts according to the scenarios.

4.2. Dataset

Table 5. Dataset used for lahar modelling in this thesis.

Dataset for Lahar Modelling			
Parameter	**Data**	**Type**	**Source**
Elevation	Digital Elevation Model	Raster	CHARIM Project (2016)
Mannings N (Surface Roughness)	Sentinel-2 based land cover data	Raster	Classified land cover data into Manning value (derived from FastFlood).
Solid Height	Steady state soil depth model	Raster	Calculated a balance between weathering, creep, and movement according to a flux accumulation estimate (derived from LISEM).
Water Height	Solid height * porosity	Value	Penta et al. (1961) and Ahmad (2018)
Solid Rock Size	Literature	Value	Horwell et al. (2022) and USGS (2016).
Internal Friction Angle	Literature	Value	Heath et al. (1998), (Villeneuve & Heap, 2021)
Solid Density	Literature	Value	Gueugneau et al. (2023)
Rainfall Rate	Literature	Value	Phillips et al. (2023)
Dataset for Ashfall Modelling			
Meteorological Information	Pressure on surface and upper level	Raster	ERA 5 Land Re-analysis
Physical parameters	Literature	Value	Cole et al. (2023) and Constantinescu et al. (2023)
Model types	Literature	Value	Poret et al. (2017)

The dataset used in this thesis depends on the results of the retrospective assessment. However, in this chapter the dataset will be explained according to the data that were used throughout the process of the thesis in general. The readers are advised to refer to the results of the retrospective assessment in Section 5.1.3 for reference and better understanding.

In general, this thesis uses literature as the basis for the retrospective assessment and impact chains. After obtaining the significant risk components, suitable parameters were obtained from literasture and applied to the model for the scenarios. This thesis uses LISEM (https://lisemmodel.com/) and FALL3D (https://fall3d-suite.gitlab.io/) for modelling lahars and tephra dispersal scenarios. The source of reference for each input data that is used in this thesis are shown in Table 5 for hazard modelling and

Table 6 for elements-at-risk.

The value of each parameter for each hazard model could vary depending on the scenario that is modelled. The rainfall rate used in this thesis varies from the minimum rainfall rate that could result in a lahar to rainfall rate associated with a cyclone event. The parameters variation also applies in the tephra modelling. However, in tephra modelling the changes are only on the meteorological information from different tropical cyclone events. Therefore, we can expect that the condition and direction of the tephra pathways could be different as well. Regarding the physical parameters used in the model are those related to bulk density, plume height, time step, vent source, and source type. Whereas for the model types are chosen according to the best model to simulate tephra of La Soufrière tested by Poret et al. (2017) which are horizontal turbulence model, vertical turbulence model, particle aggregation model, and distribution model. More explanation how the data is interpreted, processed, and used in the simulation, as well as the resolution of the data are detailed on Section 4.5.1 for ashfall simulation and 4.5.2 for lahar simulation.

Table 6. Dataset used for ashfall modelling in this thesis.

Data	Format	Source	Details
Building footprints	Vector	PARATUS.	Only contains the footprints.
Road network	Vector	PARATUS.	Contains categorization of road network level.
Bridge and river crossings	Vector	Field work.	Only contains the location.
Vulnerability for ashfall	Tabular	(Jenkins et al., 2014)	Categorization of damage and intensity (Annex 11).

4.3. Retrospective Assessment using Impact Chains

This thesis uses literature review and interview with stakeholders to obtain information especially for the case study of the 2021 event. This information is used to assess the historical records on volcanic and tropical cyclone events in Saint Vincent. In order to assess the historical disaster events, we presented each event using Impact Chain framework. Considering the infrequent volcanic eruption in Saint Vincent, this study developed the impact chains based on the reports and literature review, as well as the information from stakeholders. However, a field visit was conducted to observe the current condition as well as to discuss the matter with local people and the government of Saint Vincent.

In this thesis, impact chains were developed for each volcanic and tropical cyclone event to assess the risk pathways in Saint Vincent. After that, a general impact chain was generated to identify which hazard and elements-at-risk create significant impacts for Saint Vincent. This identification was useful to develop the potential future scenario of the compounding volcanic and tropical cyclone hazards in Saint Vincent. Identifying elements-at-risk to be prioritized is also useful to focus the impact assessment to be done in further steps. Additionally, considering the limited timeframe of this research, it was important to limit the work and prioritize on the most important hazards and impacts.

4.4. Field Work

After assessing historical events, field visit was conducted together with several partners of PARATUS project (Eurac Research GLOMOS, United Nations University Institute for Environment and Human Security, and Prepared International) to Saint Vincent. The aim of this field work for this thesis is to understand the terrain after the eruption, impacts and conditions during the eruption, as well as discussion and interview with key stakeholders to provide feedback on the initial results of this thesis. Before the fieldwork, preparations were made for arranging questions to be raised during the fieldwork. Several maps were also produced as a guiding during the field visit especially to the volcano.

The interview questions were prepared together with the partners to align the purpose of field work with PARATUS project. 510 Digital Initiatives for the Netherlands Red Cross supported in reviewing the questions. 510 also provided feedback on how to proceed with the meetings to the stakeholders so that the interview will be engaging and held in two-ways. The stakeholders that participated were Ministry of Transport and Works, Physical Planning Unit, Red Cross of Saint Vincent and the Grenadines, NEMO, and Ministry of Education.

The questions revolve around the work of each stakeholder and how was it affected by the 2021 event. Additional questions were also added depending on the stakeholder questioned. For instance, more emphasize on geospatial data management for Physical Planning Unit, emphasize on infrastructural damage and recovery with Ministry of Transport and Works, and on hazard and risk assessments with NEMO.

The maps were prepared by overlaying hazard maps from literature with elements-at-risk or affected areas (presented in Annex 1). These maps were useful to compare the situation described in the literature with current situation. Ashfall map from the World Bank (Government of Saint Vincent and the Grenadines, 2021) and lahar map (Phillips et al., 2023) were overlaid with the main roads and villages. During the field work, a visit to some affected areas were conducted as well as a talk with some residents.

4.5. Hazard Simulation

4.5.1. Ashfall Simulation

Tephra simulation in this thesis will cover the whole island due to its spread across the island. Using similar approach with the 1979 simulation by Poret et al. (2017), this thesis uses the ADS model from FALL3D to simulate the tephra dispersal and ashfall ground load. In order to understand the process of this tool, the author participated in a training organized by Barcelona Supercomputing Center as the institution which develop FALL3D. Afterwards, the author kept in touch with one of the researchers to consult the results in every step of the way. During the processing, the author encountered computational limitation and therefore the Geospatial Computing Platform (CRIB; Girgin (2021)) was utilized. FALL3D is installed into the UBUNTU system and the simulations are proceed in the platform. The model configuration is shown in https://github.com/salsablrp/thesis_itc/ and will be explained below.

As explained in Section 2.6.1, there are 13 blocks to define the model input in FALL3D. However, not all configuration blocks of FALL3D are used in this thesis. The first block used is to define variables related to date and time. The main explosion on 9-10 April 2021 is modelled because there is information regarding the particle materials and deposits for validation. During this period, there are two explosions happened at 13.20-14.50 on the 9th and 19.10-05.10 on 10th (Cole et al., 2023). Based on this information, the further scenario simulations will also adopt the timeframe with the 2nd day as the day when the cyclone occurred.

The modelled species and source types are defined in another block. There are various types of species can be modelled using FALL3D, however this thesis uses TEPHRA as the species type which includes SO_2 aerosol species and comes from PLUME source type. FALL3D also provides particle aggregation model. Aggregation influences the dispersal and sedimentation behaviour of tephra in which larger aggregates fall out faster and closer to the volcano compared to individual ash particles (Tsuji et al., 2020). According to Cole et al. (2023), ash aggregation only abundant in upper deposit layers from the eruption. Other physical model types are also defined in this file. GANSER model for terminal velocity, RAMS for horizontal turbulence model, and SIMILARITY for vertical turbulence model are used because they were also used in the 1979 tephra model and showed good results (Poret et al., 2017).

Another block is used to define the particle TGSD. In this block, the range for particle density is defined and this thesis uses 1000-1500 kg/m^2 as the density after trial-and-error and according to Cole et al. (2023). TGSD distribution model is also defined here and according to Poret et al. (2017), for the 1979 tephra dispersal model, Bi-weibull distribution shows the best goodness-of-fit model. Bi-weibull distribution characterizer tephra by the scale and shape parameters, each defining the particle sizes, and spread and skewness consecutively (Costa et al., 2016).

Related to the meteorological inputs, FALL3D supports several meteorological models. However, out of all the options, ERA5 European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 is the most suitable for the purpose and capacity of this thesis. This is because the other supported models either have limitations on simulating past events, not available for the Caribbean region, or only available by special requests. However, despite the coarse resolution, ERA5 has been used previously for tephra modelling such as for the Neapolitan and La Fossa volcanoes in Italy (Biass et al., 2016; Massaro et al., 2023). The use of ERA5 is also suggested for tephra modelling in a doctoral thesis by Kuenzli et al. (2021). Macedonio et al. (2016) also mentions that meteorological dataset will affect in defining the zone subject to tephra fallout. The use of a coarse meteorological dataset (ERA5) is expected to have a wider and coarser tephra fallout area if compared with other data with higher resolution.

However, another block is used to define the grid of the model. This block defines the horizontal and vertical mapping grids, the longitude and latitude for the domain area, and the grid resolution. Using the defined parameters in this block, the meteorological data is interpolated into the grid resolution. Therefore, ERA5 is still suitable for tephra simulation in this thesis.

4.5.2. Lahar Simulation

According to discussion with one of the main authors of the LISEM model, lahar modelling using LISEM is first done in this thesis. Therefore, several adjustment and trial-and-error were a part of this exercise especially to find the best approach of lahar modelling in LISEM. However, there still needs a lot of improvement in the models that are produced in this thesis (explained in Section 5.5).

Generally, debris flow models require initiation points to define the starting point of the flow. The initiation points can be derived from slope failure calculations such as shear stress. Shear stress can be used as a basis to see which areas are most likely to have a failure for the runout. The peak time of the shear stress can be calculated to identify the time in which the slope would fail after the rainfall. The shear stress map can then be used as the initiation points of the debris flow. The process of incorporating the shear stress into the lahar models requires another study itself. Therefore, the shear stress calculation in this thesis is only performed to see the most-likely initiation points and duration of the simulation.

The model is simulated using solid height with the ash thickness map from the World Bank presented in PDNA report. This is meant to see the possible solid runout given the characteristics of the ash deposits. Simultaneously, the water height is also proceeded by considering the defined rainfall rate using the triangle peak approach without initial water height. From this process, water height and solid height for the lahar simulation are obtained. However, the result for the solid height might not be precise as physical process of the slope, such as the slope failure is not considered.

The elevation model used in this thesis is taken from Caribbean Handbook on Risk Management (CHARIM) project in 2015 which was generated using Light Detection and Ranging (LiDAR) data masked with DEM from Shuttle Radar Topography Mission (SRTM) surrounding the summit of La Soufrière. The resolution of this DEM is initially 5 meters, but due to limited computational capacity, the resolution was resampled to 10 meters using bilinear resampling. This resampling method was chosen because it is more appropriate for continuous data such ash elevation, where a smoother representation of the surface is desirable (Wu et al., 2008). The surface roughness is considered using Mannings N value derived from Sentinel-2 based WorldCover with 10 meters resolution that was downloaded through Fast Flood (https://fastflood.org/). Drag force coefficient of 100 is used in this model due to its fitness to capture highly co-moving flow which means that solids and fluids have mutual drag and move together representing the characteristic of lahar behaviour.

Several input parameters are used varyingly according to the conditions or scenarios to be modelled. The solid height information is obtained using Steady State Soil function from LISEM which finds a balance among weathering, creep, and movement according to a flux accumulation estimate (Bout, Lombardo, Westen, et al., 2018). Whereas for the ashfall thickness assumption, the ashfall map from the World Bank that is mentioned in the PDNA report is used. The map provides a contour-like map for ashfall thickness which later is converted into raster for the usage in this thesis. For water height, the same solid height map with incorporation of soil porosity is used. The value 0.7 is used to represent high porosity because around the flanks of La Soufrière consists of volcanic and alluvial soils. The rock size (particle size) value used is 0.002 m to represent the main particle size for volcanic ash (Penta et al., 1961). For solid density, 2000 kg/m^2 is used (Gueugneau et al., 2023; USGS, n.d.).

As mentioned earlier, lahars in the Eastern Caribbean occur after a significant rainfall event. According to Phillips et al. (2023), minimum 20 mm rainfall is enough to result in a lahar. Therefore, the minimum rainfall 20 mm will be incorporated into the simulation to see the 'minimum' expected lahars footprints. Another rainfall rate to be considered is 70.5 mm which is the rainfall associated with lahars recorded on 3rd May 2021 in Overland catchment which lasted for one hour (Phillips et al., 2023). The simulation using this rainfall rate will be used for validation of model to see how well the simulation is performed. Another rainfall rate to consider is 107 mm which is the rainfall during Hurricane Elsa in 2021 to see the difference in lahar footprints if it happened at the same time as the hurricane (Phillips et al., 2023).

It needs to be noted that the assumption of pyroclastic density currents (PDCs) deposition is not specifically integrated in the solid height for the input parameter. The dynamic characteristic of soil coverage and tephra is also not integrated in the model. The associated parameter values are assumed to be static and homogenous over the northern part of the island. The source code for the modelling process is available in https://github.com/salsablrp/thesis_itc/.

4.6. Impact Assessment

Assessing the impact is initiated by considering the interactions between the hazards and the other risk components such as vulnerability, exposure, and impacts focusing on time. The result from the first objective on identifying the hazard interaction (Section 5.1) is used as the basis to assess the impact in this thesis. Next, performing multi-hazard impact assessment is conducted. This thesis considers on impacts to infrastructure with focus on buildings, roads, and bridges (explanation on the choice of elements-at-risk is explained in Section 5.1).

The assessment is conducted using RiskChanges (https://riskchanges.org/), which is an open-source spatial decision support tool for the analysis of dynamic multi-hazard risk. Using this tool, hazard maps from the simulations as well as the elements-at-risk data are uploaded. For ashfall, the hazard information from the simulation is the ground load. Meanwhile, the information needed in RiskChanges for ashfall is the thickness. Therefore, the ground load was converted into ashfall thickness by dividing the ground load to the bulk density which is 1500 kg/m^2 according to Cole et al. (2023). After being uploaded, the type of hazard and elements-at-risk were identified, as well as connecting the elements-at-risk with vulnerability curves. The connection relies on the type of materials and hazard intensity for both ashfall and lahars.

After setting up the input files, the first step of the assessment is exposure assessment. This was done by overlaying the hazard and elements-at-risk maps to see which element is exposed by which hazard. For bridges and roads, only exposure assessment was conducted because there is no information of their materials. The building information also does not contain the building material information. However, PDNA report mentioned 91% of the houses in Saint Vincent uses metal sheet roof material. Therefore, assumption is made that the buildings have the same materials and the scenario which results in more damage to the building is identified.

The vulnerability assessment used in this study is obtained from Jenkins et al (2014) which is a part of MIA-VITA project to develop building vulnerability functions for all volcanic hazards, emphasizing on buildings commonly found in tropical and developing countries. This is seen suitable to be used in this thesis. The vulnerability assessment for each defined roof classes can be seen in Annex 11. This thesis will use the roof class C_{AF} which represents metal sheet roofs on timber rafters or trusses in average condition. After finishing the vulnerability assessment, information on the difference of impact for each scenario and how does the scenario affect the degree of damage will be obtained.

5. RESULTS

5.1. Retrospective Assessment of Volcanic and Tropical Cyclone Events in Saint Vincent

After understanding the historical events of volcanic eruptions and tropical cyclones in Saint Vincent as explained in Section 3.2 and 3.3, impact chains for each event were generated. Each of these impact chains is unique for each event due to the specific references used to develop those models. For example, the impact chain for the eruption in 1979 is different than that of the 1902-03 and 1812 events even though they are all explosive eruptions. The same is the case for the impact chains for tropical cyclone. Each of them presents a different situation and conditions of both hazard and elements-at-risk. However, the general condition for volcanic and tropical cyclone hazards in Saint Vincent can be assessed through these impact chains. It also does not mean that the impacts which are not mentioned in a specific event did not actually happen during the event, it can also be that it is not mentioned in the reports because it is less prioritized compared to other mentioned impacts, the difference in intensity, or the not updated report.

The impact chains were constructed using the tools Kumu[2] and Miro[3] which can be accessed using the links provided in the footnotes. Although this thesis does not focus on assessing the difference of both tools, identifying its functionality is important, especially considering that the impact chains in this thesis are used to complement the deliverables in the PARATUS project (Section 1.6). The use of both tools does not affect the context and meaning of the impact chains. Both tools support the function to add comments and descriptions for each component and can visualize different connections as well. However, each tool serves better for a specific purpose. For instance, Kumu will provide a better tree-like visualization to show the overall risk pathways of an event. Whereas Miro provides better tools for visualizing the sequence of events due to its flexibility to generate mind maps.

5.1.1. Impact Chain for Volcanic Events in Saint Vincent

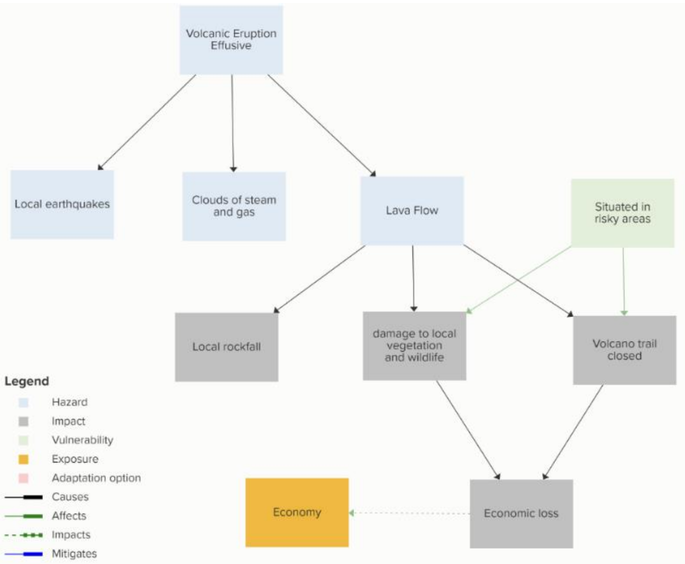


Figure 10. General impact chain for effusive eruption in Saint Vincent.

The impact chains for each eruption event are shown in Annex 1 to 9. Those impact chains are used as the preliminary assessment to obtain a generalized impact chain for eruption event in Saint Vincent. From historical records, it is noticed that La Soufrière experienced both effusive and explosive eruptions. The general impact chains of effusive and explosive eruption are presented in Figure 10 and Figure 11. These generalized impact chains are generated by combining the event-based impact chains. This way, the overall possible impacts that has happened previously can be identified. Considering that the effusive explosion only impacted the area around the crater, which mostly are vegetative areas, the scenarios in this thesis do not consider effusive eruptions.

[2] https://kumu.io/aslasrp/thesis-impact-chains#volcanic-hazard
[3] https://miro.com/app/board/uXjVKIOHdAE=/

As mentioned in Section 4.3, these impact chains are aimed to understand the most significant hazard and elements-at-risk for each event. From the general impact chain for the explosive, it can be observed that most impacts are caused by lahars. After lahars, ashfall caused the most impacts in Saint Vincent. These statements are also supported by the PDNA report and the testimony from the people interviewed during the field work (Section 4.4). Therefore, we can conclude that lahars and ashfall are the main significant volcanic hazards in Saint Vincent.

Additionally, the choice of elements-at-risk to be prioritized can also be determined using impact chains. According to the PDNA report, buildings are the most physically affected elements-at-risk due to a volcanic eruption. Whereas roads and bridges are often not destroyed, they are impacted, and have effect on other aspects such as emergency response, evacuation process, and flow of goods. It can also be identified from the impact chains that the damage related to infrastructure has more connections to other components in the impact chains as well.

5.1.2. Impact Chain for Tropical Cyclone Events in Saint Vincent

As mentioned previously, EM-DAT records show that tropical cyclone events are the most-frequent hazard occurring in Saint Vincent. This fact is also confirmed during the field work and the discussions we had, the government agreed that tropical cyclones along with rainfall-related events are the most significant hazards in Saint Vincent. It is almost every one-to-five-year tropical cyclone occurs, ranging from storm-scale to hurricane-scale events.

There are five cyclone events that are considered in generating the impact chains: Tropical Storm Bret in 2023, Hurricane Elsa in 2021, Tropical Storm Harvey in 2017, Tropical Storm Matthew in 2016, and Hurricane Tomas in 201. The reason being is that those events represent better the current situation and have more information and reports as compared to older events. Additionally, aside from these five events, there were other tropical cyclone events in Saint Vincent in between. After briefly assessing the other events, these five were considered because these tropical cyclones directly or slightly hit Saint Vincent, whereas the others were comparably further away. The impact chain for each of these events are presented in Annex 7, 8, 9, 10, and 11. After assessing these impact chains, a general impact chain for tropical cyclone is developed and presented in Figure 12.

The impacts for tropical storms and hurricanes are comparable, therefore we did not create a separate impact chain for storm and hurricane. As mentioned in Section 2.2.2, the difference between those two is the wind speed. Wind speed will affect the severity of damage and it is closely related to the infrastructure materials. Most of the damages are resulted from strong wind and the secondary hazards of heavy rainfall.

Depending on the intensity of the cyclone and how it hits the country, sometimes some of these hazards do not occur in an event. Out of the five most-recent tropical cyclone events in Saint Vincent, only Hurricane Elsa and Tropical Storm Bret produced a storm surge. Heavy rainfall and strong wind seem to always happen in all five events. However, after reading reports for each one, the impacts from heavy rainfall and strong wind are sometimes not significant for some cases. For instance, Tropical Storm Matthew had both significant strong winds and heavy rainfall impacts which is proven by two detailed separated reports for each of them. Whereas for Hurricane Elsa and Tropical Storm Bret, both only had report for strong winds. Assessing the impact of a cyclone is not as straightforward as assessing the impact of a volcanic eruption. So far, there has not been a direct cyclone hit in Saint Vincent, and the reports for each event only mentioned the impacts in general without specifying the sectors and associated loss and damage. Additionally, identifying the most affected elements-at-risk for cyclone events is challenging due to the lack of specific needs assessment reports for cyclone events.

5.1.3. Takeaways from the Impact Chains

The purpose of developing impact chain in this thesis is to identify significant hazard and exposed elements-at-risk for more precise impact assessment target. According to the impact chain results obtained in this chapter, the most significant hazards for La Soufrière eruption are volcanic materials deposits from ashfall, as well as lahars during rainy season. Whereas for tropical cyclone events, strong wind has more significant impacts than that of heavy rainfall. However, considering the compounding hazards between volcanic eruption and tropical cyclone, heavy rainfall could result in a significant impact as well due to lahars occurrence.

For tropical cyclone impacts, the wind mostly damages the building roofs, electricity poles, and trees. Considering these aspects, the next assessment of this thesis will be focused on ashfall and rainfall-induced lahars impact towards building damage, exposed road length and number of bridges in Saint Vincent. Ashfall or tephra load and rainfall-induced lahars are chosen in this thesis because of its dependence on meteorological component that can be exacerbated through the presence of tropical cyclone event during the eruption.

5.2. Hazard Interaction: Volcanic and Tropical Cyclone in the 2021 Event of Saint Vincent

Identifying the interaction between hazards is important to assess the compounding impacts of the event. Hazard interaction in compounding hazards impact assessment allows us to obtain comprehensive results by considering the sequence of events. In the 2021 event of Saint Vincent, the interaction might differ according to the specific hazard studied. As mentioned earlier, volcanic and tropical cyclone hazards are itself a multi-hazard. Therefore, understanding the process of each hazard was conducted in this thesis through observation from reports, news, articles, and residents' testimony to create the timeline of the event.

5.2.1. Hazard Interaction of the 2021 Event

The 2021 event consists of multiple hazards between two events: a volcanic eruption and a tropical cyclone (Hurricane Elsa). Each of the hazard might interact and resulted in secondary hazards. According to eruption processes of La Soufrière and timeline of the 2021 event in Section 3.1, as well the hazard interaction classification mentioned in Section 2.1, the interaction between hazards of the 2021 event are concluded as Independent and Cascading (Domino).

