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Challenges and Opportunities for Risk Management of Volcanic Hazards in Small-Island Developing States

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The explosive volcanic eruptions of La Soufrière volcano, St Vincent and the Grenadines, in April 2021 caused the displacement of thousands of people, resulting in heavy disruption of livelihoods and economic activities, destruction of critical infrastructure, and volcanic ash deposits that affected the entire mountainous island of St Vincent and the neighboring island of Barbados. The resulting triple crisis in the region included volcanological risks, the prevailing COVID-19 pandemic, and hydrometeorological risks due to the approaching hurricane season. This article analyzes the scientific and operational activities that The University of the West Indies Seismic Research Centre undertook after effusive activity was detected in December 2020, as well as the actions taken during an official response mission of the United Nations, led by the Joint Environment Unit of the United Nations Environment Programme and the United Nations Office for the Coordination of Humanitarian Affairs in Geneva and upon request for international environmental assistance from the Government of St Vincent. It examines the interplay and collaboration between these 2 organizations and other disaster risk reduction agencies. The article also highlights how the interconnected, systemic nature of risks and disasters emphasizes the ultimate need for regional coordination and collaboration across sectors, including scientific monitoring networks; national, regional, and international emergency preparedness and response agencies; academia; and the private sector. The presented case study for elucidating the ongoing lahar hazard at La Soufrière volcano supports a long-term view for planning and mitigation in this challenging topography. This will help to ensure that the volcanic risks in the Caribbean region are appropriately considered a major component of the multihazard approach undertaken by national authorities and scientists to manage community safety and sustainable economic development through adequate means of disaster risk reduction and emergency preparedness.

Keywords: *volcanic hazards; La Soufrière; small-island developing states; humanitarian; multihazard; lahar; land use planning; risk sensitive.*

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Introduction

Risk management and mitigation is always a challenging task in complex environments, such as mountainous regions, where steep gradients in topography, microclimates, and remoteness introduce additional accessibility obstacles (Wymann von Dach et al 2017). This is compounded in island settings, where geographical isolation and limited land can necessitate wide-spanning mitigation and response activities. Residential space is often limited, and most locations are subject to multiple natural hazards (Zimmermann and Keiler 2015).This may call for competing mitigation strategies and/or introduce a bias to the most frequently occurring natural hazard such that there may only be minimal preparedness for other hazards.

Volcanic hazards are one component of this complex mountain hazardscape (Thouret 2014). Although a given volcano can often be viewed as a natural resource because of its association with rich agricultural soils, clean water sources, and abundant source of construction aggregate, it can often be underestimated as a hazard, especially when the volcano erupts infrequently (Loughlin et al 2015). The focus of volcanic hazard management is on volcano monitoring, which is critical for providing advice to guide short- to medium-term planning. However, long-term mitigation of the impacts of volcanic eruptions is essential for achieving sustainable development that is risk sensitive and harnesses the opportunity to create more resilient populations following a natural hazard event (ie building back better). This requires the development of a long-term preparedness

BOX 1: Defining the scientific and operational response entities

UWI-SRC is the scientific agency responsible for monitoring earthquakes and volcanoes in the anglophone islands of the Eastern Caribbean. UWI-SRC began operations in 1953 to monitor and understand volcanic activity in the Lesser Antilles. Its mandate was subsequently extended to include tectonic earthquakes and to undertake operational monitoring in nonvolcanic islands, including Trinidad and Tobago, where it is based. In addition to operating the largest monitoring network in the Caribbean, UWI-SRC is responsible for enhancing disaster preparedness related to seismic and volcanic hazards in the region. UWI-SRC plays an active role in promoting geologic hazard awareness and shares real-time seismic data with the Pacific Tsunami Warning Centre, which provides tsunami warning services for the Caribbean and adjacent areas. UWI-SRC works closely with national disaster preparedness coordinators (or the equivalent), through whom it reports to respective contributing governments. To provide advice and warnings, UWI-SRC maintains a permanent seismic network and continuous and campaign-style GPS networks. It monitors changes in the composition of hydrothermal fluids through direct sampling of hot springs and fumaroles and in situ gas measurements. In addition, UWI-SRC is involved in fundamental research in seismology, volcanology, and education and outreach. The support to authorities throughout the Caribbean includes providing advice on geophysical hazards in the region, assisting with volcano contingency planning, and promoting awareness of geophysical hazards to create better prepared communities.

GLOMOS is a collaborative program and scientific alliance between the UN University Institute for Environment and Human Security and Eurac Research based in Bolzano, Italy. GLOMOS represents an interface between the international mountain research community and the UN system. GLOMOS conducts applied and transdisciplinary research to support livelihoods and sustainable mountain development and facilitates a greater recognition of mountain-related topics within international frameworks and the 2030 Agenda for Sustainable Development. The goals of GLOMOS are to contribute to the development of resilient mountain communities toward natural and anthropogenic hazards and disaster risks, protect the wealth of biological and cultural diversity, and support adaptive solutions and sustainable transformation processes within these highly sensitive social–ecological systems.

The JEU assists member states in preparing for and responding to environmental emergencies by coordinating international efforts and mobilizing partners to aid affected countries that request assistance. By pairing the environmental expertise of the UN and the humanitarian response network coordinated by the UN OCHA, the JEU ensures an integrated response to environmental emergencies. The Environmental Emergencies Centre (www.eecentre.org) is an online tool designed to build the capacity of national responders to environmental emergencies. EHA Connect (www.ehaconnect.org) is an online repository of tools and guidance to support humanitarian responders to integrate the environmental dimensions of emergencies and crises into their response and recovery strategies and activities. Both have been developed by the JEU.

strategy that includes considered land management practices and embedded communication and awareness (eg Tilling 1989; Fearnley et al 2017). Small-island settings present an additional challenge, because the impetus for development that encroaches upon the increasingly higher elevations of mountainous regions can be greater where land is both limited and subject to competing uses. There is also the potential for this to intensify various challenges, such as reductions in the amount of available land, increased socioeconomic inequality, and climate change–induced migration and displacement.

The volcanic islands of the Caribbean are subject to multiple natural hazards, some of which affect the islands annually. These small islands are dominated by one or more volcanic complexes, and the amount of available land that may not be affected during a volcanic event is often limited or nonexistent (Lindsay et al 2005). Furthermore, the proximity of the Caribbean islands means that they are vulnerable to distal volcanic hazards, such as volcanic ash or tsunami originating from neighboring islands. This was observed during the 9–22 April 2021 explosive eruptions at La Soufrière volcano (LSV), St Vincent and the Grenadines (SVG), when ashfall covered Barbados with an estimated 3–6 mm of ash. Barbados was also affected by the 1718, 1812, and 1902 LSV eruptions (Defoe 1718; Anderson and Flett 1903; Smith 2011), along with neighboring islands of Antigua, St Lucia, and Martinique, resulting in damage to infrastructure, agricultural losses, and gross domestic product losses. Similarly, ashfall from the active phases of the most recent eruption of the Soufrière Hills volcano, Montserrat (1995–2010), affected the islands of Guadeloupe, Dominica, and St Lucia (Baxter et al 2014). Local tsunamis because of volcanic flank collapse and underwater landslides have been associated with volcanic activity at the Soufrière Hills volcano, LSV, Mt Pelée, Martinique, and Kick'em Jenny underwater volcano near Grenada (Pararas-Carayannis 2006).