A volcanic eruption and a tropical cyclone both have different trigger factors, which makes them have an independent interaction. However, for some volcanic hazards, their occurrence happened in a certain way by the cause of meteorological component of tropical cyclone. For instance, lahar occurrence and the rainfall associated with the tropical cyclone. Although lahars happen regardless the presence of tropical cyclones, heavy rainfall caused by the tropical cyclone could cause more intense and frequent lahar events.

The identification of hazard interaction defines how an impact occurs or worsened after the event happened. For instance, damage on buildings due to ashes was worsened with the damage from the wind and rain. Another example is the frequency and intensity of lahars that was increased, leading to more damage to the bridges because the bridges are more exposed to heavier load from the lahars. However, a mutual exclusion impact could also happen. According to an interview with an engineering from the Ministry of Transportation and Works of Saint Vincent and the Grenadines, there are houses that were prevented to being destroyed by the strong wind because the combination between ash load and rainfall strengthened the roofs. By identifying the interaction, the impact assessment can be more thorough, and more perspective can be considered.

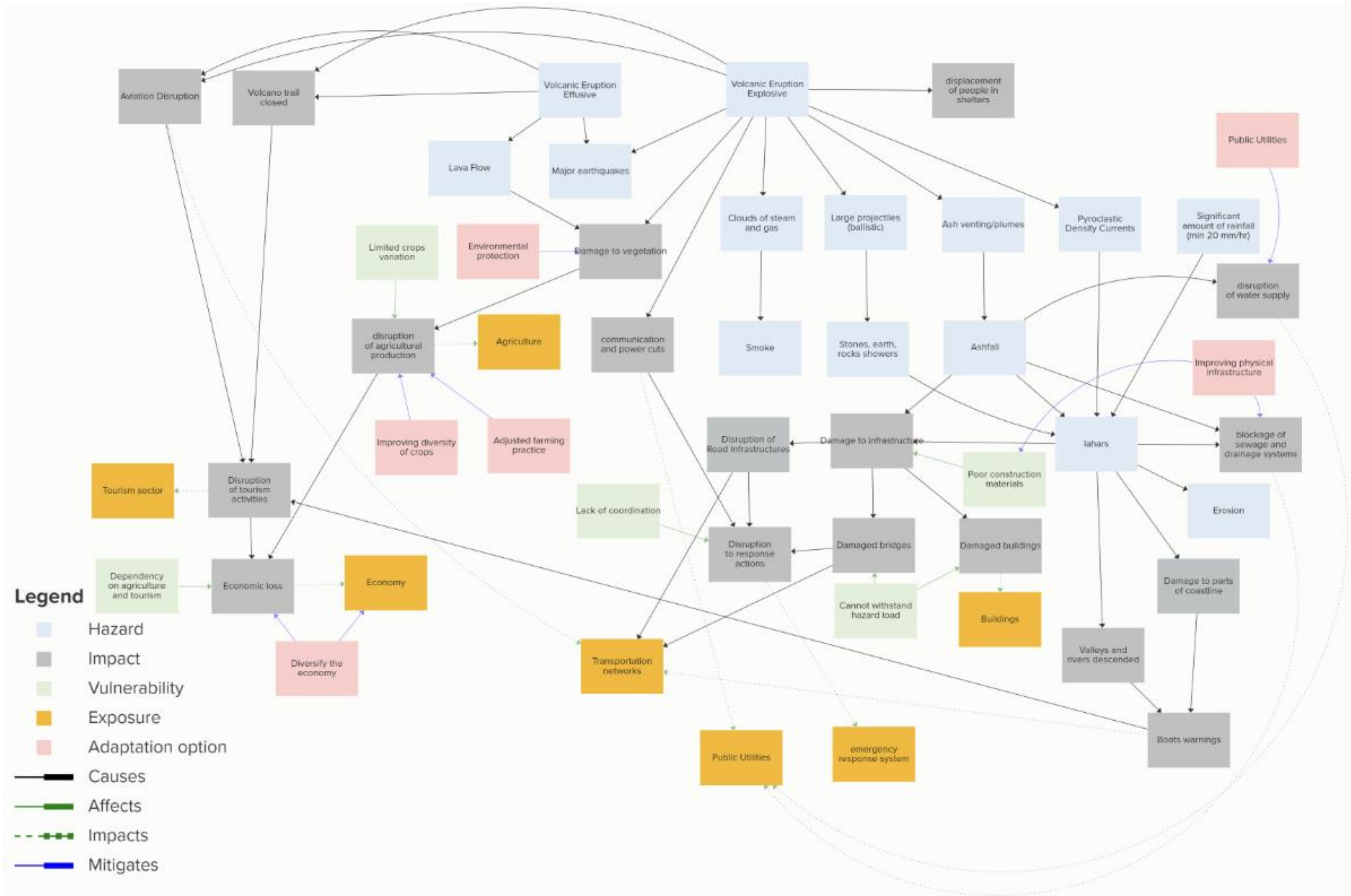


Figure 11. General impact chain for explosive eruption in Saint Vincent.

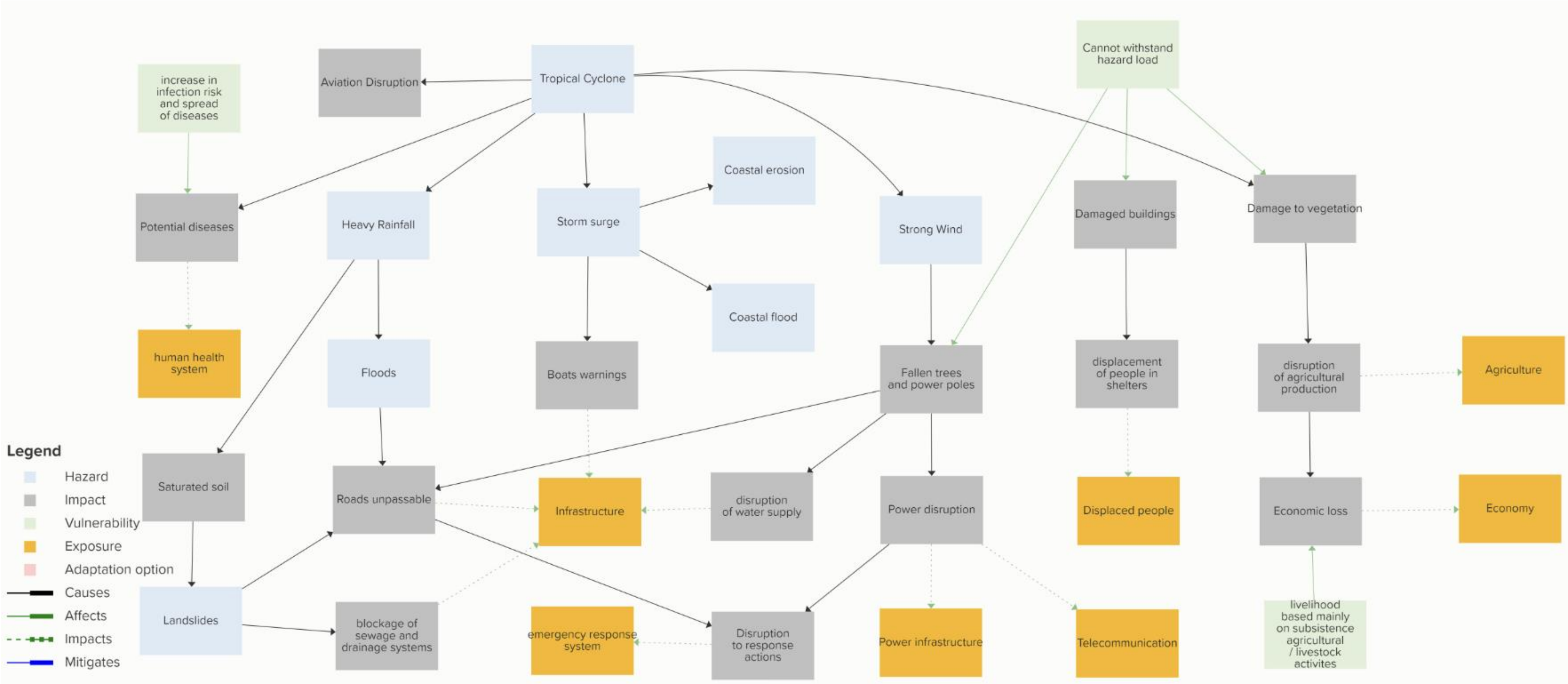


Figure 12. General impact chain for tropical cyclone in Saint Vincent.

During the internship period, improvement of the impact chains presented in this thesis was done together with colleagues from GLOMOS. This improvement is aimed for supporting the deliverables of PARATUS project. The improved impact chain showcases the compounding risk pathways from volcanic eruption and Hurricane Elsa in Saint Vincent. The detailed information for each element has been completed in this improved impact chain. This impact chain can be accessed through this link: https://kumu.io/aslasrp/saint-vincent-impact-chain

5.3. Field Work

The field work was held in the first two weeks of March 2024. As mentioned in Section 4.4, the field work was conducted together with several partners of the PARATUS project. During the field work, we met with several stakeholders as well as some residents. For some, it was a planned meeting where we had discussions and interviews, but for some it was an informal talk. Other than that, some visits were conducted such as a hike to the volcano, visiting the northernmost village which is also the closest one to the volcano and the last village along the Windward side; Fancy, visiting Rabacca River in Georgetown which was highly impacted to lahars, and visiting the western valleys in which the lahars are travelled and deposited there as well (see map of the study area in Figure 4).

Figure 13. View of the crater of La Soufrière.

Figure 14. Slope steepness on the flanks of La Soufrière.

The author joined in the interviews with the Ministry of Transport and Works, Physical Planning Unit, NEMO, and also participated in the impact chain workshop held with SVG Red Cross, Ministry of Health, and Ministry of Education. For the interviews, the questions were aimed to understand how the events affected their works, as well as what are the needs of the stakeholders in terms of assessing multi-hazard risk. These questions are not directly related to this thesis work, as those were aimed to fulfil the objectives for the PARATUS project. However, the author was able to grasp the condition, impacts, and vulnerabilities that Saint Vincent faced during the 2021 event, even earlier eruptions. This information is useful to complement the retrospective assessment and impact chains that are elaborated in Section 5.1. Additionally, the author was given the opportunity to present the aim as well as the preliminary result of this thesis. After the presentation, the stakeholders showed interests in the topic, provided some feedback, as well as connected the author to meet and talk with individuals who work at the same field of hazard and impact assessment.

The impact chain workshop was not related to the work of this thesis. It was aimed to disseminate and give the stakeholders a hands-on training on how to develop and utilize impact chain methodology. The impact chain was focused mainly on the health risk in Saint Vincent, especially towards volcanic hazards. Although this activity was also not directly related to the thesis work, through this workshop, the author was able to understand the perspective of hazard and risk in health systems from the stakeholders of Saint Vincent. This information is useful as well to complement the impact chain.

The hiking gave the author perspective on the terrain around the volcano. Starting off with gradual elevation changes, the slope turns steep after the second dry river close to the peak. The rivers were mostly dry, however when there is enough amount of rainfall, the water starts to flow. The variety of vegetation of the forest ranges from rain forest, montane forest, to palm brake and elfin woodland. Around the crater (Figure 13), some vegetation already grew back with exception to those which roots are completely destroyed. The picture of the slope on the peak is shown in Figure 14.

Figure 15. Trace of lahar deposits on Rabacca River (left) and Larikai River (right).

Other visits were also conducted to several other areas in Saint Vincent. Fancy, the northernmost village and the closest one to the volcano was highly affected by the thick ashfall due to its proximity to the volcano. However, no lahars and other volcanic hazard affected the village because there are two hills separating the village from the volcano. Traces of lahar deposits are still present on Rabacca River on the Windward side (Georgetown, as well as the valleys of the Leeward side of the volcano (one of which is Larikai River; Figure 15). Additionally, during the fieldwork, the author also collected the coordinate of some river crossings or bridges due to the lack of information available. This data is useful for the exposure assessment in this thesis.

5.4. Ashfall Simulation

5.4.1. Simulating the Event of 9 – 10 April 2021

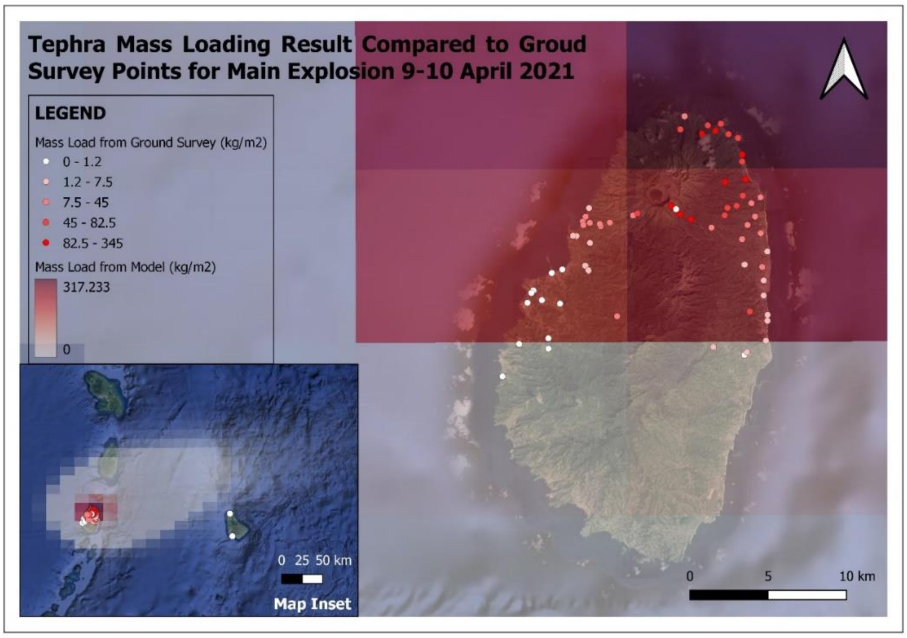


Figure 16. Ashfall simulation result for the main explosion of 2021.

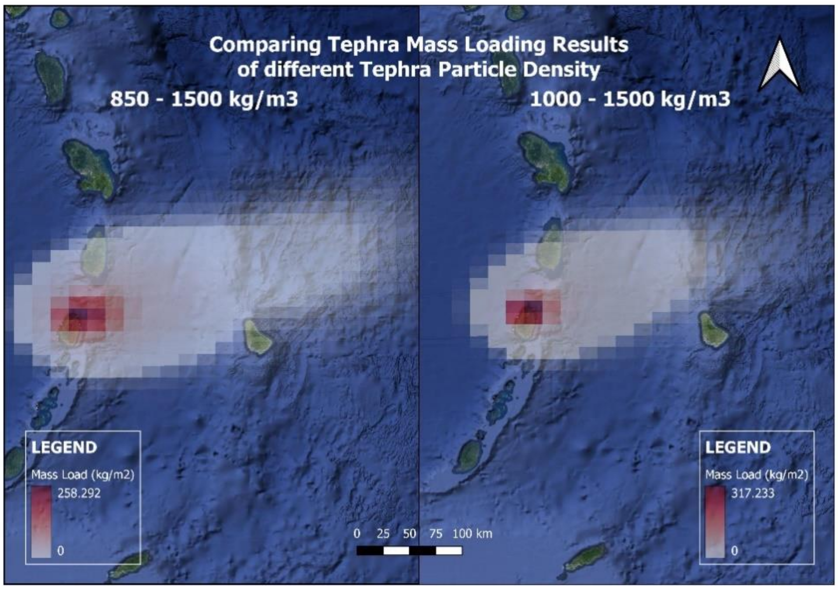


Figure 17. Comparison of tephra mass loading results for different tephra particle density.

The first ash simulation done in this thesis was for the actual event of the main explosions in 9 and 10 April 2021. This simulation is intended to see how the model behaves and how does it deviate from the actual event. The result of this simulation is shown in Figure 16. Comparison to ground data from Horwell et al. (2022) was also conducted to see the difference in the estimated value. The result presented in this thesis is the best-fit one after several trials compared to the ground truth information. In the result we can see that the pixel with the highest tephra value is not located where the crater is. The highest tephra load value also has difference for approximately 30 kg/m² compared to the ground data.

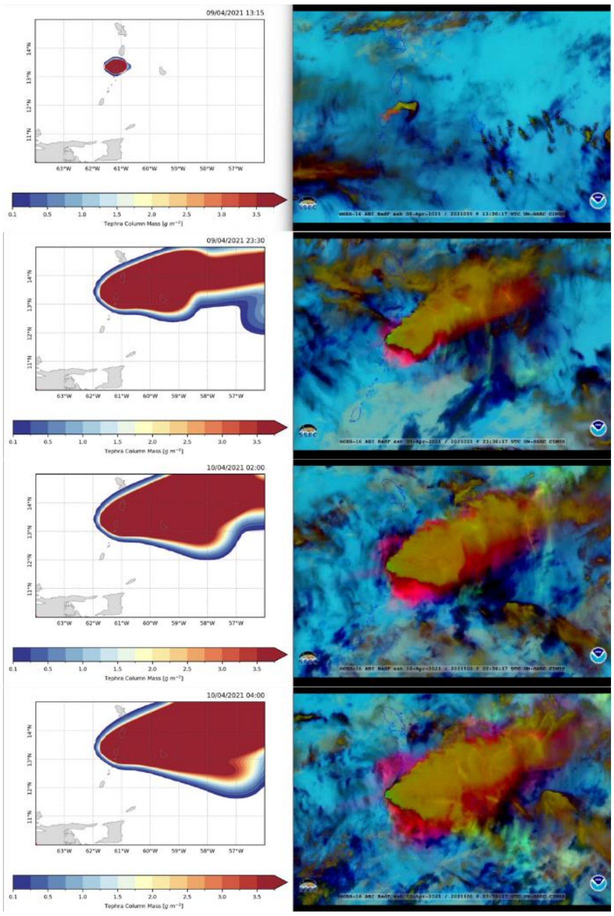


Figure 18. Tephra plumes pathway from this thesis model (left) and satellite monitoring from NOAA (right).

There are several assumptions for this reasoning. The first assumption is because of the coarse resolution of ERA5 that was used. However, after consultation with a researcher from Barcelona Supercomputing Center, that should not be the case because the resolution of the model is defined in the Block Grid. The meteorological data is interpolated into the defined grid resolution (Section 4.5.1). However, this might still be the case and needs to be assessed more thoroughly as the modelling for the 1979 eruption could fit the pixels and value well with a better resolution meteorological data (Poret et al., 2017).

The second assumption is the particle density and the grid resolution that was defined. According to (Cole et al., 2023), the tephra particle density is around 1500 kg/m². Initially, this thesis uses the range 850 – 1500 kg/m³ as the tephra density. Then, through the consultation it was changed to 1000 – 1500 kg/m³ to have a denser tephra dispersal for the aim of limiting the ash dispersal movement. Nevertheless, the result still does not show a corresponding pixel location. However, as we can see in the figures, the tephra mass load value for both models show a drastic change from 258.23 kg/m² to 317.233 kg/m² (Figure 17). Considering that the ground truth maximum value is 345 kg/m², the denser tephra particle was chosen in for this thesis.

The third assumption is the definition for aggregation and TGSD models. The aggregation was initially not considered from the model. However, the value of tephra load decreased significantly and deviates too much from ground truth. Therefore, to match the value range of the tephra load, the aggregation was still included in the simulation. For the TGSD model, initially the Bi-Weibull model was implemented. However, after consultation it was suggested to use the Estimate model instead which considers the column height and magma viscosity. When processed with Estimate model, the discrepancy between the model and the ground value increases significantly. In conclusion, the simulation using Bi-Weibull with aggregation was then applied in the continuation of this thesis with the reason explained in the next paragraph.

The tephra load results might not show a plausible pixel location. However, the values do not deviate much from the ground reality. In addition, when compared to the ash plume monitoring from NOAA (Cole et al., 2023), the tephra dispersal shows a similar pathway (Figure 18 and The GIF file is available here). Since this thesis tries to understand the interaction between the meteorological data with ash dispersal, this model can still be used as long as the particle characteristic inputs are consistent for all the scenarios. Nonetheless, when applied to simulate the scenarios, careful assessment needs to be conducted considering that the highest pixel might not be located around the crater area.

The deficiencies of this model are the deviation of resulted values and the location of the highest pixel value. This can be overcome with using meteorological data with better resolution or defining higher resolution for the model. In addition, comparing other TGSD model might also be useful to obtain the best modelling approach especially for this specific event.

5.4.2. Simulating Ashfall Scenarios

After understanding the behaviour of the ashfall model, scenarios using different meteorological data input are conducted. ERA5 data for each cyclone event cases explained in Section 4.5.1 was used to generate the scenarios. The result of the scenarios is shown in Figure 19 and the GIF files for the tephra column mass are available on https://www.youtube.com/playlist?list=PLaelAVfmgjZRCgaGr4ksO9xmdUyJn_H7U. The readers are advised to see the GIFs to obtain better understanding. Visually, we can identify that each of the scenario have different ground load dispositions. This is caused by the difference in wind direction for each meteorological data. As mentioned in previously, each cyclone follows their individual track. The name of the cyclone event in this section onwards refers to the ashfall scenarios associated with the meteorological condition for each cyclone.

Storm Bret has the most different mass load result than the other scenarios. The deposition does not spread to the neighbouring islands, including Saint Lucia (the island northern to Saint Vincent). The tephra column mass shows a motionless movement for most of the simulation period. This might be the reason of non-scattered deposition from Bret scenario. Another reason might be that after approaching Saint Vincent, Bret was indicated to lose organization due to the increase in the vertical wind shear, resulting in minimal convection near the centre (CCRIF, 2023).

The mass load result from Elsa shows the farthest reach of tephra deposition towards the northwest side or Saint Vincent. The column mass result also shows linear direction to the deposition, moving away from the volcano. This movement might affect the deposition to reach wider, due to the far movement of the column mass. When compared to the cyclone track, Elsa did move westward and attained hurricane status before entering Saint Vincent (CCRIF, 2021). Elsa had a rapid intensification and fast forward motion (Cangialosi et al., 2022), which can be the reason of the wider reach of the deposition and the column mass.

Similarly, tephra model from storm Harvey also shows deposition direction towards the west with northward movement. The column mass result also shows a smooth movement of the tephra westward, ending in a slight movement towards the northwest. The cyclone itself has a westward movement. When approaching Saint Vincent, Harvey just attained its storm status with a slightly strengthened system (CCRIF, 2017). Soon after, its wind shear imparted weakening and degenerated into a tropical wave (Berg, 2017). This slow pressure movement might be the cause that the tephra column mass moves smoothly.

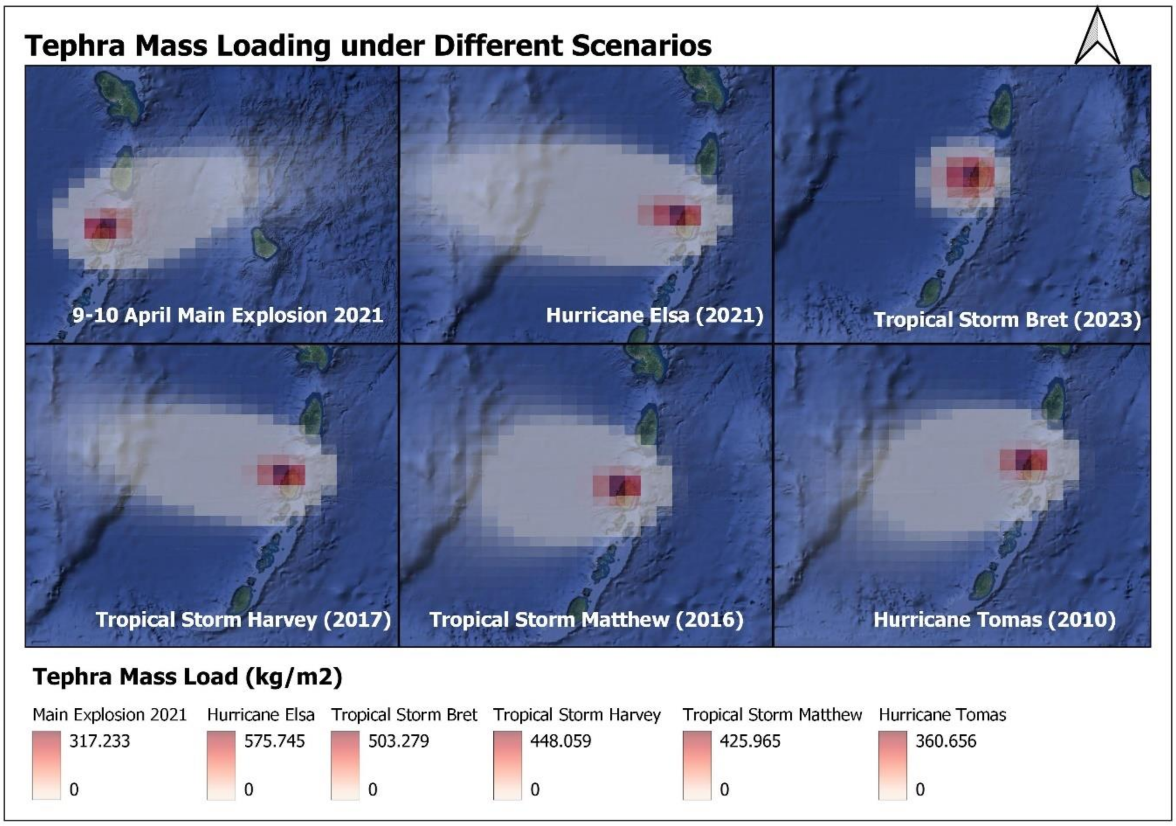


Figure 19. Tephra mass loading under different scenarios.

Tephra mass load result from storm Matthew shows deposition with westward direction from the volcano. The column mass also shows a westward direction of the plume with the plume staying on the same location for a comparably longer period. This causes the ground load to not have a widespread deposition as the other deposits such as Tomas, Harvey, and Elsa. When compared to the cyclone track, it matches that Matthew entered the Lesser Antilles, battered, as well as strengthening across the Eastern Caribbean for about 12 hours (CCRIF, 2016b). This might be the cause of the longer stay of the plume on the atmosphere for a longer period.

Tomas' movement was towards the west-northwest of Saint Vincent with its centre passed north of Saint Vincent. This results in tephra dispersal to move towards the same direction and ends in a circular motion around the island counterclockwise. It might occur because right when passing Saint Vincent, Tomas attained hurricane status, which also caused the abrupt circular motion after the orderly motion northwest ward (Stewart, 2010). Additionally, this motion affected the mass load as well. In Figure 19 we can see the mass load is skewed on the west side southward. This might also be caused by the circular motion, considering the similar direction of the mass load.

For conducting impact assessment, the mass load results are converted into ashfall thickness by dividing it with bulk density which is 1500 kg/m^3 (Cole et al., 2023). The value after conversion is presented in Table 7. This table also shows the associated wind and central pressure characteristics of each cyclone. From this table, there is no correlation between the cyclone characteristics and the modelled tephra mass load. Elsa, despite resulting in the highest mass load value and widest reach, its central pressure is not the highest among other scenarios. Similarly, Tomas which has the lowest mass load value also does not have the lowest wind speed and central pressure. Additionally, the tephra simulations show majority of westward movement this is caused by the surface winds in the tropics or the trade winds that move from the east to the west. This causes the cyclones to have westward motion and affects the tephra dispersal when compounded simultaneously with an eruption.

Table 7. Cyclone characteristics with mass load results from the simulations.

Cyclone	Max value from the model		Characteristics when passing Saint Vincent		
	Mass load (kg/m²)	Thickness (m)	Highest Winds (mph)	Highest Winds (km/h)	Minimum Central Pressure (mb)
2021	317.233	0.211	-	-	-
Elsa	575.745	0.384	75	120	995
Bret	503.279	0.336	60	95	1004
Harvey	448.059	0.299	45	70	1005
Matthew	425.965	0.284	60	95	934
Tomas	360.656	0.244	75	121	982

5.5. Lahar Simulation

5.5.1. Simulating the Lahar Event on the 3rd of May 2021

The lahar simulation process started with calculating the shear stress to obtain the duration of the peak shear stress. Higher shear stress value means that there is a significant force dragging the materials parallel to the surface, meaning that it is likely to have a failure. The longer the simulation, the more behaviour can be captured and observed. Therefore, for the shear stress calculations, 20000 timesteps (equal to 5.5 hours) were used. In the results, it was observed that there is a peak at steps 1706 and 1707 (equal to approximately 28 minutes), and then the value went down. However, the shear stress then went up and became static after steps ~12000. Shear stress calculations were then conducted again for hurricane Elsa and minimum rainfall scenarios. Yet, the shear stress shows similar pattern between the three calculations. Approximately for the first 5000 steps, the three calculations show similar shear stress value for each timesteps (Figure 20). After that, the pattern of increased value and becomes static are the same, but the values differ quite significantly. Therefore, considering the seemingly more reliable results due to the fitness in the shear stress graph, the next simulations will use timesteps of 5000 (equal to 1.4 hours).

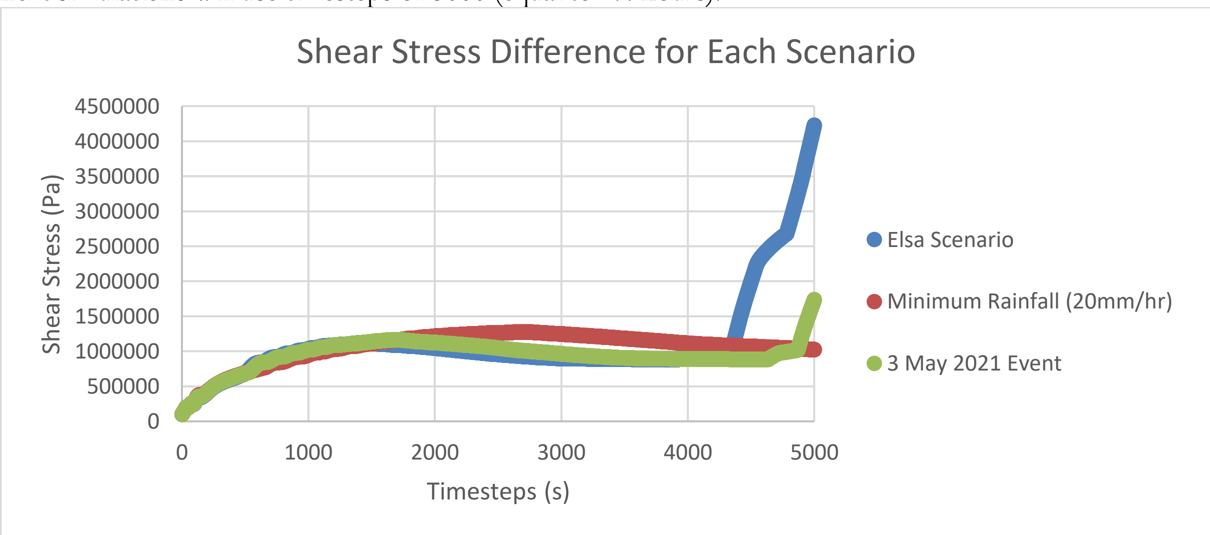


Figure 20. Shear stress time series for each lahar scenario.

The reason on the static value of shear stress might be because of the 'fake depressions' in the DEM. The results show the shear stress converges on the coast. After consultation with one of the main authors of LISEM, checking of the DEM was conducted. It was found that there are noises along the coast as well as height noises inland (Figure 21). These were not noticed earlier and corrections for both the depressions and coastal noises were conducted. The corrections for the coastal noises were done by defining the pixel values for areas outside the island as 0. Meanwhile, the corrections for the depression were processed through monotonic interpolation which preserves monotonicity and ensures that the DEM does not introduce any local extremes (Gregory & Delbourgo, 1982).


Figure 21. Noises in elevation model: on the coasts (left) and 'fake depression' inland (right).

After the corrected DEM is produced, the lahar simulation was conducted using 5000 timesteps. These timesteps are considered suitable for the simulation because it is within the range of the event to be recreated (4.5.2). The author realizes that it would be better if the shear stress will be based on the corrected DEM to have better results of less noises. However, due to the time constraints and limited computational capabilities, the shear stress calculation is left as it is.

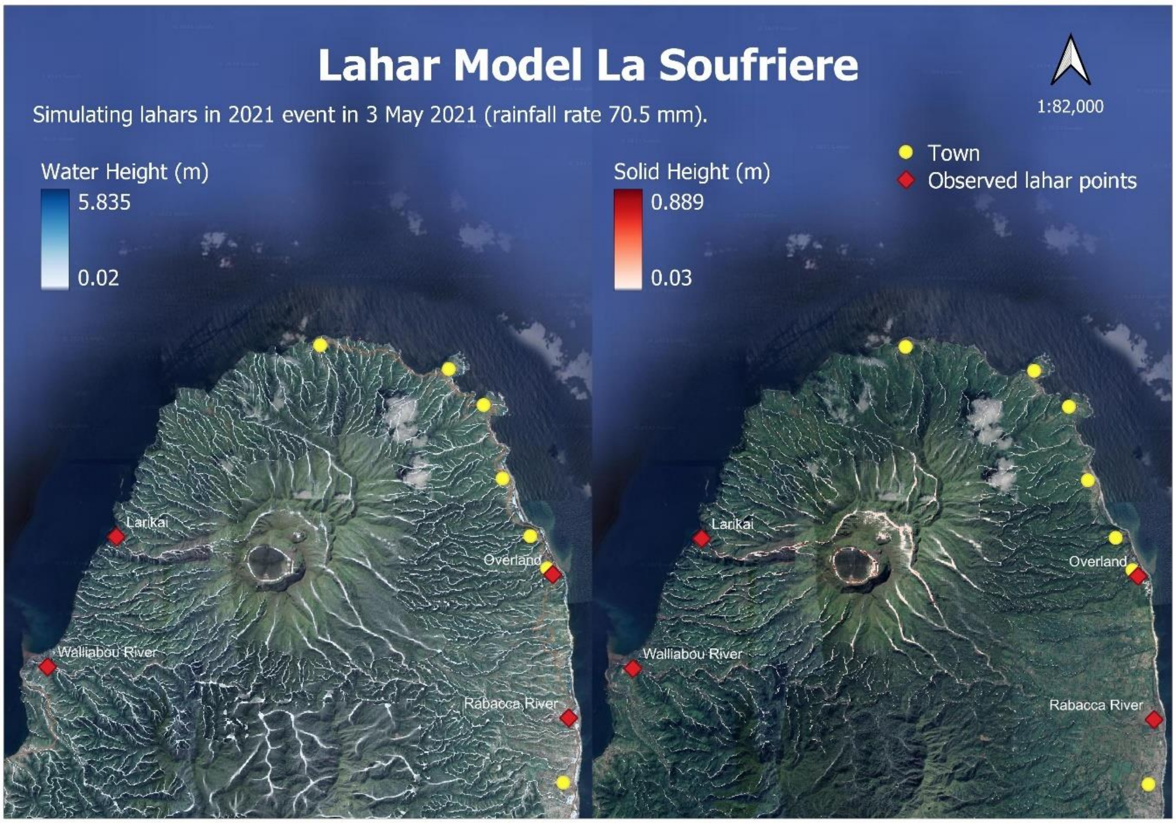


Figure 22. Lahar model results for simulating the event in 3rd of May 2021.

The result for the simulation is presented in Figure 22. For visualization purpose, the solid and water height results for lahar models in this thesis are presented with a minimum value of 0.02 – 0.03 m. This is due to the input soil depth has value for all pixels. The reason also owing to the defined rainfall rate for all areas and not specified locally. Additionally, since the initiation points are not involved, the results also count the value for all areas outside the modelled lahars. The minimum value of 0.02 and 0.03 are seen suitable because below that value, the damage impact is negligible. Exception is made for the minimum rainfall scenario for the water height. Owing to its small value range, changing the minimum values will make the results undetected. Therefore, the minimum value for minimum rainfall scenario results will be kept at 0.

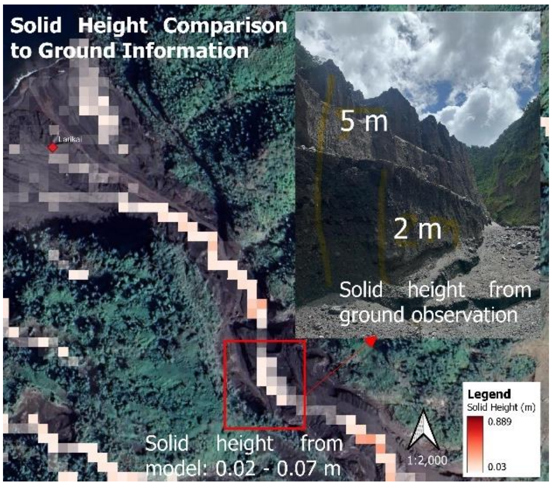


Figure 23. Larikai model solid height comparison.

The water runout from the model follows the pathway of the valleys downstream reaching the coasts. Based on the field visit, three locations confirm that the lahars reach the coasts which are Rabacca, Walliabou, and Larikai. The model also detects lahars inside the crater. This cannot be confirmed since there is no information of lahars on the crater reported. Furthermore, the result around the crater will not be considered in this thesis because of the coarser resolution due to the masking of SRTM elevation model (refer to Section 4.5.2). In addition, all the residential areas and towns are located on the coasts, hence no infrastructures are located around the crater.

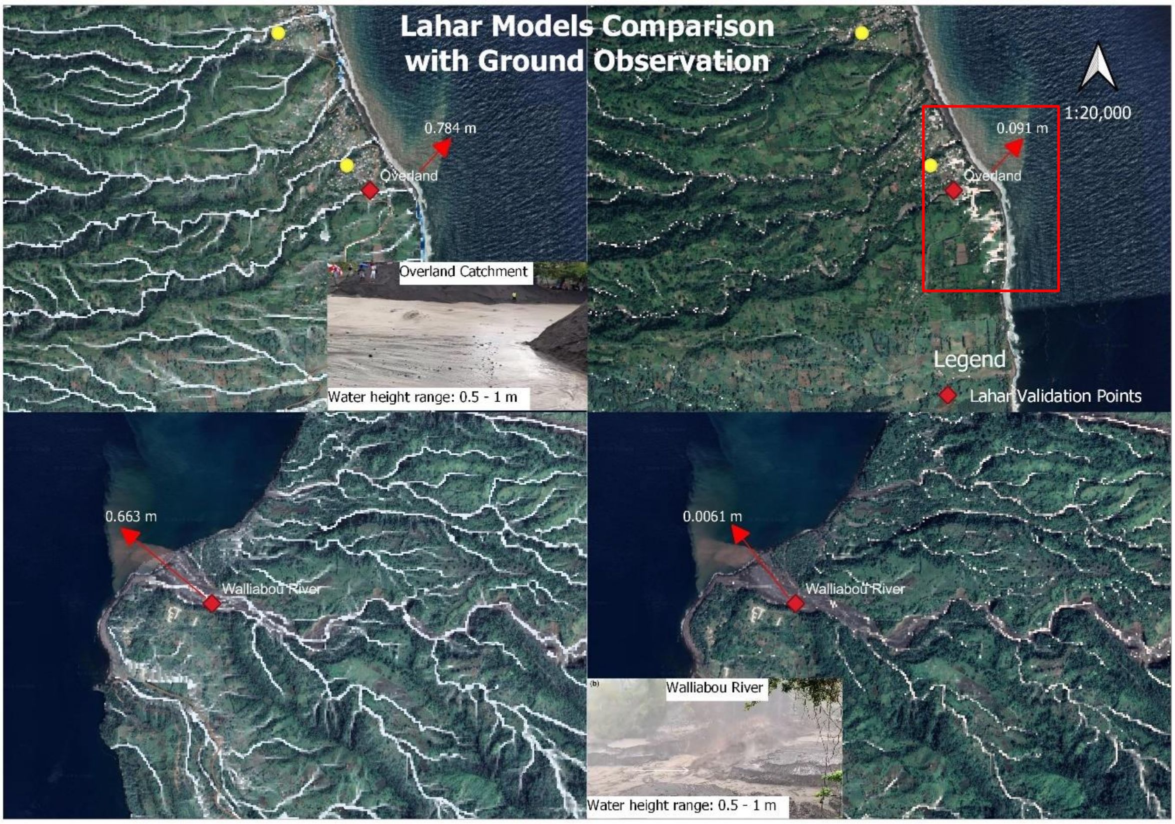


Figure 24. Lahar models compared to ground information from 3rd of May 2021 event.

The model does not result in solid runout to the eastern coasts of Saint Vincent. The difference between both sides might be because on the west coasts, the distance from the volcano is closer and steeper than the east coasts. Additionally, this model only considers the solids from ashfall depositions. PDCs are not incorporated into the model, as well as existing depositions from previous eruptions. Hence, the solid might have lower height if compared to the ground data. Unfortunately, the ground information available of the solid deposition from lahar is only for Larikai from the field work (Figure 15 and Figure 23). Figure 23 also shows that the lahar solid partly reach the coast in Larikai. However, these comparisons are not neck and neck. In one hand, the models only consider ash deposits as the debris materials. On the other hand, there is no information of the solid depositions that correspond to the modelled event. It might be that the deposits in Larikai is accumulated from several lahar events. As mentioned by Phillips et al. (2023) that the post-explosion lahar deposits (approximately 1-2 m depths) filled the channels and valleys formed by earlier sync-eruptive lahars (up to 20 cm thick). In addition, before the 3rd of May lahar event, other lahars were detected from mid-April to end of April 2021.

For water height, comparison was conducted using ground information from Phillips et al. (2023) which monitored the lahar events in Overland catchment and Walliabou river for one hour in 3rd of May 2021. The comparison result is shown in Figure 24. The water height in Overland catchment and Walliabou river fit the range of water height from the monitoring. However, it cannot be guaranteed that the water height for the other valleys is in accordance with ground truth as no information is available for comparison. Another reason is that the model assumes the same parameter for all valley without considering the topography dynamics and therefore might cause deviations in the model.

Additionally, in Overland catchment, solid deposition is noticeable in the simulation result. Considering that no lahar deposition can be seen on the background imagery, it can be concluded that there is an issue in the model. This could be because the model detects the source of solid on the crater along the valley. This source has an elevation model with coarser resolution from the SRTM mask (refer to Section 4.5.2). Therefore, that might be the reason this anomaly occurs.

5.5.2. Simulating Lahar Scenarios

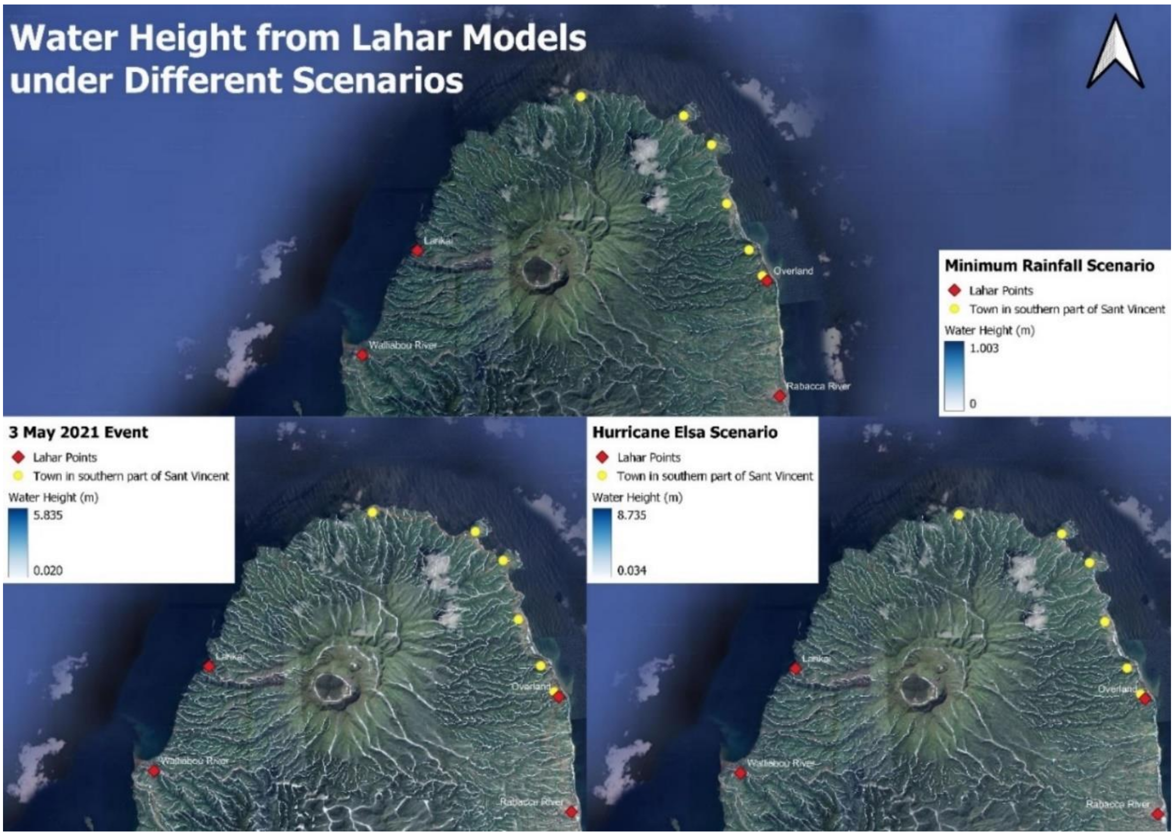


Figure 25. Lahar water height under different scenarios.

Three scenarios are conducted for lahar simulations. The results can be seen in Figure 25 for the water height which increases linearly with the rainfall rate input. However, the maximum water height for the scenarios is mostly located on the coast. This is because the runout flows downwards and accumulated on the coast. There is not much difference from the pathways aside from the water height difference. However, most differences can be noticed on the east coast. Walk-through comparison on the coast was conducted and can be watched through https://youtu.be/4w8ZS4Siq-U. From this observation, the east coast shows the most comparable results for each scenario, therefore the scenario comparison will be focused on the east coast area.

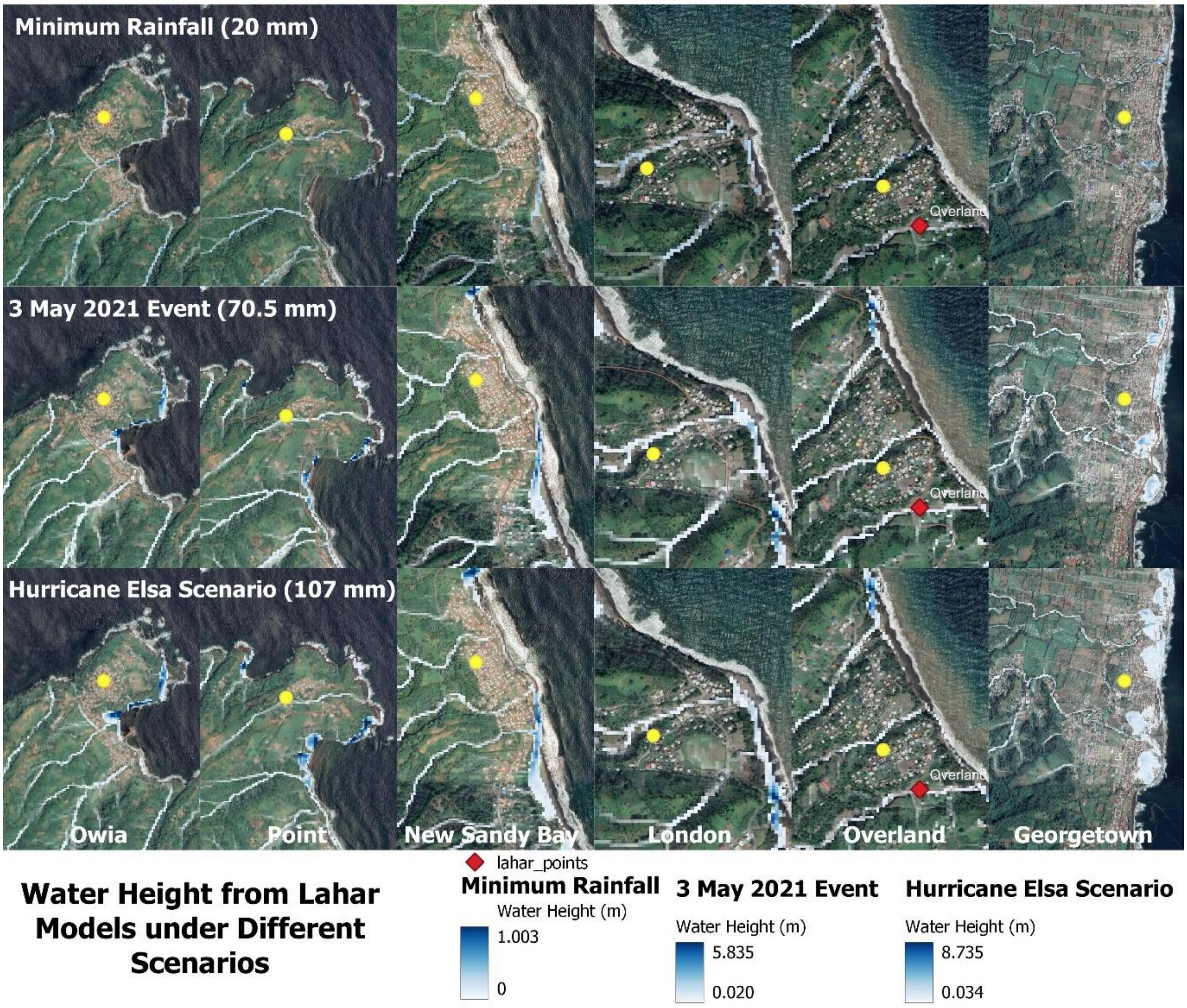


Figure 26. Water height model comparison for towns in east coast of Saint Vincent.

The east coast towns focused on for the comparison are Owia, Point, New Saindy Bay, London, Overland, and Georgetown (Figure 26). From this figure we see most differences are located on the coast with the highest water height comes from hurricane Elsa scenario. This corresponds to the rainfall amount used. It is also noticed that in some towns the inundation does not reach the city. This phenomenon occurs in the model for New Sandy Bay, London, and Overland. Looking at the water initiation in Figure 25, for Owia, Point, and Rabacca, the water starts closer to the towns compared to New Sandy Bay, London, and Overland. However, that may not be the sole reason for that. For Owia, no valleys or rivers are going through the town, making the runout goes directly to the coast. For Points, the waterway that goes through the town runs below the town and therefore not flooding the town. For New Sandy Bay, the river brings the water directly to the coast and therefore it disembogues there, as well as London and Overland.

However, for Georgetown, the town is inundated by water. This might be because in Georgetown, the number of waterways is more than that in London and Overland. Observing from the size from the imagery, the waterways are narrower as well. These might be the reason of the inundation.

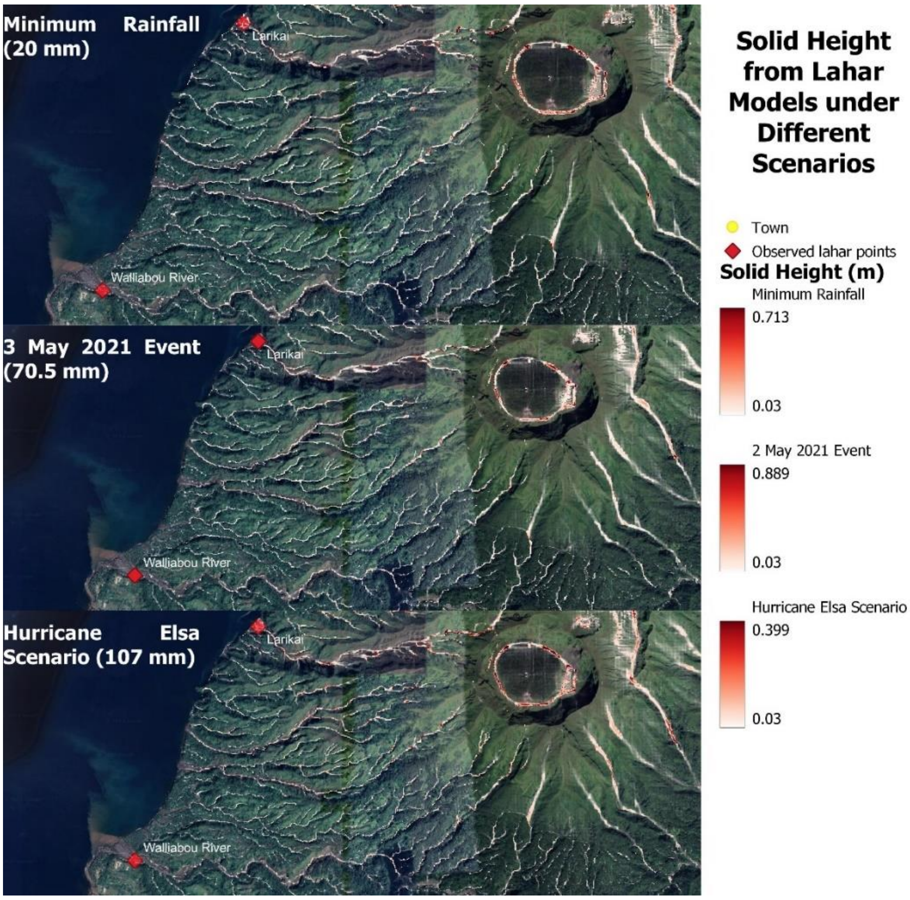


Figure 27. Solid height model comparison for areas in west coast of Saint Vincent.

Comparison for solid height was also conducted. However, the comparison is only done for the west coast of Saint Vincent considering that not much debris is resulted from the map in the east coast as explained previously. The map for comparison can be seen in Figure 27. Difference can be seen from the maximum solid height for each scenario. However, the difference is not linear with the associated rainfall rate. After checking, the highest solid height is in the crater. Elsa scenario results in the lowest value among the other scenarios. This might be because of the high rainfall value; the solid material is washed away from the crater. After checking the value of sample location for both minimum rainfall and 3 May event scenarios, minimum rainfall scenario has higher solid height compared to the 3 May event. This confirms the theory of washed away materials from a higher rainfall value. However, this does not apply when the values are compared from location inside the crater. The coarse resolution around the crater might cause this issue (Section 4.5.2).

The models still need improvement especially in using better input information both for the model and for the validation. Modelling lahars for the whole area using single input might not be the best choice considering the dynamic characteristics of the terrain. Considering that there are more noises and uncertainties from the solid height model, for further steps in this thesis the solid height will not be included. In addition, water height is seen more reliable in seeing the effect of different rainfall rates for the scenarios to the model only if the other parameter input is consistent. However, using water height results for impact assessment in this thesis needs a careful thought as the result might deviates from the real impact.

5.6. Impact Assessment Hazard Scenario

5.6.1. Impact Assessment for Ashfall Scenarios

Impact assessment for ashfall is conducted for each of the scenario. The assessment is conducted in the parish level because no information regarding the village or town administrative level is available. For better understanding, a map for the parish division is provided in Figure 28. The first result is exposure assessment for each scenario. This result is shown in Table 8.

Table 8. Exposure table for ashfall scenarios.

Parish	Ashfall Thickness (m)	Number of Exposed Buildings						Total
		2021 Ash Thickness (m)	Bret Ash Thickness (m)	Elsa Ash Thickness (m)	Harvey Ash Thickness (m)	Mathew Ash Thickness (m)	Tomas Ash Thickness (m)	
Charlotte	< 0.01	0	0	0	0	0	0	0
	0.01 - 0.05	9829	0	9829	9829	0	0	29487
	0.05 - 0.1	0	9829	0	0	9829	9829	29487
	0.1 - 0.15	0	0	0	0	0	1246	1246
	0.15 - 0.2	4801	0	0	4801	1246	4807	15655
	0.2 - 0.25	1252	6053	6053	1252	4807	0	19417
	> 0.25	0	0	0	0	0	0	0
Saint Andrew	< 0.01	0	0	0	0	0	0	0
	0.01 - 0.05	6705	0	0	0	0	0	6705
	0.05 - 0.1	0	0	6705	6705	6705	0	20115
	0.1 - 0.15	0	6705	0	0	0	6705	13410
	0.15 - 0.2	0	0	0	0	0	0	0
	0.2 - 0.25	0	0	0	0	0	0	0
	> 0.25	0	0	0	0	0	0	0
Saint David	< 0.01	0	0	0	0	0	0	0
	0.01 - 0.05	0	0	0	0	0	0	0
	0.05 - 0.1	0	0	0	0	0	0	0
	0.1 - 0.15	3317	0	0	0	0	165	3482
	0.15 - 0.2	97	0	0	20	165	20	302
	0.2 - 0.25	165	185	185	165	20	3394	4114
	> 0.25	0	3394	3394	3394	3394	0	13576
Saint George	< 0.01	8103	0	5102	5102	0	0	18307
	0.01 - 0.05	13366	8103	8780	8780	8103	8103	55235
	0.05 - 0.1	0	5779	7587	7587	13366	5779	40098
	0.1 - 0.15	0	7587	0	0	0	7587	15174
	0.15 - 0.2	0	0	0	0	0	0	0
	0.2 - 0.25	0	0	0	0	0	0	0
	> 0.25	0	0	0	0	0	0	0
Saint Patrick	< 0.01	0	0	0	0	0	0	0
	0.01 - 0.05	3679	0	0	0	0	0	3679
	0.05 - 0.1	0	0	3679	3679	3679	0	11037
	0.1 - 0.15	678	3679	0	0	0	3679	8036
	0.15 - 0.2	0	0	0	0	0	0	0
	0.2 - 0.25	0	0	0	0	0	678	678
	> 0.25	0	678	678	678	678	0	2712

The number of exposed buildings for each parish shows an identical amount. This is caused by the broad pixel of the ashfall models. However, the difference of impact due to tephra thickness can be assessed from this result. The parish Charlotte and Saint George are the most affected parishes (shown with the red-coloured texts in Table 8). Considering the area and building density as shown in Figure 28, this might be because Charlotte and Saint George are the two biggest parishes in Saint Vincent. Therefore, the tephra dispersal might not affect the impacts to these areas. Hence, impact exposure assessment by looking at the average ashfall thickness for each scenario was conducted (Table 9).

Table 9. Exposure assessment of ashfall thickness for each scenario.

Parish	Average Ashfall Thickness for each Scenario					
	2021 Ash Thickness (m)	Bret Ash Thickness (m)	Elsa Ash Thickness (m)	Harvey Ash Thickness (m)	Mathew Ash Thickness (m)	Tomas Ash Thickness (m)
Charlotte	0.091	0.129	0.105	0.092	0.113	0.096
Saint Andrew	0.022	0.113	0.064	0.054	0.094	0.101
Saint David	0.142	0.329	0.345	0.264	0.279	0.235
Saint George	0.018	0.065	0.033	0.030	0.055	0.060
Saint Patrick	0.040	0.148	0.108	0.087	0.124	0.123

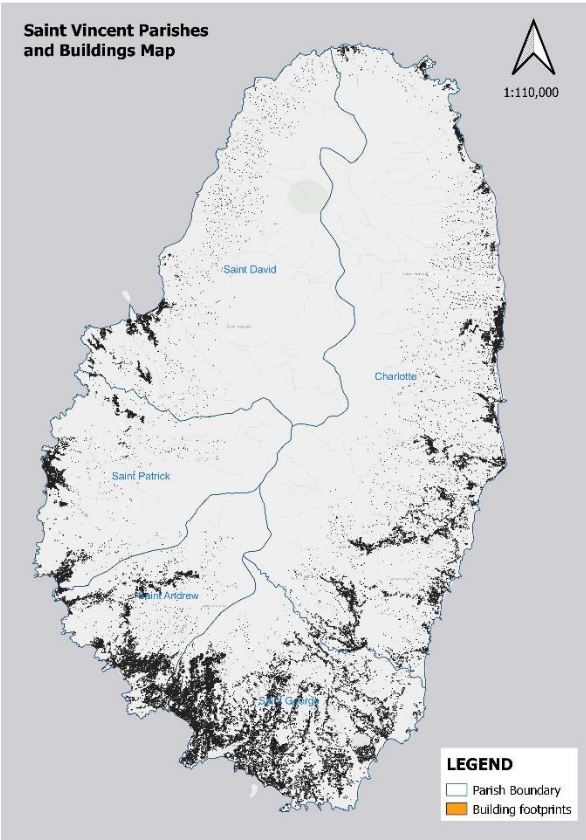


Figure 28. Map of parishes and buildings in Saint Vincent.

Saint David, located the closest from La Soufrière, received the most ashfall deposits from Elsa scenario. This is because the wind movement is towards the northwest side of the island continuously without disorientation such as Harvey or Tomas scenarios. The motion creates deposition confined on the northwestern side only, making the other parishes are not severely affected by this scenario.

Bret scenario results in the highest ashfall impact to most of the parishes, which are Charlotte, Saint Andrew, Saint George, and Saint Patrick. Meanwhile Saint David, which is where La Soufrière is located, suffered most from the Elsa scenario (see the red-coloured texts in Table 9). This is because of the motionless column mass dispersal that remains on top of the island. The ashfall converged and caused a thicker deposition in the island.

Vulnerability assessment was also conducted to identify scenario which results in the highest damage to metal sheet roofs, the most used roof materials in Saint Vincent as well as the most vulnerable to ash. From the vulnerability classification (Annex 11), the damage for metal sheet roof ranges from tephra mass load of 1.5 – 5.3 kPa, with an average of 2.0 kPa. The tephra mass load was converted into kPa by multiplying it with conversion rate (0.00980665 kPa). The result of the conversion is presented in Table 10.

Table 10. Variety of tephra mass load for each scenario converted into kPa according to vulnerability classification. The orange texts show mass load which can damage buildings. Purple texts represent damages above average.

2021 Ash Thickness (m)	(kPa)	Harvey Mass Load (kg/m2)	(kPa)
3.517	0.034	5.356	0.053
5.679	0.056	10.341	0.101

21.564	0.211	30.343	0.298
32.844	0.322	53.727	0.527
138.161	1.355	187.684	1.841
159.182	1.561	206.066	2.021
177.725	1.743	266.025	2.609
211.489	2.074	298.706	2.929
Bret Mass Load (kg/m2)	**(kPa)**	**Matthew Mass Load (kg/m2)**	**(kPa)**
15.341	0.150	12.036	0.118
28.958	0.284	21.937	0.215
65.890	0.646	57.393	0.563
112.851	1.107	94.154	0.923
217.264	2.131	199.824	1.960
235.713	2.312	205.668	2.017
305.399	2.995	276.355	2.710
335.519	3.290	283.977	2.785
Elsa Mass Load (kg/m2)	**(kPa)**	**Tomas Mass Load (kg/m2)**	**(kPa)**
4.406	0.043	18.075	0.177
10.665	0.105	36.075	0.354
29.667	0.291	56.167	0.551
63.512	0.623	101.299	0.993
224.732	2.204	143.899	1.411
240.607	2.360	165.629	1.624
349.915	3.431	202.427	1.985
383.830	3.764	240.438	2.358

All scenarios result in physical damage to metal sheet roofs as coloured in Table 10. Tomas scenario has the lowest mass load value with most deposits result in no to lower-than-average damage to buildings. Meanwhile, Bret and Elsa scenarios both result in above average damages for almost half of the deposits. As mentioned earlier, the wind motion from the cyclone might affect the deposition. When looking at storm Harvey and hurricane Elsa, they both have similar tephra motion but with quite a difference in the tephra load values. Few things that differentiate them are the wind speed and pressure characteristics. Elsa has higher wind speed and pressure, as well as adding the fact that when approaching Saint Vincent, Elsa attained hurricane status with rapid intensification and fast motion. Whereas for Harvey, after attained storm status, it slowly weakened and degenerated into tropical wave. These conditions might affect the resulting mass load values despite the similar motion of the column mass.

5.6.2. Impact Assessment for Lahars Scenarios

Impact assessment for lahar scenarios in this thesis will not include vulnerability assessment. It is because only water height is considered in the assessment. It will not be righ66t to assume that the water height is equal to the intensity of debris flow. Hence, only exposure assessment is conducted for lahar scenarios. Similar to the focus in Section 5.5.2, this assessment will only focus on the east coast towns considering the exposed population in that area. Figure 29 shows the map of the east coast focused on this section. Whereas for the result of the exposure assessment is presented in Figure 30.

The result for minimum rainfall scenario shows that the most damaged bridge / river crossing is located near Overland for all scenarios. This means that the towns north of Overland must be able to provide first aid emergency because due to the high lahar in Overland the roads could be blocked and impassable. These towns are Fancy, Owia, Point, New Sandy Bay, and London. According to PDNA (Government of Saint Vincent and the Grenadines, 2021), there is a clinic each in Fancy, Owia, and New Sandy Bay. However, referring to information from a resident who was met during the fieldwork, the clinic in Fancy has limited capacity and people usually go to Owia. Therefore, investment in improving the facilities in Owia Clinic might need to be considered.

Figure 29. Roads and bridges or river crossings in east coast of Saint Vincent.

Additionally, for both scenario 3rd of May and Elsa, water height of around 700 – 800 cm is modelled after Georgetown. Therefore, the town Overland needs to be independent in case this 'trapped' scenario occurs. Overland has a clinic itself, which means that investment for improving the facilities is also needed for Overland Clinic. Furthermore, the water height affecting Georgetown reaches 500 cm, making a possibility that Georgetown could also be 'trapped'. However, considering that Georgetown is one of the biggest towns in Saint Vincent and closer to the safer part from lahars, the people in Georgetown who lives far from the lahar area might still be able to evacuate.

Building exposure was also done for lahar simulations in Charlotte parish. There are 4686 buildings inside this parish that will be assessed the exposure. The result of the exposure is presented on Table 11. In the table, the minimum, maximum, and average water height for each water height scenario which affects the building are presented. It can be noticed that the maximum water height for the event on 3 May and scenario Elsa shows 4.8 and 9.3 m height. This does not seem right because such water height might be an overestimation. When checked on the map, this value affects a building on the coast of Owia (Figure 31). Although the water height value might not make sense, the building location is in a vulnerable area for lahar. Additionally, the maximum water height for minimum rainfall scenario is also on the coast of Georgetown (Figure 31). Therefore, further action might be needed for reducing the risk and exposure to lahars in this area, especially along the coast.

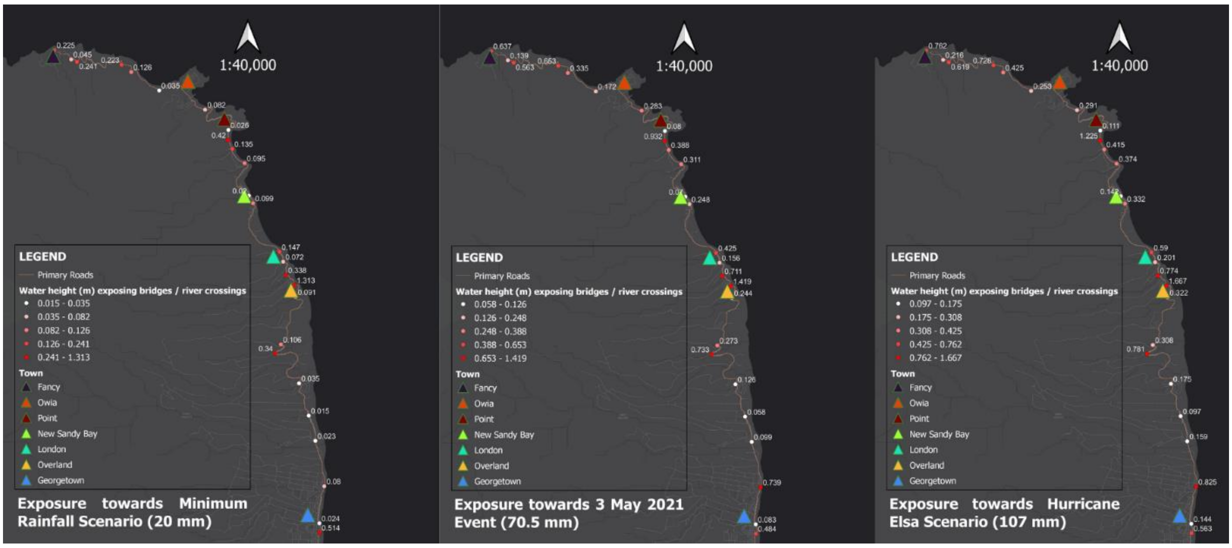


Figure 30. Exposure assessment result for roads, bridges, and river crossings in the east coast of Saint Vincent.

Table 11. Water height exposure towards buildings.

Water Height (m)	Scenarios		
	Minimum Rainfall Scenario	3 May 2021 Event	Elsa Scenario
Minimum	0.002	0.022	0.037
Maximum	0.765	4.856	9.315
Average	0.033	0.162	0.312

Figure 31. Building exposure map for Georgetown (left) and Owia (right).

6. DISCUSSION AND CONCLUSIONS

This chapter discusses the main issues, challenges, and solutions for each methodology. The reflection of the use of the results for future implementation is also discussed. The discussion follows the same sequence as the methodology chapter, followed by conclusions and recommendations.

6.1. Retrospective Assessment using Impact Chains

The retrospective assessment helps in providing insight into what happened in the past and how impacts differ through time along with social conditions and hazard intensity. Meanwhile, impact chains support in visualizing and identifying risk elements and pathways and which to be prioritized for a time constraints in this thesis. Initially, this thesis constructed impact chains which focus more on the hazard processes and less on other aspects such as exposure and vulnerabilities. This made the impact chains more difficult to be explained especially when trying to look at the risk pathways. Therefore, improvements in constructing the impact chains were done with the guidance from the GLOMOS team during the author's internship.

The impact chains presented in this thesis look at a specific event and try to understand and grasp the bigger picture of the event, associated impacts, and the difference through time. For this thesis, this type is sufficient to identify the significant hazards and elements-at-risk aside from visualizing the risk pathways. However, another construction approach can also be implemented for other purposes such as specific physical processes of a phenomenon and associated risk elements to support hazard assessment for mitigation and adaptation decision-making. Additionally, impact chains which look at a specific risk can be beneficial for planning risk reduction efforts in combatting the focused risk. The variety of impact chains serve different implementation purpose and therefore is useful to identify the purpose of the study before constructing impact chains.

6.2. Field Work

The field work supported the work of this thesis in understanding the condition on ground and the perspective of the people regarding the 2021 event, even the volcanic eruption and cyclones in general. The interview and discussion with the stakeholders add more perspective on the lessons learned from their point of views and what are the sectors that need improvement in the future. Additionally, in the author's presentation regarding this thesis to the stakeholders, the author received suggestions that improved the work of the thesis such as for the hazard modelling process and more information on the exposed systems and elements-at-risk in the 2021 event. Aside from thesis improvements, through this field work the author also learned how to communicate and to work with the stakeholders as what was observed during the field work together with the PARATUS team. Furthermore, this field work expands networking and might be useful for future collaborations on research or another project.

6.3. Ashfall Simulation

The main issue of the ashfall simulation is the location of the pixel with the highest value which is not around the crater. Discussions and consultation with the expert were constantly taken place throughout the process. Modifying several parameters and type of model in the input were tried to obtain a better result, yet the pixel location is still not satisfactory. The coarse resolution of the model grid might cause this result. However, increasing the resolution for this thesis was not an option due to the limit in computational capability. Additionally, the coarse resolution of the meteorological that is used in this thesis (ERA5) might also cause this discrepancy, although for this reason we are still not sure as the meteorological data resolution

should have been interpolated into the model grid resolution. Nevertheless, this is worth to investigate to solve the issue for this model.
Aside from the highest-value pixel location, another issue is the value of the tephra ground load results in 30 kg/m² discrepancies with the ground information. After several trials, it is found that the particle density together with the TGSD model have the biggest contribution for the ground load. The larger the density, the more ground load is produced. However, larger particle density also defines the wetter ash particles. In addition, the larger the density, the narrower and more confined the tephra deposition. Considering that this thesis tries to see the effect of meteorological data variation to tephra dispersal, the particle density range of 1000 – 1500 kg/m² (between wet and dry) was used. This range is not too large, and the variation of ground load coverage is still observable.

6.4. Lahar Simulation

The lahar simulation in this thesis uses LISEM and to the best of our knowledge is the first implementation of debris modelling in LISEM. The challenge arises in the first step on how to start the model for lahars. Initially, 'initiation points' were introduced as the starting point for the lahar runout based on the initiation points from Miller et al. (2022). However, this process means that lahars are treated as landslide and rather as erosion which how lahars behave in Saint Vincent. Therefore, the initiation points were removed, and the full layer of ash thickness map was used instead. This way, the runout will not be forced through initiation points.
This approach still has drawbacks in the implementation. First, all valleys for the whole simulated area are treated the same way with the same input parameters. This means that the simulation assumes that all valleys will fail given the input rainfall which might not be accurate. Each valley should be treated differently due to the dynamics of the topography. This leads to the second point which is when compared to the ground information, it only matches with specific valleys in which the input parameters are based on. Reflecting upon these results, initiation points are needed to have more accurate results on where the failure might occur. However, instead of using the same initiation points from Miller et al. (2022), the calculation of shear stress should be conducted.
Implementing shear stress has been tried in this thesis. However, due to the carelessness of neglecting the DEM correction at earlier stage, the shear stress results are unreliable at some point. After discussing with an expert, the shear stress can be left as is and only be considered for the first 5000 steps. After realizing this mistake, DEM correction was conducted, and lahar simulations are based on the corrected DEM.
The simulations for debris flow in LISEM consists of two materials: solid and water. It is fortunate that there is ground information available from literature for the water height to compare this thesis' models with. The results show good agreement of water height between the simulated lahars and ground information. On the other hand, the solid height does not have a proper ground information to compare with aside from the one collected from the field work. This as well is not in accordance with the simulated solid height. For solid height, the comparison is not neck and neck and therefore is not considered for the assessing the impact as it might differ too much from the reality.

6.5. Impact Assessment

Assessment is conducted for both ashfall and lahar scenarios. However, only exposure is conducted for the lahar as not the whole component of lahars is included in the assessment. This makes the vulnerability curves / assessment might not be suitable for the models' character. For ashfall, an aggregated vulnerability assessment was conducted assuming the same roof material for the whole island. Despite the fact that 91% of the dwellings in Saint Vincent uses this material, the impact assessed in this thesis might be overestimated. In addition, the coarse resolution of the model might overlook the details of ashfall deposition in areas closer to the volcano.

6.6. Recommendation for Stakeholders (especially in Saint Vincent)

This thesis tries to unveil the interaction of compounding volcanic eruption and cyclone hazards. As this combination does not occur often, the concept of this thesis is useful to consider the possibility of future scenarios. Especially considering that the cyclones are projected to occur more often, this thesis is beneficial to support mitigation planning. Additionally, all the tools used in this thesis are open source and the documentations are available online, therefore it is possible to re-create the assessment and models. Modification of the models to a certain scenario is also possible, such as using the forecast from the MET office to model tephra scenario according to forecasted cyclone.

Despite the limitations, the result of this thesis helps in providing first insight and recommendations on Saint Vincent's improvement to mitigate the risks due to compounding event of volcanic eruption and cyclone. For the ashfall, the most severe scenario affects Saint David parish. Especially because most cyclones have a westward direction, Saint David needs to be prioritized. Considering that most areas in Saint David are plantations, the impacts might not affect directly to the population. However, a lot of Vincentians have agriculture lands there and therefore this could impact their livelihoods. For lahars, focusing on the north-east coast of Saint Vincent is recommended. Especially in improving the facilities for clinics in Owia, New Sandy Bay, Overland, and Georgetown as those areas might be trapped under a certain lahar scenario.

6.7. Recommendation for Future Research

1. The retrospective assessment in this thesis is mostly based on literature review with additional information from the field work. Due to the low frequency of the eruption, social and cultural aspects have changed and are not included in the assessment in this thesis.
2. The stakeholders involved in this thesis mainly supports in providing more information, rather than partnering in the process of the work. More thorough involvement of more stakeholders especially in the process of impact chain development would be more enriching to the results.
3. Some of the data input have low resolutions that affects the behaviour of the resulted models. The usage of a higher resolution data might result in better simulations.
4. For ashfall models, low resolution of the grid is defined due to the low computational capability. If possible, considering processing the model with a higher grid resolution might show more accurate results and capture the details of the ashfall deposits.
5. For lahar models, all channels and valleys are treated the same and assumed to be homogenous. Incorporating the dynamics especially the land cover and specific volcanic materials characteristics might improve the models. Additionally, considering using the shear stress calculations to define the initiation slope failure could detect the starting point of the lahars better.
6. The vulnerability dynamics are not included in this thesis. Including these can show specific areas of improvement for the focused exposed system.

6.8. Conclusion

In conclusion, compounding multi-hazard impact assessment requires a comprehensive understanding of each risk elements. Retrospective assessment helps to understand the historic events and define which specific hazard and elements-at-risk to focus on in this thesis. Hazard simulations under different scenarios were modelled and assessed, as well as the associated impacts. However, hazard simulations in this thesis are still not perfect yet and has areas of improvement for future works. The ashfall simulations need better resolutions for both meteorological data and grid model. The lahars simulations need to include a proper shear stress calculation and include the assumption of dynamic land cover into the model. The impact assessment needs to be more thorough and include information for vulnerability assessment. Despite the drawbacks, this thesis has already achieved its objective to assess the impacts of compounding volcanic eruption and cyclone which incorporates the interaction between the two hazards.

LIST OF REFERENCES

Ahmad, N. (2018). Part I: Soils investigations carried out in St. Vincent and the Grenadines prior to 2003. In *Baseline Study on the Soils of St. Vincent and the Grenadines with Emphasis on Maintenance of Productivity*. Richmond Vale Academy. https://issuu.com/richmondvaleacademy/docs/part_i_-_soil_of_st._vincent_and_be

Albulescu, A.-C., & Armaş, I. (n.d.). *An Impact Chain-based exploration of multi-hazard vulnerability dynamics. The multi-hazard of floods and the COVID-19 pandemic in Romania*. https://doi.org/10.5194/nhess-2024-5

Alvey, G. R., & Hazelton, A. (2022). How Do Weak, Misaligned Tropical Cyclones Evolve Toward Alignment? A Multi-Case Study Using the Hurricane Analysis and Forecast System. *Journal of Geophysical Research: Atmospheres*, *127*(20), e2022JD037268. https://doi.org/10.1029/2022JD037268

Angeli, S. de, Malamud, B. D., Rossi, L., Taylor, F. E., Trasforini, E., & Rudari, R. (2022). A multi-hazard framework for spatial-temporal impact analysis. *International Journal of Disaster Risk Reduction*, *73*, 2212–4209. https://doi.org/10.1016/j.ijdrr.2022.102829ï

Aspinall, W. P., Sigurdsson, H., & Shepherd, J. B. (1973). Eruption of Soufrière Volcano on St. Vincent Island, 1971-1972. *Science*, *181*(4095), 117–124. https://www.jstor.org/stable/1736842?typeAccessWorkflow=login&seq=3

Balzter, H., Macul, M., Delaney, B., Tansey, K., Espirito-Santo, F., Ofoegbu, C., Petrovskii, S., Forchtner, B., Nicholes, N., Payo, E., Heslop-Harrison, P., Burns, M., Basell, L., Egberts, E., Stockley, E., Desorgher, M., Upton, C., Whelan, M., & Yildiz, A. (2023). Loss and Damage from Climate Change: Knowledge Gaps and Interdisciplinary Approaches. *Sustainability 2023, Vol. 15, Page 11864*, *15*(15), 11864. https://doi.org/10.3390/SU151511864

Barberi, F., Macedonio, G., Pareschi, M. T., & Santacroce, R. (1990). Mapping the tephra fallout risk: An example from Vesuvius, Italy. *Nature*, *344*(6262), 142–144. https://doi.org/10.1038/344142A0

BBC. (2023, August 29). *Montserrat profile*. https://www.bbc.com/news/world-latin-america-20256517

Berg. (2017). *Remnants of HARVEY*. https://www.nhc.noaa.gov/archive/2017/al09/al092017.public.011.shtml?

Biass, S., Bonadonna, C., di Traglia, F., Pistolesi, M., Rosi, M., & Lestuzzi, P. (2016). Probabilistic evaluation of the physical impact of future tephra fallout events for the Island of Vulcano, Italy. *Bulletin of Volcanology*, *78*(5), 1–22. https://doi.org/10.1007/S00445-016-1028-1/TABLES/4

Blackett, M. (2023, August 8). *How climate change triggers more earthquakes and volcanic eruptions*. The Conversation. https://www.preventionweb.net/news/how-climate-change-might-trigger-more-earthquakes-and-volcanic-eruptions

Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005). Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. *Journal of Geophysical Research: Solid Earth*, *110*(B3), 1–21. https://doi.org/10.1029/2003JB002896

Bonasia, R., Turchi, A., Madonia, P., Fornaciai, A., Favalli, M., Gioia, A., & Di Traglia, F. (2022). Modelling Erosion and Floods in Volcanic Environment: The Case Study of the Island of Vulcano (Aeolian Archipelago, Italy). *Sustainability (Switzerland)*, *14*(24), 16549. https://doi.org/10.3390/SU142416549/S1

Bout, B., Lombardo, L., van Westen, C. J., & Jetten, V. G. (2018). Integration of two-phase solid fluid equations in a catchment model for flashfloods, debris flows and shallow slope failures. *Environmental Modelling & Software*, *105*, 1–16. https://doi.org/10.1016/J.ENVSOFT.2018.03.017

Bout, B., Lombardo, L., Westen, C. J. van, & Jetten, V. G. (2018). Integration of two-phase solid fluid equations in a catchment model for flashfloods, debris flows and shallow slope failures. *Environmental Modelling & Software*, *105*, 1–16. https://doi.org/10.1016/J.ENVSOFT.2018.03.017

Brazier, S., Davis, A. N., Sigurdsson, H., & Sparks, R. S. J. (1982). Fall-out and Deposition of Volcanic Ash During the 1979 Explosive Eruption of the Soufriere of St. Vincent. *Journal of Volcanology and Geothermal Research*, *14*(3–4), 335–359. https://doi.org/10.1016/0377-0273(82)90069-5

Britannica. (2024, April 25). *Antilles*. Encyclopedia Britannica. https://www.britannica.com/place/Antilles

British Geological Survey. (n.d.). *Volcanic hazards*. Discovering Geology - Volcanoes. Retrieved June 17, 2024, from https://www.bgs.ac.uk/discovering-geology/earth-hazards/volcanoes/volcanic-hazards/

Camejo-Harry, M., Pascal, K., Euillades, P., Grandin, R., Hamling, I., Euillades, L., Contreras-Arratia, R., Ryan, G. A., Latchman, J. L., Lynch, L., & Jo, M. (2023). Monitoring Volcano Deformation at La Soufrière, St Vincent during the 2020–21 Eruption with Insights into Its Magma Plumbing System Architecture. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-270

Cangialosi, J. P., Delgado, S., & Berg, R. (2022). *National Hurricane Center Tropical Cyclone Report: Hurricane Elsa*.

Capra, L., Borselli, L., Varley, N., Gavilanes-Ruiz, J. C., Norini, G., Sarocchi, D., Caballero, L., & Cortes, A. (2010). Rainfall-triggered lahars at Volcán de Colima, Mexico: Surface hydro-repellency as initiation process. *Journal of Volcanology and Geothermal Research*, *189*(1–2), 105–117. https://doi.org/10.1016/J.JVOLGEORES.2009.10.014

Caribbean Institute of Meteorology and Hydrology, World Meteorological Organization, & Environment and Climate Change Canada. (2018). *Country Profile: St. Vincent and the Grenadines*. http://www.slumet.gov.lc/

Caricchi, L., Townsend, M., Rivalta, E., & Namiki, A. (2021). The build-up and triggers of volcanic eruptions. *Nature Reviews Earth & Environment 2021 2:7*, *2*(7), 458–476. https://doi.org/10.1038/s43017-021-00174-8

CCRIF. (2016a). *Covered Area Rainfall Event (28-30 September 2016) Tropical Cyclone Matthew Excess Rainfall Event Briefing St. Vincent & the Grenadines*. www.ccrif.org

CCRIF. (2016b). *Tropical Cyclone MATTHEW (AL142016) Wind and Storm Surge Preliminary Event Briefing Windward Islands and Barbados*. www.ccrif.org

CCRIF. (2017). *Tropical Cyclone Harvey (AL092017) Wind and Storm Surge Preliminary Event Briefing Windward Islands*. www.ccrif.org

CCRIF. (2021). *Tropical Cyclone Elsa (AL052021) Wind and Storm Surge Final Event Briefing Windward Islands*.

CCRIF. (2023). *Tropical Cyclone Bret (AAL032023) Wind and Storm Surge Final Event Briefing Barbados Saint Lucia Vincent and The Grenadines*.

CDEMA. (n.d.). *About Us*. Retrieved June 18, 2024, from https://www.cdema.org/index.php/about

CDEMA. (2010). *SUMMARY OF IMPACT OF HURRICANE TOMAS ON CDEMA PARTICIPATING STATES OF SAINT LUCIA AND ST. VINCENT AND THE GRENADINES Damage, Response Actions, Immediate Recovery and Rehabilitation Needs*.

CDEMA. (2017). *CDEMA Situation Report #2 - Tropical Storm Harvey - as of 11:00am on August 22nd, 2017*. https://reliefweb.int/report/saint-vincent-and-grenadines/cdema-situation-report-2-tropical-storm-harvey-1100am-august

CDEMA. (2023). *Tropical Storm Bret Synopsis on Tropical Storm Bret*. www.cdema.orgTel:

CDEMA, & MapAction. (2021). *Multi-hazard risks of Saint Vincent (as at 30 Apr 2021)*. https://maps.mapaction.org/dataset/a025155e-3027-4724-a315-5ef9182a285b

Cegan, J. C., Golan, M. S., Joyner, M. D., & Linkov, I. (2022). The importance of compounding threats to hurricane evacuation modeling. *Npj Urban Sustainability 2022 2:1*, *2*(1), 1–4. https://doi.org/10.1038/s42949-021-00045-7

Chaganti, V., Cheruvu, M. K., Chaganti, V., & Cheruvu, M. K. (2022). An Experimental Methodology for Storm Mitigation. *Atmospheric and Climate Sciences*, *12*(4), 648–678. https://doi.org/10.4236/ACS.2022.124037

Ching, A., Morrison, L., & Kelley, M. (2020). Living with natural hazards: Tropical storms, lava flows and the resilience of island residents. *International Journal of Disaster Risk Reduction*, *47*, 101546. https://doi.org/10.1016/J.IJDRR.2020.101546

CIA. (2024, June 6). *Saint Vincent and the Grenadines*. Explore All Countries: Central America and the Caribbean. https://www.cia.gov/the-world-factbook/countries/saint-vincent-and-the-grenadines/

Clifford, N. (2017, April 29). *The eruption of La Soufrière on St Vincent*. https://www.naomiclifford.com/eruption-st-vincent/

Cocuccioni, S., Romagnoli, F., Pittore, M., Ergün Konukçu, B., Kundak, S., Göksu, Ç., Aşıcı, A., Arslanlı, K., Kalkanlı, D., Pak, E. Ö., Savelberg, L., Kalubowila, P., Armas, I., Danila, D. T., Osaci, G., Albulescu, C., Wenzel, T., Marr, P., Atun, F., … Witvliet, B. (2023). *Report on participatory workshops in the four application case study sites, including impact chains diagrams for each analysed event*. https://doi.org/10.5281/ZENODO.8200493

Cole, P. D., Barclay, J., Robertson, R. E. A., Mitchell, S., Davies, B. V., Constantinescu, R., Sparks, R. S. J., Aspinall, W., & Stinton, A. (2023). Explosive sequence of La Soufrière, St Vincent, April 2021: insights into drivers and consequences via eruptive products. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-292

Constantinescu, R., White, J. T., Connor, C., Cole, P., Fontijn, K., Barclay, J., & Robertson, R. (2023). Estimation of eruption source parameters for the 2021 La Soufrière eruption (St Vincent): implications for quantification of eruption magnitude on volcanic islands. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2023-38

Cooke, E. (2021, July 2). Hurricane Elsa leaves a trail of destruction in St Vincent. *St. Vincent Times*. https://www.stvincenttimes.com/hurricane-elsa-leaves-a-trail-of-destruction-in-st-vincent/

Costa, A., Macedonio, G., & Folch, A. (2005). *A three-dimensional Eulerian model for transport and deposition of volcanic ashes*. https://doi.org/10.1016/j.epsl.2005.11.019

Costa, A., Pioli, L., & Bonadonna, C. (2016). Assessing tephra total grain-size distribution: Insights from field data analysis. *Earth and Planetary Science Letters*, *443*, 90–107. https://doi.org/10.1016/J.EPSL.2016.02.040

Daily Press. (1979, April 16). Little Activity Recorded at St. Vincent Volcano (1979) Newspapers.com™. *Newspapers.Com*. https://www.newspapers.com/article/daily-press-little-activity-recorded-at/75774637/

Darnell, A. R., Phillips, J. C., Barclay, J., Herd, R. A., Lovett, A. A., & Cole, P. D. (2013). Developing a simplified geographical information system approach to dilute lahar modelling for rapid hazard assessment. *Bulletin of Volcanology*, *75*(4), 1–16. https://doi.org/10.1007/S00445-013-0713-6/FIGURES/9 de Sanctis, V., Soliman, A. T., Daar, S., Tzoulis, P., Fiscina, B., Kattamis, C., Banchev, A., Stoyanova, D., Angastiniotis, M., Christou, S., Elsedfy, H., El Kholy, M., Khater, D., Kattamis, A., Delaporta, P., Bozorgi, H., Karimi, M., Campisi, S., Di Maio, S., … Canatan, D. (2022). Retrospective observational studies: Lights and shadows for medical writers. *Acta Biomedica Atenei Parmensis*, *93*(5), e2022319–e2022319. https://doi.org/10.23750/ABM.V93I5.13179

Deeming, K. R., McGuire, B., & Harrop, P. (2010). Climate forcing of volcano lateral collapse: evidence from Mount Etna, Sicily. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *368*(1919), 2559–2577. https://doi.org/10.1098/RSTA.2010.0054

Durant, A. J. (2015). RESEARCH FOCUS: Toward a realistic formulation of fine-ash lifetime in volcanic clouds. *Geology*, *43*(3), 271–272. https://doi.org/10.1130/FOCUS032015.1

Edelman, Z. (2021, June 28). Four decades later: How the impact of two volcanic eruptions differ. *ISRA AID*. https://www.israaid.org/media/four-decades-later-how-the-impact-of-two-volcanic-eruption-differ/

Ehrlich, A. (2017, September 2). Hurricane Harvey Timeline. *Caller-Times*. https://eu.caller.com/story/weather/hurricanes/2017/09/02/harvey-timeline-see-how-storm-developed-and-marched-across-texas-and-louisiana/625563001/

Ellouze, M., Abida, H., & Safi, R. (2009). A triangular model for the generation of synthetic hyetographs. *Hydrological Sciences Journal*, *54*(2). https://doi.org/10.1623/hysj.54.2.287

Esse, B., Burton, M., Hayer, C., Contreras-Arratia, R., Christopher, T., Joseph, E. P., Varnam, M., & Johnson, C. (2023). SO2 Emissions During the 2021 Eruption of La Soufrière, St Vincent, Revealed with Back-Trajectory Analysis of TROPOMI Imagery. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-77

European Commission. (2022). *Caribbean*. European Civil Protection and Humanitarian Aid Operations. https://civil-protection-humanitarian-aid.ec.europa.eu/where/latin-america-and-caribbean/caribbean_en

European Union. (2019). *11th EDF National Indicative Programme (2014-2020) for Co-operation between Saint Vincent and the Grenadines and the European Union*. https://international-partnerships.ec.europa.eu/system/files/2019-09/nip-saint-vincent-and-the-grenadies-2014-2020_en.pdf

Folch, A., Mingari, L., Gutierrez, N., Hanzich, M., Macedonio, G., & Costa, A. (2020). FALL3D-8.0: A computational model for atmospheric transport and deposition of particles, aerosols and radionuclides - Part 1: Model physics and numerics. *Geoscientific Model Development*, *13*(3), 1431–1458. https://doi.org/10.5194/GMD-13-1431-2020

Frey, H. M., Manon, M. R., Barclay, J., Davies, B. V., Walters, S. A., Cole, P. D., Christopher, T. E., & Joseph, E. P. (2023). Petrology of the explosive deposits from the April 2021 eruption of La Soufrière volcano, St Vincent: a time-series analysis of microlites. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-291

Gattuso, A., Bonadonna, C., Frischknecht, C., Cuomo, S., Baumann, V., Pistolesi, M., Biass, S., Arrowsmith, J. R., Moscariello, M., & Rosi, M. (2021). Lahar risk assessment from source identification to potential impact analysis: the case of Vulcano Island, Italy. *Journal of Applied Volcanology*, *10*(1), 1–23. https://doi.org/10.1186/S13617-021-00107-6/FIGURES/14

GFDRR. (2010). *Design and Execution of a Damage, Loss and Needs Assessment Guidance Note for Task Managers*. www.worldbank.org

GFDRR. (2013). *POST-DISASTER NEEDS ASSESSMENTS*. https://www.undp.org/sites/g/files/zskgke326/files/publications/PDNA%20Volume%20A%20FINAL%2012th%20Review_March%202015.pdf

Gibbs, T. (2001). Natural Hazards in the Caribbean. *USAID/OAS PGDM*. https://www.oas.org/pgdm/document/BITC/papers/gibbs/gibbs_02.htm

Gill, J. C., & Malamud, B. D. (2016). Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. *Earth System Dynamics*, *7*(3), 659–679. https://doi.org/10.5194/ESD-7-659-2016

Girgin, S. (2021). Using FOSS to develop and operate a geospatial computing platform. *FOSS4GNL*. https://doi.org/10.5281/ZENODO.6025282

Global Volcanism Program. (1979). Report on Soufriere St. Vincent (Saint Vincent and the Grenadines) - 1979. In *Scientific Event Alert Network Bulletin* (Vol. 4, Issue 4). Smithsonian Institution. https://doi.org/10.5479/SI.GVP.SEAN197904-360150

Goldschmidt, K. H., & Kumar, S. (2016). Humanitarian operations and crisis/disaster management: A retrospective review of the literature and framework for development. *International Journal of Disaster Risk Reduction*, *20*, 1–13. https://doi.org/10.1016/J.IJDRR.2016.10.001

Government of Saint Vincent and the Grenadines. (n.d.). *Weather*. Retrieved June 2, 2023, from http://tourism.gov.vc/tourism/index.php/svg-facts/70-weather

Government of Saint Vincent and the Grenadines. (2014). *Rapid Damage and Loss Assessment (DaLA) December 24-25, 2013 Floods*. https://reliefweb.int/report/saint-vincent-and-grenadines/rapid-damage-and-loss-assessment-dala-december-24-25-2013-floods

Government of Saint Vincent and the Grenadines. (2021). *La Soufrière Volcanic Eruption Executive Summary*. https://www.undp.org/barbados/publications/post-disaster-needs-assessment-pdna-st-vincent-and-grenadines

Government of Saint Vincent and the Grenadines, & World Bank. (2014). *Rapid Damage and Loss Assessment (DaLA) Floods*. https://www.gfdrr.org/sites/default/files/publication/SVG_Rapid_DaLA_Report_0_0.pdf

Government of SVG. (2016). *Rapid Damage and Loss Assessment Floods*.

Graf, H. F., Herzog, M., Oberhuber, J. M., & Textor, C. (1999). Effect of environmental conditions on volcanic plume rise. *Journal of Geophysical Research: Atmospheres*, *104*(D20), 24309–24320. https://doi.org/10.1029/1999JD900498

Gregory, J. A., & Delbourgo, R. (1982). Piecewise Rational Quadratic Interpolation to Monotonic Data. *IMA Journal of Numerical Analysis*, *2*(2), 123–130. https://doi.org/10.1093/IMANUM/2.2.123

Gueugneau, V., Charbonnier, S., Miller, V. L., Cole, P., Grandin, R., & Dualeh, E. W. (2023). Modelling pyroclastic density currents of the April 2021 La Soufrière, St Vincent eruption: from rapid invasion maps to field-constrained numerical simulations. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-290

Hairani, A., & Rahardjo, A. P. (2021). A Theoretical Model for Debris Flow Initiation by Considering Effect of Hydrodynamic Force. *Proceedings of the 4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (ICoSITEA 2020)*, *199*, 38–42. https://doi.org/10.2991/AER.K.210204.008

Harris, A. J. L., & Rowland, S. K. (2015). FLOWGO 2012. *Geophysical Monograph Series*, *208*, 457–481. https://doi.org/10.1002/9781118872079.CH21

Hawaiian Volcano Observatory. (2004, March 11). Volcano Watch — Chronology of a volcanic disaster. *USGS*. https://www.usgs.gov/news/volcano-watch-chronology-volcanic-disaster

Heath, E., Macdonald, R., Belkin, H., Hawkesworth, C., & Sigurdsson, H. (1998). Magmagenesis at Soufriere Volcano, St Vincent, Lesser Antilles Arc. *Journal of Petrology*, *39*(10), 1721–1764. https://doi.org/10.1093/PETROJ/39.10.1721

Heger, M. ;, Julca, A. ;, & Paddison, O. (2008). Analysing the Impact of Natural Hazards in Small Economies. *ECONSTOR*. http://hdl.handle.net/10419/63505

Heidarzadeh, M., & Rabinovich, A. B. (2021). Combined hazard of typhoon-generated meteorological tsunamis and storm surges along the coast of Japan. *Natural Hazards*, *106*(2), 1639–1672. https://doi.org/10.1007/S11069-020-04448-0/TABLES/5

Hielkema, L., Suidman, J., & Jaime, C. (2021, November 15). *Multi-hazard Risk Analysis Methodologies*. Anticipation Hub. https://www.anticipation-hub.org/news/multi-hazard-risk-analysis-methodologies

Hincks, T. K., Komorowski, J. C., Sparks, S. R., & Aspinall, W. P. (2014). Retrospective analysis of uncertain eruption precursors at La Soufrière volcano, Guadeloupe, 1975-77: Volcanic hazard assessment using a Bayesian Belief Network approach. *Journal of Applied Volcanology*, *3*(1), 1–26. https://doi.org/10.1186/2191-5040-3-3/FIGURES/8

Hiroki, K. (2013). Strategies for Managing Low-probability, High-impact Events. In *Knowledge Note 6-5, Cluster 6: The economics of disaster risk, risk management, and risk financing*. The World Bank.

Horwell, C. J., Damby, D. E., Stewart, C., Joseph, E. P., Barclay, J., Davies, B. V., Mangler, M. F., Marvin, L. G., Najorka, J., Peek, S., & Tunstall, N. (2022). Physicochemical hazard assessment of ash and dome rock from the 2021 eruption of La Soufrière, St Vincent, for the assessment of respiratory health impacts and water contamination. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2023-46

Hurst, A. W., & Turner, R. (1999). Performance of the program ASHFALL for forecasting ashfall during the 1995 and 1996 eruptions of Ruapehu volcano. *New Zealand Journal of Geology and Geophysics*, *42*(4), 615–622. https://doi.org/10.1080/00288306.1999.9514865

IFRC. (2017). *Caribbean: Tropical Storm Harvey - Information Bulletin N° 1*. https://reliefweb.int/report/saint-vincent-and-grenadines/caribbean-tropical-storm-harvey-information-bulletin-n-1

IFRC. (2021). *Saint Vincent and the Grenadines and surrounding countries: La Soufrière Volcanic - Operation Update no. 1 (MDRVC005)*. https://reliefweb.int/report/saint-vincent-and-grenadines/saint-vincent-and-grenadines-and-surrounding-countries-la-0

IPCC. (2022). Annex II: Glossary. In V. Möller, R. van Diemen, J. B. R. Matthews, Jan. S. Fuglestvedt, C. Méndez, A. Reisinger, & S. Semenov (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability* (pp. 2897–2930). Cambridge University Press. https://doi.org/10.1017/9781009325844.029

Irwansyah, E., Young, H., & Gunawan, A. A. S. (2023). Multi Disaster Building Damage Assessment with Deep Learning using Satellite Imagery Data. *International Journal of Intelligent Systems and Applications in Engineering*, *11*(1), 122–131. https://www.ijisae.org/index.php/IJISAE/article/view/2450

Jaggard, V. (2014, August 7). What Happens When a Hurricane Meets a Volcano? *Smithsonian Magazine*. https://www.smithsonianmag.com/science-nature/what-happens-when-hurricane-meets-volcano-180952294/

Jeffers, B. H., Laing, A. G., & Best, S. (2022). *La Soufrière Volcanic Eruption, Heavy Rainfall, Hurricane Elsa, and the COVID-19 Pandemic: The Challenges of Multiple Hazards in St. Vincent and the Grenadines*. AMS. https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/399704

Jenkins, S. F., Spence, R. J. S., Fonseca, J. F. B. D., Solidum, R. U., & Wilson, T. M. (2014). Volcanic risk assessment: Quantifying physical vulnerability in the built environment. *Journal of Volcanology and Geothermal Research*, *276*, 105–120. https://doi.org/10.1016/J.JVOLGEORES.2014.03.002

Johns Hopkins University of Medicine. (2023, March 10). *St. Vincent and the Grenadines - COVID-19 Overview*. Coronavirus Resource Center. https://coronavirus.jhu.edu/region/saint-vincent-and-the-grenadines

Joseph, E. P., Camejo-Harry, M., Christopher, T., Contreras-Arratia, R., Edwards, S., Graham, O., Johnson, M., Juman, A., Latchman, J. L., Lynch, L., Miller, V. L., Papadopoulos, I., Pascal, K., Robertson, R., Ryan, G. A., Stinton, A., Grandin, R., Hamling, I., Jo, M. J., … Sparks, R. S. J. (2022). Responding to Eruptive Transitions During the 2020–2021 Eruption of La Soufrière Volcano, St. Vincent. *Nature Communications 2022 13:1*, *13*(1), 1–15. https://doi.org/10.1038/s41467-022-31901-4

Julien, J. (2010, December 1). Vital banana crop wiped out. *Trinidad Express Newspapers*. https://web.archive.org/web/20101102145707/http:/www.trinidadexpress.com/news/Vital_banana_crop_wiped_out-106430548.html

Kappes, M. S., Margreth, K., & Thomas, G. (2010). From single- to multi-hazard risk analyses: a concept addressing emerging challenges. *Mountain Risks: Bringing Science to Society (International Conference)*, 351–356. https://boris.unibe.ch/71645/

Kawabata, E., Bebbington, M. S., Cronin, S. J., Wang, T., Kawabata, E., Bebbington, M. S., Cronin, S. J., & Wang, T. (2013). *Modeling thickness variability in tephra deposition*. *75*, 738. https://doi.org/10.1007/s00445-013-0738-x

Kelfoun, K., & Druitt, T. H. (2005). Numerical modeling of the emplacement of Socompa rock avalanche, Chile. *Journal of Geophysical Research: Solid Earth*, *110*(B12). https://doi.org/10.1029/2005JB003758

Kelly, C. (2021). *Saint Vincent Rapid Environment Impact Assessment in Disasters*. https://envirodm.org/wp-content/uploads/2022/03/Saint-Vincent-REA-Assessment.pdf

Khaira, U., & Astitha, M. (2023). Exploring the Real-Time WRF Forecast Skill for Four Tropical Storms, Isaias, Henri, Elsa and Irene, as They Impacted the Northeast United States. *Remote Sensing 2023, Vol. 15, Page 3219*, *15*(13), 3219. https://doi.org/10.3390/RS15133219

Khajwal, A. B., & Noshadravan, A. (2021). An uncertainty-aware framework for reliable disaster damage assessment via crowdsourcing. *International Journal of Disaster Risk Reduction*, *55*, 102110. https://doi.org/10.1016/J.IJDRR.2021.102110

Kostin, V., Belyaev, G., Ovcharenko, O., & Trushkina, E. (2019). Features of some interacting tropical cyclones in the Indian Ocean after the Mount Pinatubo eruption. *International Journal of Engineering Research & Science (IJOER) ISSN*, *5*(9).

Kuenzli, P., Kuenzli, & Pierre. (2021). *HPC Multiscale Modelling and Simulation of Volcanic Tephra Related Processes*. https://doi.org/10.13097/ARCHIVE-OUVERTE/UNIGE:156386

Lagomarsino, S., Cattari, S., Ottonelli, D., & Giovinazzi, S. (2019). Earthquake damage assessment of masonry churches: proposal for rapid and detailed forms and derivation of empirical vulnerability curves. *Bulletin of Earthquake Engineering*, *17*(6), 3327–3364. https://doi.org/10.1007/S10518-018-00542-8/FIGURES/21

Latchman, J. L., & Aspinall, W. (2023). La Soufrière Volcano, St. Vincent, Eruption 2020-2021: Assessing Unrest and Eruptive States from Limited Volcano-Seismic Data. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-223

Laugé, A., Hernantes, J., & Sarriegi, J. M. (2013). *Disaster Impact Assessment: A Holistic Framework*. 730.

Lindsay, J. M., & Robertson, R. E. A. (2018). Integrating volcanic hazard data in a systematic approach to develop volcanic hazard maps in the lesser antilles. *Frontiers in Earth Science*, *6*, 366255. https://doi.org/10.3389/FEART.2018.00042/BIBTEX

Liu, B., Siu, Y. L., & Mitchell, G. (2016). Hazard interaction analysis for multi-hazard risk assessment: A systematic classification based on hazard-forming environment. *Natural Hazards and Earth System Sciences*, *16*(2), 629–642. https://doi.org/10.5194/NHESS-16-629-2016

Liu, H., & Tang, X. (2022). Tongan Volcanic Eruption Intensifies Tropical Cyclone Cody (2022). *Frontiers in Earth Science*, *10*, 904128. https://doi.org/10.3389/FEART.2022.904128/BIBTEX

Liu, M., & Huang, M. C. (2015). Compound Disasters and Compounding Processes: Implications for Disaster Risk Management. *Global Assessment Report on Disaster Risk Reduction*.

Lynch, J. S. (1991). Mount Pinatubo—Explosive Volcanic Eruptions. *Weather and Forecasting*, *6*(4), 576–580. https://doi.org/10.1175/1520-0434(1991)006

Macedonio, G., Costa, A., Scollo, S., & Neri, A. (2016). Effects of eruption source parameter variation and meteorological dataset on tephra fallout hazard assessment: Example from Vesuvius (Italy). *Journal of Applied Volcanology*, *5*(1), 1–19. https://doi.org/10.1186/S13617-016-0045-2/FIGURES/17

Manga, M., Carn, S. A., Cashman, K. V., Clarke, A. B., Connor, C. B., Cooper, K. M., Fischer, T., Houghton, B., Johnson, J. B., Plank, T. A., Roman, D. C., Segall, P., McNutt, S., Whitney, G., Arscott, R. L., Cameron, C., Ewing, R. C., Harden, C. P., Harrison, T. M., … Chappetta, R. M. (2017). Volcanic eruptions and their repose, unrest, precursors, and timing. *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*, 1–122. https://doi.org/10.17226/24650

Martin. (2021, April 12). Soufrière St. Vincent Volcano (St. Vincent Island, West Indies): Heavy ash Fall Covered Entire Island. *Volcano Discovery*. https://www.volcanodiscovery.com/soufriere-st-vincent/news/127131/Soufriere-St-Vincent-volcano-St-Vincent-Island-West-Indies-heavy-ash-fall-covered-entire-island.html

Massaro, S., Stocchi, M., Martínez Montesinos, B., Sandri, L., Selva, J., Sulpizio, R., Giaccio, B., Moscatelli, M., Peronace, E., Nocentini, M., Isaia, R., Titos Luzón, M., Dellino, P., Naso, G., & Costa, A. (2023). Assessing long-term tephra fallout hazard in southern Italy from Neapolitan volcanoes. *Natural Hazards and Earth System Sciences*, *23*(6), 2289–2311. https://doi.org/10.5194/NHESS-23-2289-2023

Matthews, A. J., Barclay, J., & Johnstone, J. E. (2009). The fast response of volcano-seismic activity to intense precipitation: Triggering of primary volcanic activity by rainfall at Soufrière Hills Volcano, Montserrat. *Journal of Volcanology and Geothermal Research*, *184*(3–4), 405–415. https://doi.org/10.1016/J.JVOLGEORES.2009.05.010

McCraine, S., & Surminski, S. (2019). *Understanding decisions and disasters: A retrospective analysis of Hurricane Sandy's "focusing power" on climate change adaptation policy in New York City*. www.cccep.ac.uk

Miller, V. L., Joseph, E. P., Sapkota, N., & Szarzynski, J. (2022). Challenges and Opportunities for Risk Management of Volcanic Hazards in Small-Island Developing States. *Https://Doi.Org/10.1659/MRD-JOURNAL-D-22-00001.1*, *42*(2), D22–D31. https://doi.org/10.1659/MRD-JOURNAL-D-22-00001.1

Murray, R. (2014). *Disaster Risk Reduction Country Profile: Saint Vincent and the Grenadines, 2014*. https://dipecholac.net/docs/files/789-cd-svg.pdf

NASA. (2021). *Tracking La Soufrière's Plume*. Earth Observatory. https://earthobservatory.nasa.gov/images/148190/tracking-la-soufrieres-plume

NEMO. (n.d.). *Vision & Mission*. Retrieved June 18, 2024, from https://nemo.gov.vc/nemo/index.php/about-us/vision-mission

New, M., Reckien, D., Vinier, D., Adler, C., Cheong, S.-M., Conde, C., Constable, A., Coughlan de Perez, E., Lammel, A., Mechler, R., Orlove, B., & Solecki, W. (2022). Decision-Making Options for Managing Risk. In R. Klein & Zi. Zommers (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability* (pp. 2539–2654). Cambridge University Press. https://doi.org/10.1017/9781009325844.026

NOAA. (n.d.-a). *How do hurricanes form?* National Ocean Service Website. Retrieved June 17, 2024, from https://oceanservice.noaa.gov/facts/how-hurricanes-form.html#:~:text=Warm%20ocean%20waters%20and%20thunderstorms,enhancing%20shower%20and%20thunderstorm%20activity

NOAA. (n.d.-b). *Hurricane and Tropical Storm Watches, Warnings, Advisories and Outlooks*. NOAA's National Weather Service.

NOAA. (n.d.-c). Tropical Cyclone Climatology. In *Tropical Cyclone Climatology*. Retrieved June 17, 2024, from https://www.nhc.noaa.gov/climo/

NOAA. (2023a). *Cyclone Hazards & Safety*. https://www.noaa.gov/jetstream/tc-hazards

NOAA. (2023b, January 20). *What is the difference between a hurricane and a typhoon?*

O'Brien, J. S., Julien, P. Y., & Fullerton, W. T. (1993). Two-Dimensional Water Flood and Mudflow Simulation. *Journal of Hydraulic Engineering*, *119*(2), 244–261. https://doi.org/10.1061/(ASCE)0733-9429(1993)119:2(244)

Otker, I., & Srinivasan, K. (2018). *Building Resilience in the Caribbean to Climate Change and Natural Disasters*. IMF Finance and Development. https://www.imf.org/en/Publications/fandd/issues/2018/03/otker

Papathoma-Köhle, M., Schlögl, M., Dosser, L., Roesch, F., Borga, M., Erlicher, M., Keiler, M., & Fuchs, S. (2022). Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. *Journal of Hydrology*, *607*, 127501. https://doi.org/10.1016/J.JHYDROL.2022.127501

PARATUS. (2022, October). *Learning from the past*. PARATUS Project. https://www.paratus-project.eu/about/learning-from-the-past/

Paredes-Mariño, J., Forte, P., Alois, S., Chan, K. L., Cigala, V., Mueller, S. B., Poret, M., Spanu, A., Tomašek, I., Tournigand, P. Y., Perugini, D., & Kueppers, U. (2022). The lifecycle of volcanic ash: advances and ongoing challenges. *Bulletin of Volcanology 2022 84:5*, *84*(5), 1–12. https://doi.org/10.1007/S00445-022-01557-5

Pasch, R. J., & Zelinsky, D. A. (2016, March 8). Tropical Cyclone Track Prediction. *2016 RA-IV Workshop on Hurricane Forecasting and Warning.*

Patra, A., Bevilacqua, A., Akhavan-Safaei, A., Pitman, E. B., Bursik, M., & Hyman, D. (2020). Comparative Analysis of the Structures and Outcomes of Geophysical Flow Models and Modeling Assumptions Using Uncertainty Quantification. *Frontiers in Earth Science*, *8*, 508015. https://doi.org/10.3389/FEART.2020.00275/BIBTEX

Pattantyus, A., & Businger, S. (2014). On the interaction of Tropical Cyclone Flossie and emissions from Hawaii's Kilauea volcano. *Geophysical Research Letters*, *41*(11), 4082–4089. https://doi.org/10.1002/2014GL060033

Penta, F., Croce, A., & Esu, F. (1961). Engineering Properties of Volcanic Soils. *International Society for Soil Mechanics and Geotechnical Engineering.* https://www.issmge.org/publications/online-library

Phillips, J., Barclay, J., Cole, P., Johnson, M., Miller, V., & Robertson, R. (2023). Impacts and prospective hazard analysis of rainfall-triggered lahars on St. Vincent 2021–2022. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-313

Pinatubo Volcano Observatory Team. (1991). Lessons from a major eruption: Mt. Pinatubo, Philippines. *Eos, Transactions American Geophysical Union*, *72*(49), 545–555. https://doi.org/10.1029/90EO00386

Pittore, M., Zebisch, M., Cocuccioni, S., Schneiderbauer, S., & Renner, K. (2023). *Impact Chains: Towards a shared standard for multi-hazard event conceptualization* (1).

Popp, A. (2006). The Effects of Natural Disasters on Long Run Growth. *Major Themes in Economics*, *8*, 61–82. https://scholarworks.uni.edu/mtieAvailableat:https://scholarworks.uni.edu/mtie/vol8/iss1/7

Poret, M., Costa, A., Folch, A., & Martí, A. (2017). Modelling Tephra Dispersal and Ash Aggregation: The 26th April 1979 Eruption, La Soufrière St. Vincent. *Journal of Volcanology and Geothermal Research*, *347*, 207–220. https://doi.org/10.1016/J.JVOLGEORES.2017.09.012

Porter, K. (2021). A Beginner's Guide to Fragility, Vulnerability, and Risk. *Encyclopedia of Earthquake Engineering*, 1–29. https://doi.org/10.1007/978-3-642-36197-5_256-1

Prata, A. T., Mingari, L., Folch, A., Macedonio, G., & Costa, A. (2021). FALL3D-8.0: A computational model for atmospheric transport and deposition of particles, aerosols and radionuclides - Part 2: Model validation. *Geoscientific Model Development*, *14*(1), 409–436. https://doi.org/10.5194/GMD-14-409-2021

Pudasaini, S. P. (2012). A general two-phase debris flow model. *Journal of Geophysical Research: Earth Surface*, *117*(F3), 3010. https://doi.org/10.1029/2011JF002186

Pyle, D. (2014, January 20). *A volcanic retrospective: eruptions of the Soufrière, St Vincent*. VolcanicDegassing. https://blogs.egu.eu/network/volcanicdegassing/2014/01/20/a-volcanic-retrospective-eruptions-of-the-soufriere-st-vincent/

Pyle, D. M., Barclay, J., & Armijos, M. T. (2018). The 1902–3 eruptions of the Soufrière, St Vincent: Impacts, relief and response. *Journal of Volcanology and Geothermal Research*, *356*, 183–199. https://doi.org/10.1016/J.JVOLGEORES.2018.03.005

Robertson, R. E. A., Barclay, J., Joseph, E. P., & Sparks, R. S. J. (2023). An overview of the eruption of La Soufriere Volcano, St. Vincent 2020 to 2021. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2023-95

Robock, A. (2000). VOLCANIC ERUPTIONS AND CLIMATE. *Reviews of Geophysics.*

Rogers, R. F. (2021). Recent Advances in Our Understanding of Tropical Cyclone Intensity Change Processes from Airborne Observations. *Atmosphere 2021, Vol. 12, Page 650*, *12*(5), 650. https://doi.org/10.3390/ATMOS12050650

Romagnoli, F., Calderon, L. J. O., Cocuccioni, S., Pittore, M., Schneiderbauer, S., Atun, F., & Westen, C. van. (2024). *ENHANCING DISASTER RISK ANALYSIS THROUGH THE INTEGRATION OF FORENSIC ANALYSIS AND IMPACT CHAINS: A CASE STUDY OF THE LA SOUFRIERE VOLCANIC ERUPTION.*

Rutledge, K., McDaniel, M., Teng, S., Hall, H., Ramroop, T., Sprout, E., Hunt, J., Boudreau, D., & Costa, H. (2023). Storm Surge. In J. Evers & K. West (Eds.), *National Hurricane Center.* National Geographic Socirty. https://education.nationalgeographic.org/resource/storm-surge/

Scarth, A. (2002). La catastrophe : the eruption of Mount Pelee, the worst volcanic eruption of the twentieth century. *Oxford University Press*, 246. https://archive.org/details/lacatastropheeru00scar/mode/1up

Schilling, S. P. (1998). LAHARZ; GIS programs for automated mapping of lahar-inundation hazard zones. *Open-File Report.* https://doi.org/10.3133/OFR98638

Schweikert, A., L'her, G., Nield, L., Kerber, S., Flanagan, R., & Deinert, M. (2020). *Resilience in the Caribbean: Natural Hazards Exposure Assessment and Areas for Future Work.*

Scott, M. (2022). *Future Tourism: Rethinking Tourism and MSMEs in times of COVID-19*.
Searchlight. (2021, July 2). Private homes, public infrastructure sustain damage during passage of Hurricane Elsa. *Press Release*. https://www.searchlight.vc/press-release/2021/07/02/private-homes-public-infrastructure-sustain-damage-during-passage-of-hurricane-elsa/
Self, S., Zhao, J.-X., Holasek, R. E., Torres, R. C., & King, A. J. (1993). *The Atmospheric Impact of the 1991 Mount Pinatubo Eruption*.
Shan, S., Zhao, F., Wei, Y., & Liu, M. (2019). Disaster management 2.0: A real-time disaster damage assessment model based on mobile social media data—A case study of Weibo (Chinese Twitter). *Safety Science*, *115*, 393–413. https://doi.org/10.1016/J.SSCI.2019.02.029
Shenfeld, E. (2021). *The World Bank Saint Vincent and the Grenadines Volcanic Eruption Emergency Project (P176943)*. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/869591632427152037/project-information-document-saint-vincent-and-the-grenadines-volcanic-eruption-emergency-project-p176943
Shepherd, J. B., Aspinall, W. P., Rowley, K. C., Pereira, J., Sigurdsson, H., Fiske, R. S., & Tomblin, J. F. (1979). The eruption of Soufrière volcano, St Vincent April–June 1979. *Nature 1979 282:5734*, *282*(5734), 24–28. https://doi.org/10.1038/282024a0
Shepherd, J. B., & Sigurdsson, H. (1982). Mechanism of the 1979 explosive eruption of soufriere volcano, St. Vincent. *Journal of Volcanology and Geothermal Research*, *13*(1–2), 119–130. https://doi.org/10.1016/0377-0273(82)90023-3
Silva, D. Da. (n.d.). *Hurricane Elsa – not nice at all*. The Vincentian. Retrieved June 18, 2024, from https://thevincentian.com/hurricane-elsa-h-not-nice-at-all-p22243-133.htm
Smith, S. D. (2011). Volcanic hazard in a slave society: the 1812 eruption of Mount Soufrière in St Vincent. *Journal of Historical Geography*, *37*(1), 55–67. https://doi.org/10.1016/J.JHG.2010.06.004
Sparks, S. R. J., Aspinall, W. P., Barclay, J., Renfrew, I. A., Contreras-Arratia, R., & Stewart, R. (2023). Analysis of magma flux and eruption intensity during the 2021 explosive activity at La Soufrière, St Vincent, West Indies. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-286
Stewart. (2010). *Hurricane TOMAS*. https://www.nhc.noaa.gov/archive/2010/al21/al212010.discus.005.shtml?
Stinton, A. J. (2023). Growth and evolution of the lava dome and coulée during the 2020–21 eruption of La Soufrière, St Vincent. *Geological Society, London, Special Publications*, *539*(1). https://doi.org/10.1144/SP539-2022-304
Stinton, A., Sparks, R. S. J., & Huppert, H. E. (2023). Analysis of magma rheology from lava spreading and explosive activity during the 2020–21 eruption of La Soufrière, St Vincent, with implications for eruption dynamics. *Geological Society, London, Special Publications*, *539*(1), 539. https://doi.org/10.1144/SP539-2022-284
Streva Project. (2014, November 18). *1979 Eruption - Response and Recovery - La Soufrière Volcano St Vincent [Youtube]*. https://www.youtube.com/watch?v=kmqjY0Qf-Xc
Sun, J., Cai, M., Liu, G., Yan, R., & Zhang, D. L. (2022). Uncovering the Intrinsic Intensity–Size Relationship of Tropical Cyclones. *Journal of the Atmospheric Sciences*, *79*(11), 2881–2900. https://doi.org/10.1175/JAS-D-22-0082.1
Swindles, G. T., Watson, E. J., Savov, I. P., Lawson, I. T., Schmidt, A., Hooper, A., Cooper, C. L., Connor, C. B., Gloor, M., & Carrivick, J. L. (2018). Climatic control on Icelandic volcanic activity during the mid-Holocene. *Geology*, *46*(1), 47–50. https://doi.org/10.1130/G39633.1
Taylor, I. A., Grainger, R. G., Prata, A. T., Proud, S. R., Mather, T. A., & Pyle, D. M. (2022). *Satellite measurements of plumes from the 2021 eruption of La Soufrière, St Vincent*. https://doi.org/10.5194/acp-2022-772
The Miami Herald. (1979, April 14). St. Vincent volcano erupts; Villages ordered evacuated (1979). *Newspapers.Com*. https://www.newspapers.com/article/the-miami-herald-st-vincent-volcano-eru/75775244/
Thompson, J. O., Contreras-Arratia, R., Befus, K. S., & Ramsey, M. S. (2022). Thermal and seismic precursors to the explosive eruption at La Soufrière Volcano, St. Vincent in April 2021. *Earth and Planetary Science Letters*, *592*, 117621. https://doi.org/10.1016/J.EPSL.2022.117621
Thouret, J. C., Antoine, S., Magill, C., & Ollier, C. (2020). Lahars and debris flows: Characteristics and impacts. *Earth-Science Reviews*, *201*, 103003. https://doi.org/10.1016/J.EARSCIREV.2019.103003
Tilloy, A., Malamud, B. D., Winter, H., & Joly-Laugel, A. (2019). A review of quantification methodologies for multi-hazard interrelationships. *Earth-Science Reviews*, *196*, 102881. https://doi.org/10.1016/J.EARSCIREV.2019.102881
Tsuji, T., Nishizaka, N., & Ohnishi, K. (2020). Influence of particle aggregation on the tephra dispersal and sedimentation from the October 8, 2016, eruption of Aso volcano. *Earth, Planets and Space*, *72*(1), 1–19. https://doi.org/10.1186/S40623-020-01233-Y/FIGURES/12
UNDP. (2020). National Adaptation Plans in focus: lessons from St Vincent and the Grenadines. In *UNDP Climate Change Adaptation*. https://adaptation-undp.org/explore/latin-america-and-caribbean/saint-vincent-and-grenadines

UNDRR. (n.d.-a). *Disaster*. United Nations Office for Disaster Risk Reduction. Retrieved June 18, 2024, from https://www.undrr.org/terminology/disaster
UNDRR. (n.d.-b). *Hazard*. Sendai Framework Terminology on Disaster Risk Reduction. Retrieved July 7, 2023, from https://www.undrr.org/terminology/hazard
UNDRR. (2020). *Hazard Definition & Classification Review - Technical Report*. https://www.undrr.org/media/47681/download?startDownload=true
UNDRR, & OCHA. (2023). *Overview of Disasters in Latin America and the Caribbean 2000-2022*. https://www.undrr.org/media/89900/download?startDownload=true
UNFCCC. (2017). *Report of the Executive Committee of the Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts*. https://unfccc.int/sites/default/files/resource/docs/2017/sb/eng/01a01e.pdf
USGS. (n.d.). *Volcanic Ash, Gases & Fog*. Impacts & Mitigation. Retrieved June 18, 2024, from https://volcanoes.usgs.gov/volcanic_ash/density_hardness.html
USGS. (2016). *Impacts & Mitigation - Ash Particle Size*. https://volcanoes.usgs.gov/volcanic_ash/ash_particle_size.html
UWI Seismic Research Centre. (n.d.-a). *Caribbean Volcanoes*. Retrieved November 14, 2023, from https://uwiseismic.com/volcanoes/caribbean-volcanoes/
UWI Seismic Research Centre. (n.d.-b). *History*. Retrieved June 18, 2024, from https://uwiseismic.com/about-us/history/
UWI Seismic Research Centre. (n.d.-c). *La Soufrière Eruption 2020-2021*. Retrieved June 18, 2024, from https://uwiseismic.com/volcanoes/la-soufriere-eruption-2020-2021-hub/
UWI Seismic Research Centre. (2021). *The 1979 La Soufrière Eruption [Youtube]*. https://www.youtube.com/watch?v=zSWLadLU28c
Valles, C., Marin Ferrer, A., & Poljanšek, M. (2020). *Science for Disaster Risk Management 2020: Acting Today, Protecting Tomorrow*. https://doi.org/10.2760/571085
Veeramany, A., Unwin, S. D., Coles, G. A., Dagle, J. E., Millard, W. D., Yao, J., Glantz, C. S., & Gourisetti, S. (2015). *Framework for Modeling High-Impact, Low-Frequency Power Grid Events to Support Risk-Informed Decisions*.
Velásquez, C. A., Cardona, O. D., Carreño, M. L., & Barbat, A. H. (2014). Retrospective assessment of risk from natural hazards. *International Journal of Disaster Risk Reduction*, *10*(PB), 477–489. https://doi.org/10.1016/J.IJDRR.2014.05.005
Villalta, D. E., Bravo De Guenni, L. I., Sajo-Castelli, A. M., & Campos, J. M. (2014, June). *Risk Analysis to Extreme Rainfall: A retrospective approach*.
Villamar, K. (2010, June 17). IOM and Partners Provide Emergency Assistance to Victims of Tropical Storm Agatha and Eruption of Pacaya Volcano. *International Organization for Migration*. https://www.iom.int/news/iom-and-partners-provide-emergency-assistance-victims-tropical-storm-agatha-and-eruption-pacaya-volcano
Villeneuve, M., & Heap, M. J. (2021). Calculating the cohesion and internal friction angle of volcanic rocks and rock masses. *Volcanica*, *4*(2), 279–293. https://doi.org/10.30909/VOL.04.02.279293
Vogel, A., Diplas, S., Durant, A. J., Azar, A. S., Sunding, M. F., Rose, W. I., Sytchkova, A., Bonadonna, C., Krüger, K., & Stohl, A. (2017). Reference data set of volcanic ash physicochemical and optical properties. *Journal of Geophysical Research: Atmospheres*, *122*(17), 9485–9514. https://doi.org/10.1002/2016JD026328
Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Johnston, D. M. (2012). Investigating the electrical conductivity of volcanic ash and its effect on HV power systems. *Physics and Chemistry of the Earth*, *45–46*, 128–145. https://doi.org/10.1016/J.PCE.2011.09.003
Weber, G., Blundy, J., Barclay, J., Pyle, D. M., Cole, P., Frey, H., Manon, M., Davies, B. V., & Cashman, K. (2024). Petrology of the 2020–21 effusive to explosive eruption of La Soufrière Volcano, St Vincent: insights into plumbing system architecture and magma assembly mechanism. *Geological Society Special Publication*, *539*(1), 171–200. https://doi.org/10.1144/SP539-2022-177/ASSET/1D31EE9C-673C-433D-B2AB-947A13BB230B/ASSETS/IMAGES/LARGE/SP2022-177F16.JPG
Westen, C. van. (2016). *Historical Disaster - Saint Vincent & the Grenadines*. CDEMA. https://www.cdema.org/virtuallibrary/index.php/charim-hbook/country-data/countrydocs-svg/saint-vincent-historical-disasters
Westen, C. J. van, & Greiving, S. (2017). Multi-hazard risk assessment and decision making. *Environmental Hazards Methodologies for Risk Assessment and Management*, 31–94. https://doi.org/10.2166/9781780407135_0031
World Meteorological Organization. (2023, September 20). *Tropical cyclones and their related hazards*. Fact Sheet. https://wmo.int/content/tropical-cyclones-and-their-related-hazards
Wu, S., Li, J., & Huang, G. H. (2008). A study on DEM-derived primary topographic attributes for hydrologic applications: Sensitivity to elevation data resolution. *Applied Geography*, *28*(3), 210–223. https://doi.org/10.1016/J.APGEOG.2008.02.006

Wurman, J., & Kosiba, K. (2018). Major Hurricane Harvey - August 25-29, 2017. *Monthly Weather Review*, *146*(3), 713–722. https://doi.org/10.1175/MWR-D-17-0327.1

Yamazaki, F., & Matsuoka, M. (2012). REMOTE SENSING TECHNOLOGIES IN POST-DISASTER DAMAGE ASSESSMENT. *Https://Doi.Org/10.1142/S1793431107000122*, *01*(03), 193–210. https://doi.org/10.1142/S1793431107000122

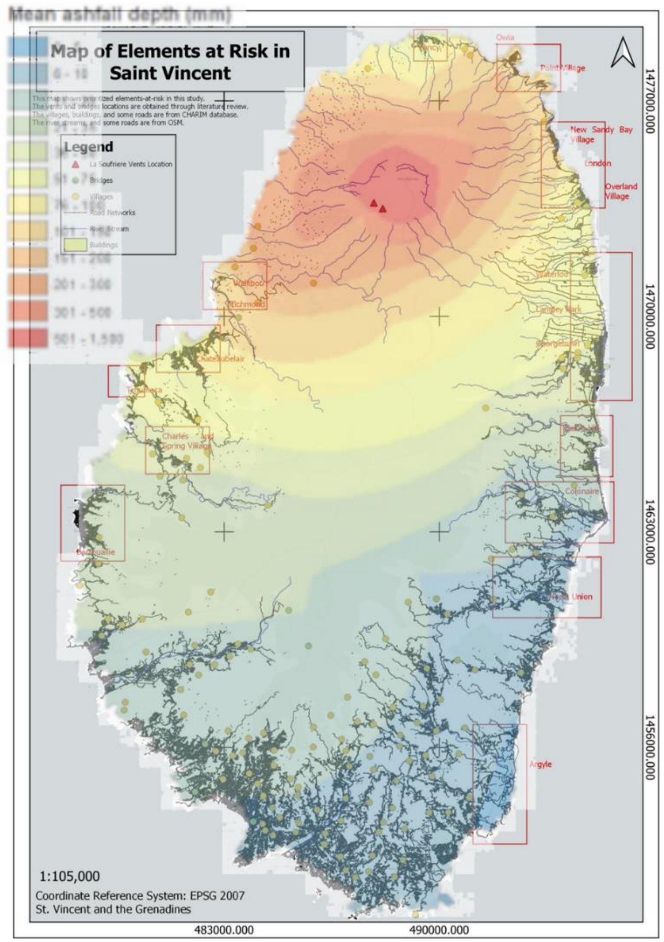
Zebisch, M., Terzi, S., Pittore, M., Renner, K., & Schneiderbauer, S. (2022). Climate Impact Chains—A Conceptual Modelling Approach for Climate Risk Assessment in the Context of Adaptation Planning. *Springer Climate*, 217–224. https://doi.org/10.1007/978-3-030-86211-4_25/FIGURES/4

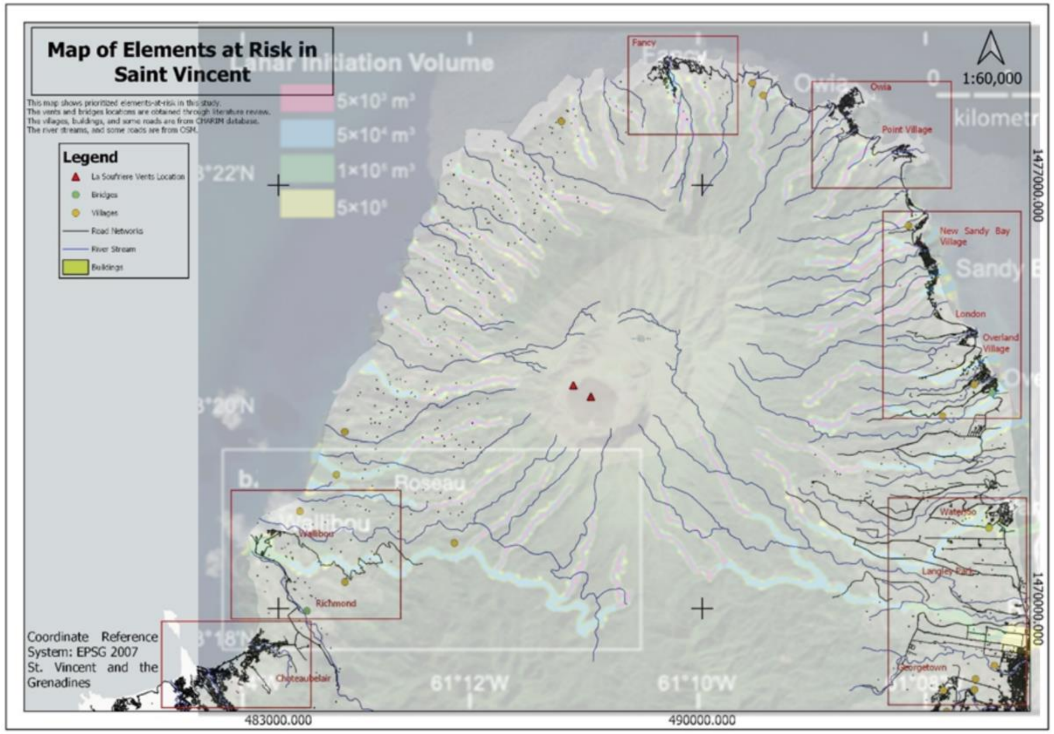
Zscheischler, J. ;, Westra, S. ;, Van Den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A. ;, Aghakouchak, A. ;, Bresch, D. N., Leonard, M. ;, Wahl, T. ;, & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3

ANNEX

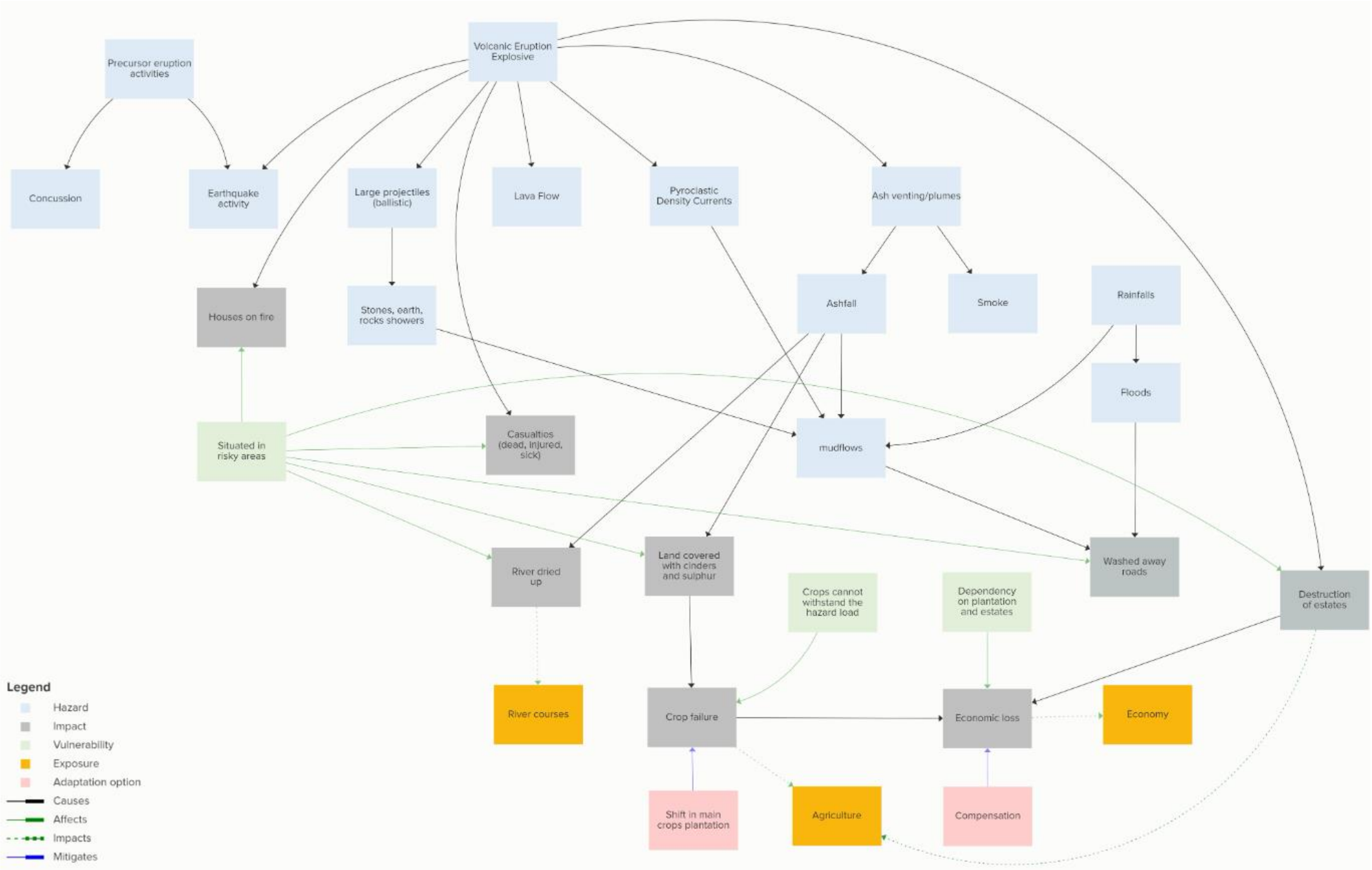
1. Maps for fieldwork preparation.

   Ash thickness map (left) and lahar map (right) overlaid with elements-at-risk components.

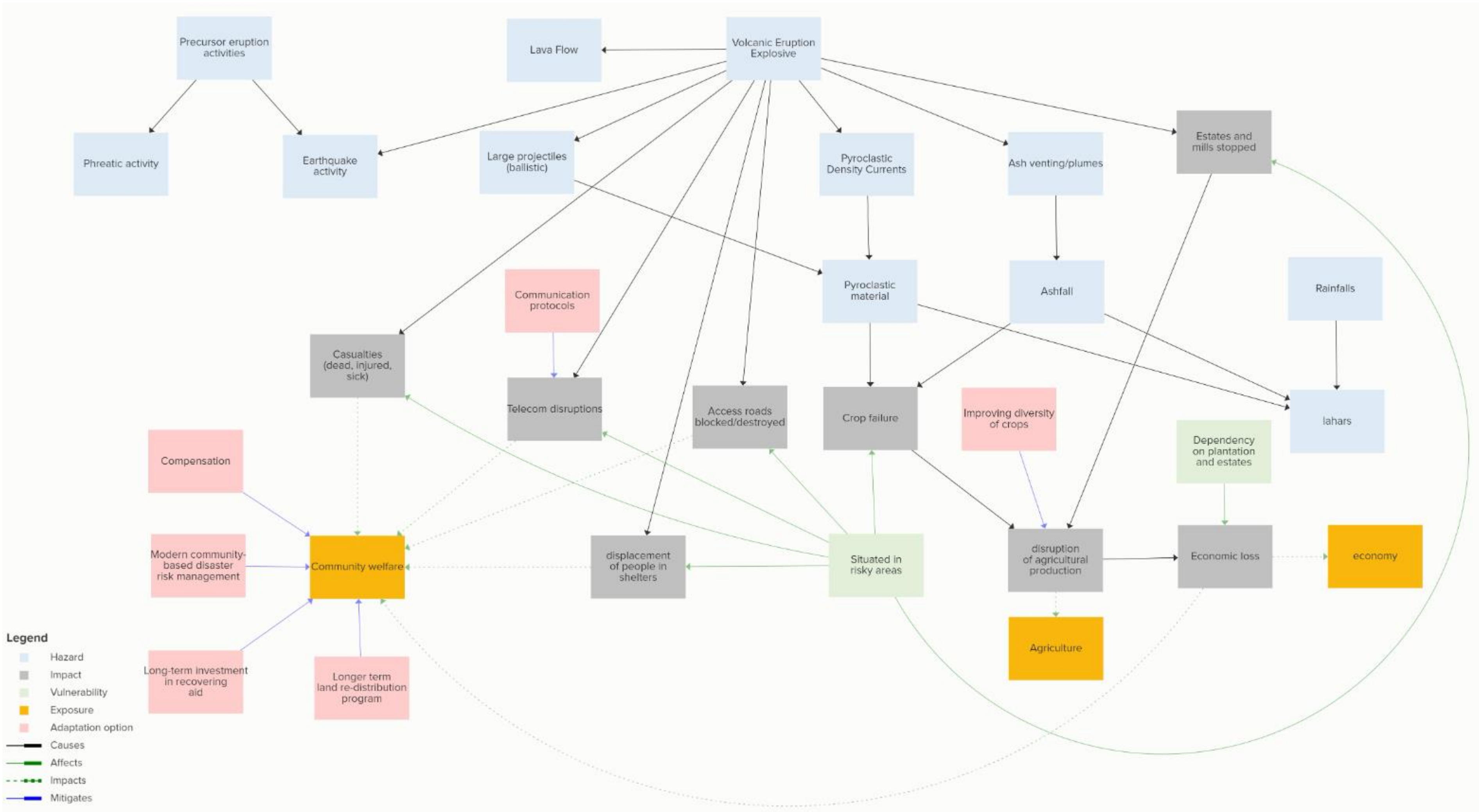




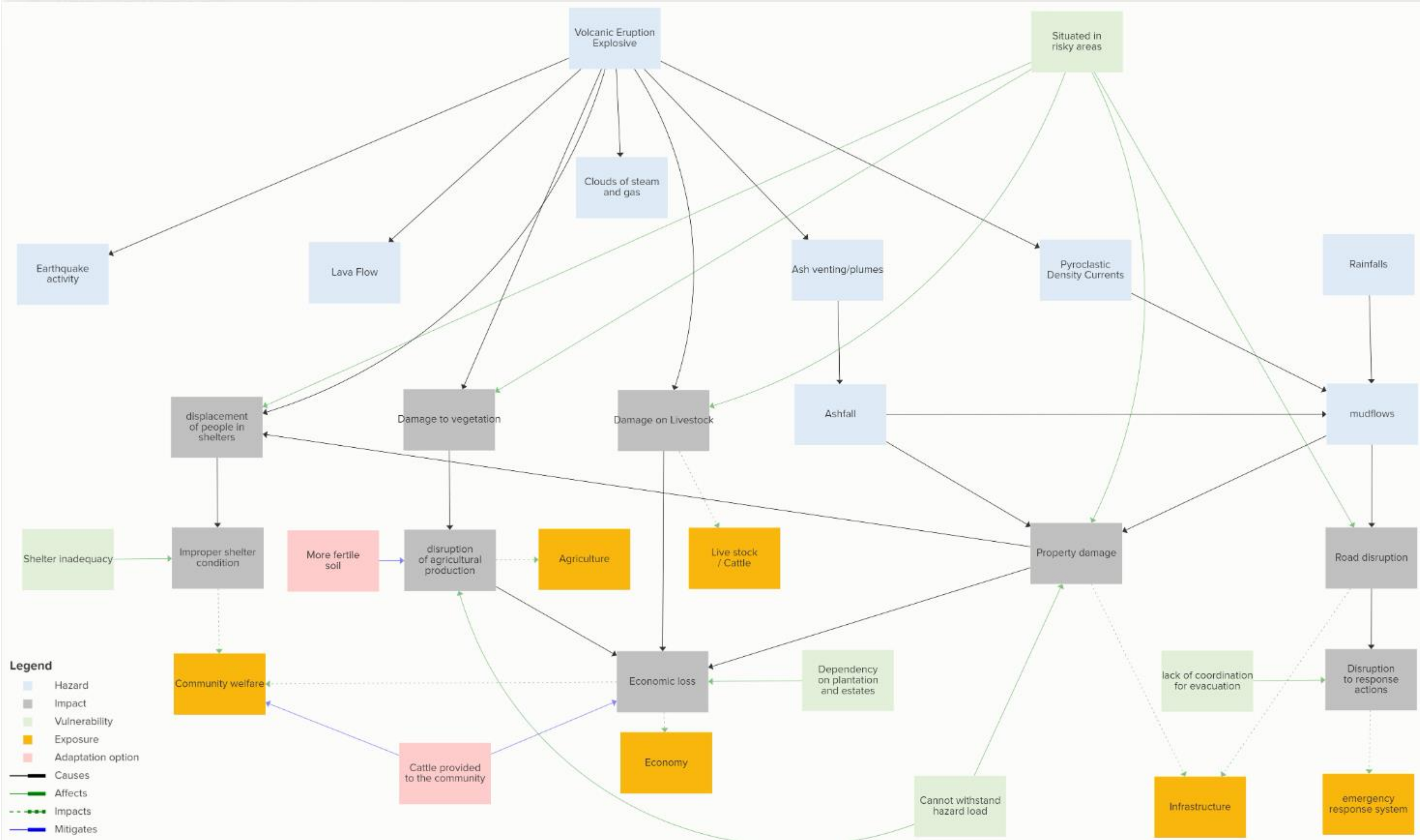
2. 2Impact chain of the 1812 eruption



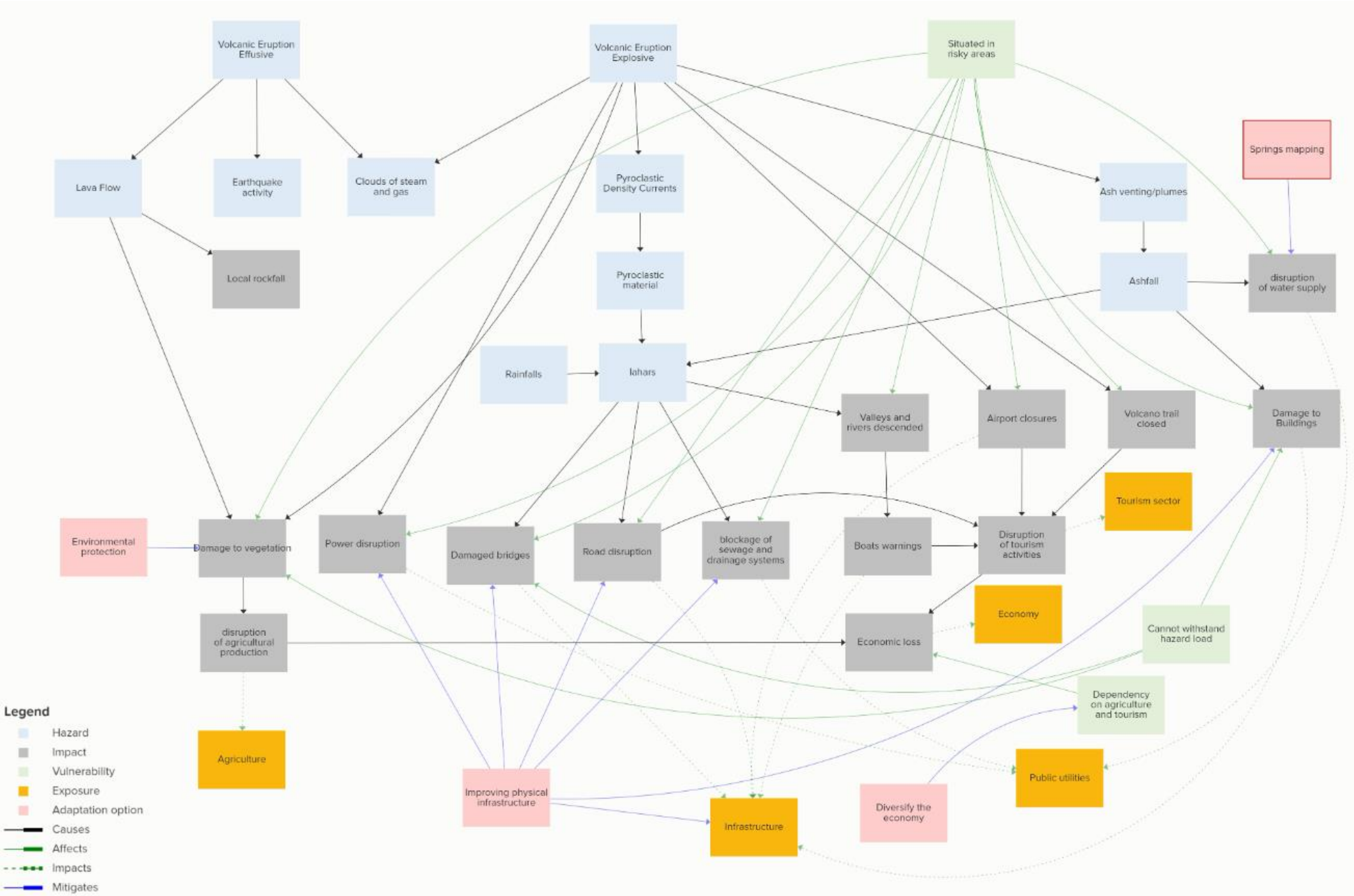
3. Impact chain of the 1902-03 eruption.



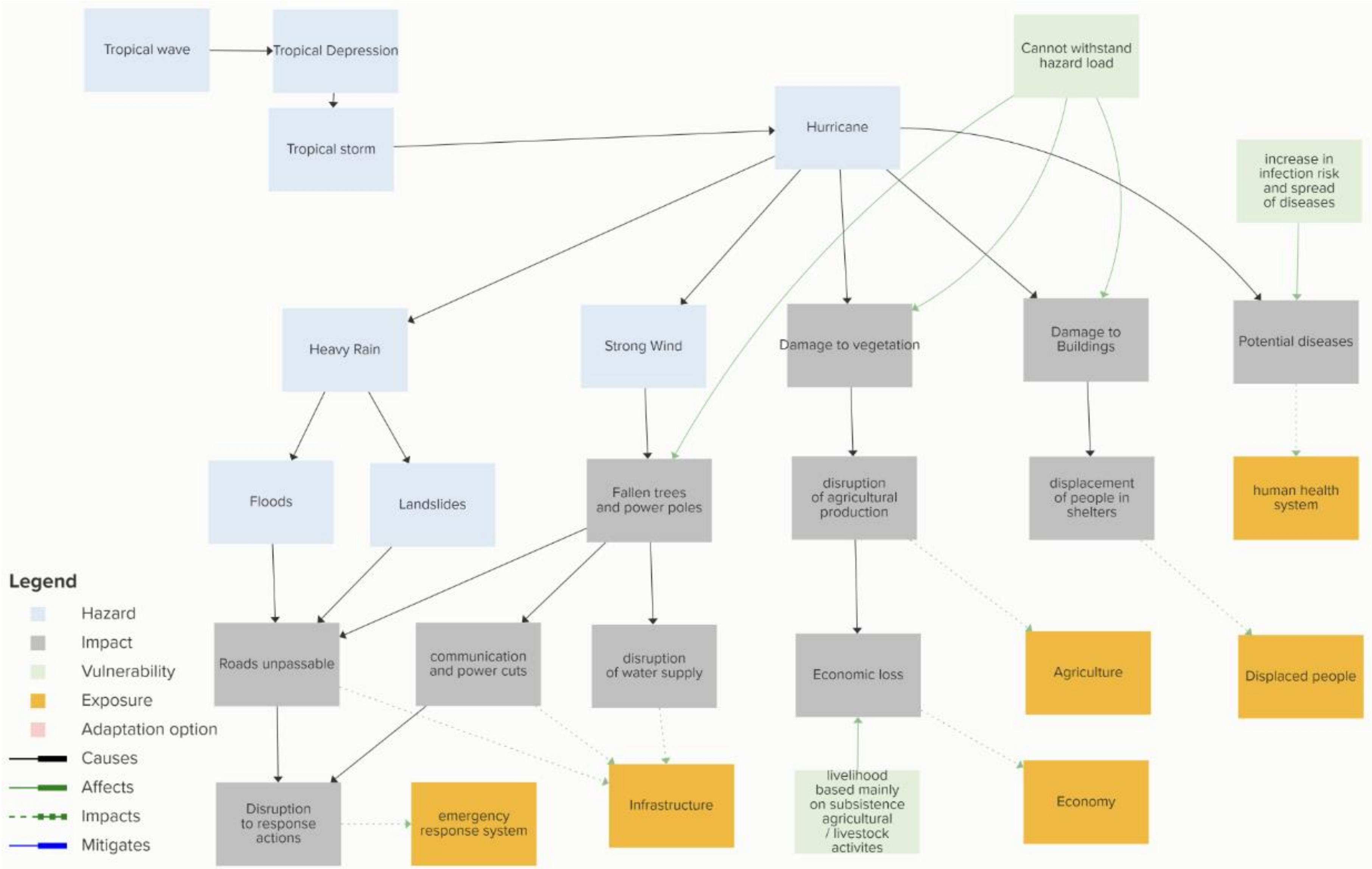
4. Impact chain of the 1979 eruption.



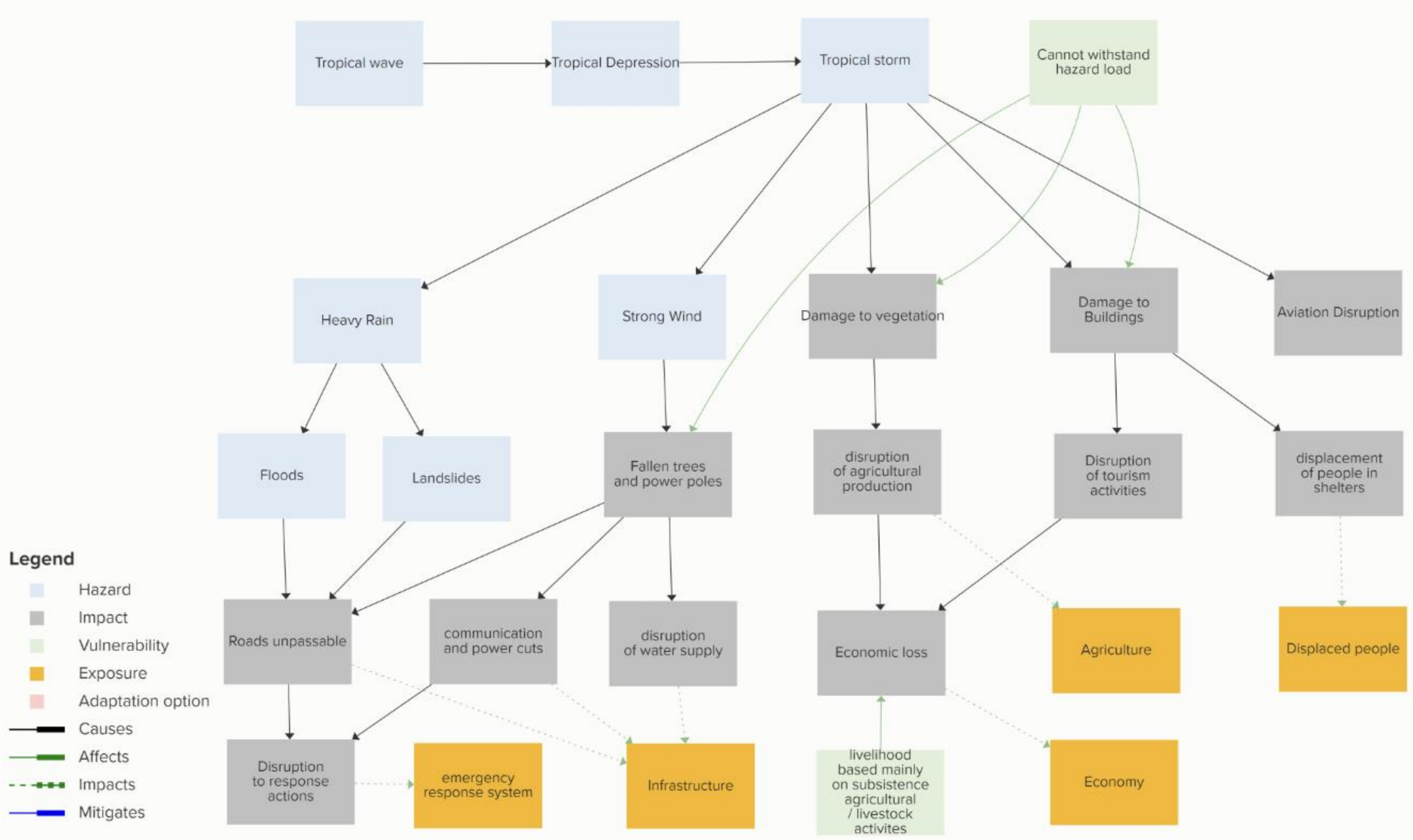
5. Impact chain of the 2021 eruption.



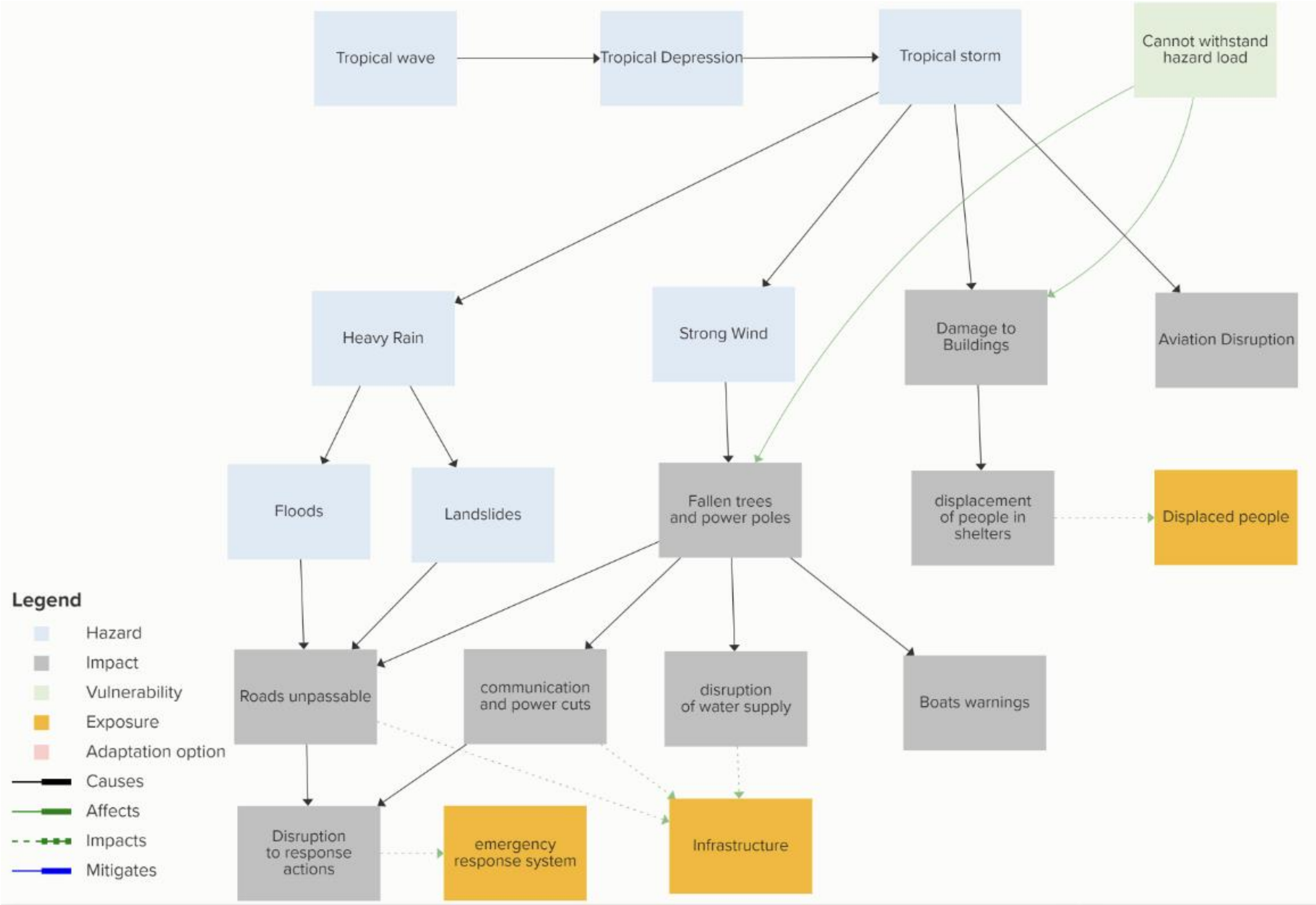
6. Impact chain of Hurricane Tomas in 2010.



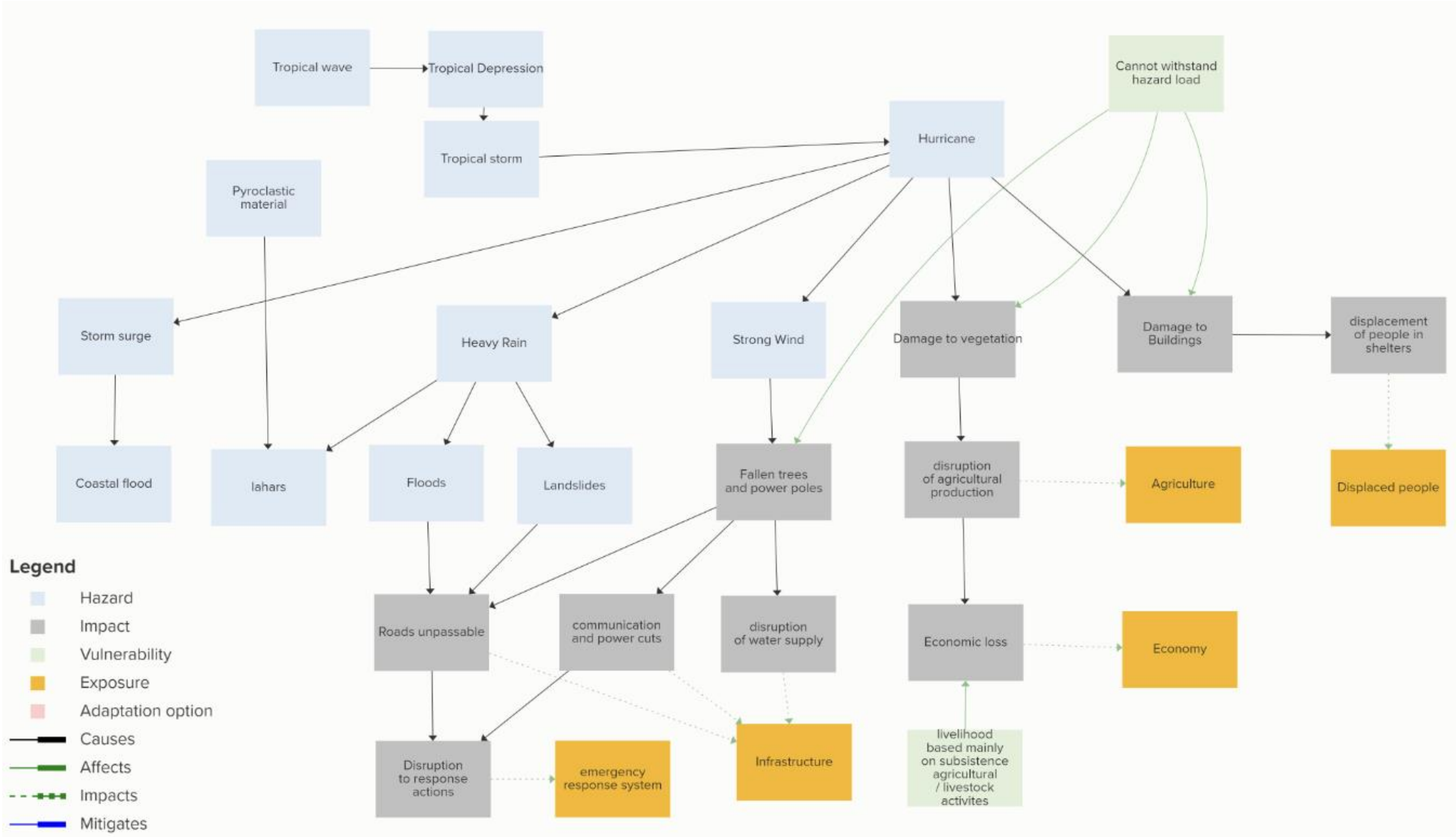
7. Impact chain of Tropical Storm Matthew in 2016.



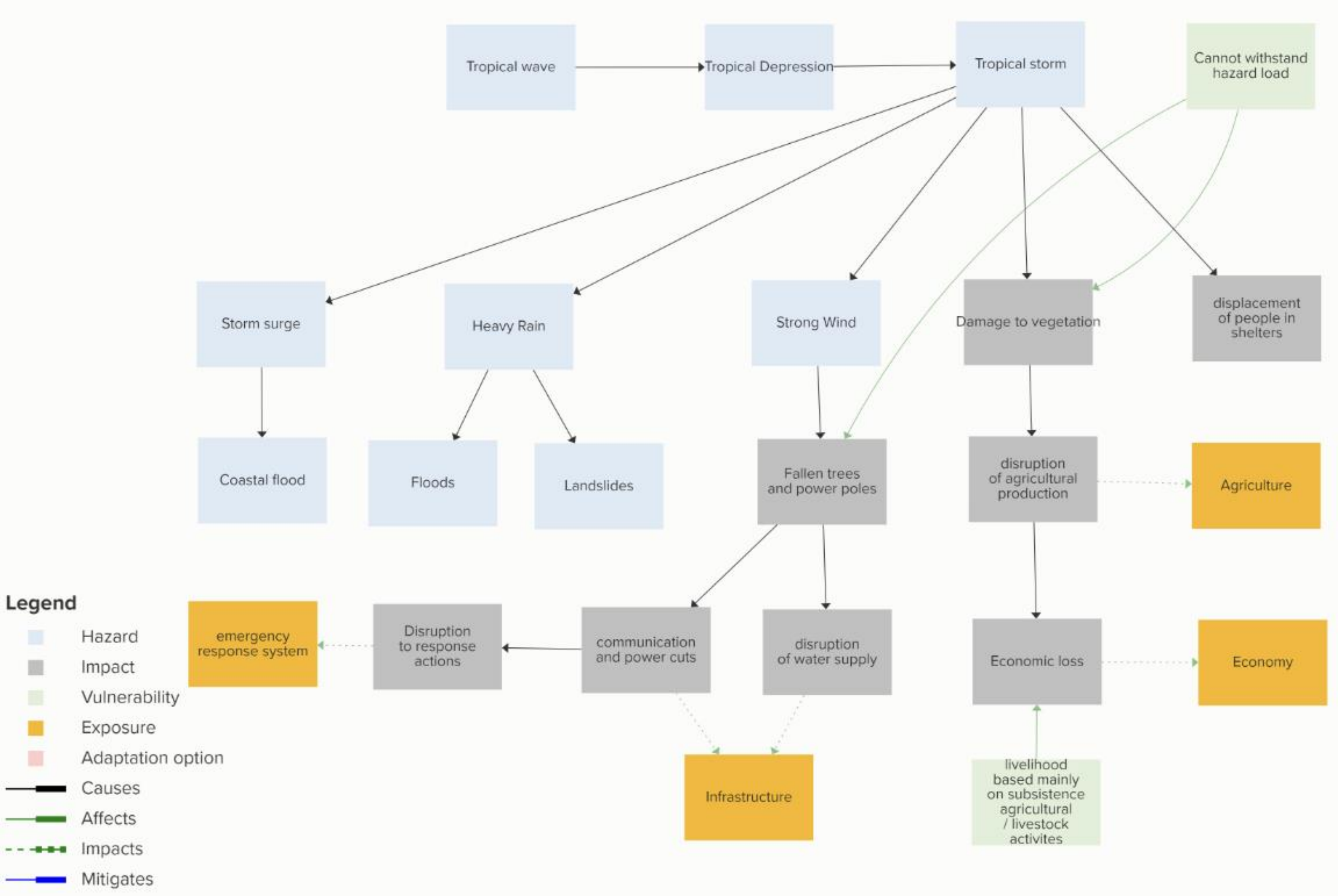
8. Impact chain of Tropical Storm Harvey in 2017.



9. Impact chain of Hurricane Elsa in 2021.



10. Impact chain of Tropical Storm Bret in 2023.



11. Vulnerability assessment for roof materials (Jenkins et al., 2014).

Roof class	Description	Collapse load (kPa)	
		Interdecile range	Mean
A_{AF}:	Weak timber boards on timber rafters/trusses; Metal sheet roofs on timber rafters/trusses, in old or poor condition; Tiles on timber rafters/trusses, of old or poor condition; Vaulted masonry	1.3 to 2.6	1.8
B_{AF}:	Long span roofs with metal sheet or fibre reinforced concrete sheets.	1.4 to 3.1	2.0
C_{AF}:	Metal sheet roofs on timber rafters/trusses, in average condition; Tiles on timber rafters/trusses, in average or good condition	1.5 to 5.3	2.8
D_{AF}:	Metal sheet roofs on timber rafters/trusses, in good condition; Strong timber on timber rafters/trusses in average or good condition	2.1 to 7.6	4.0
E_{AF}:	Flat reinforced concrete roof designed for access and generally in good condition	4.8 to 10.3	7.0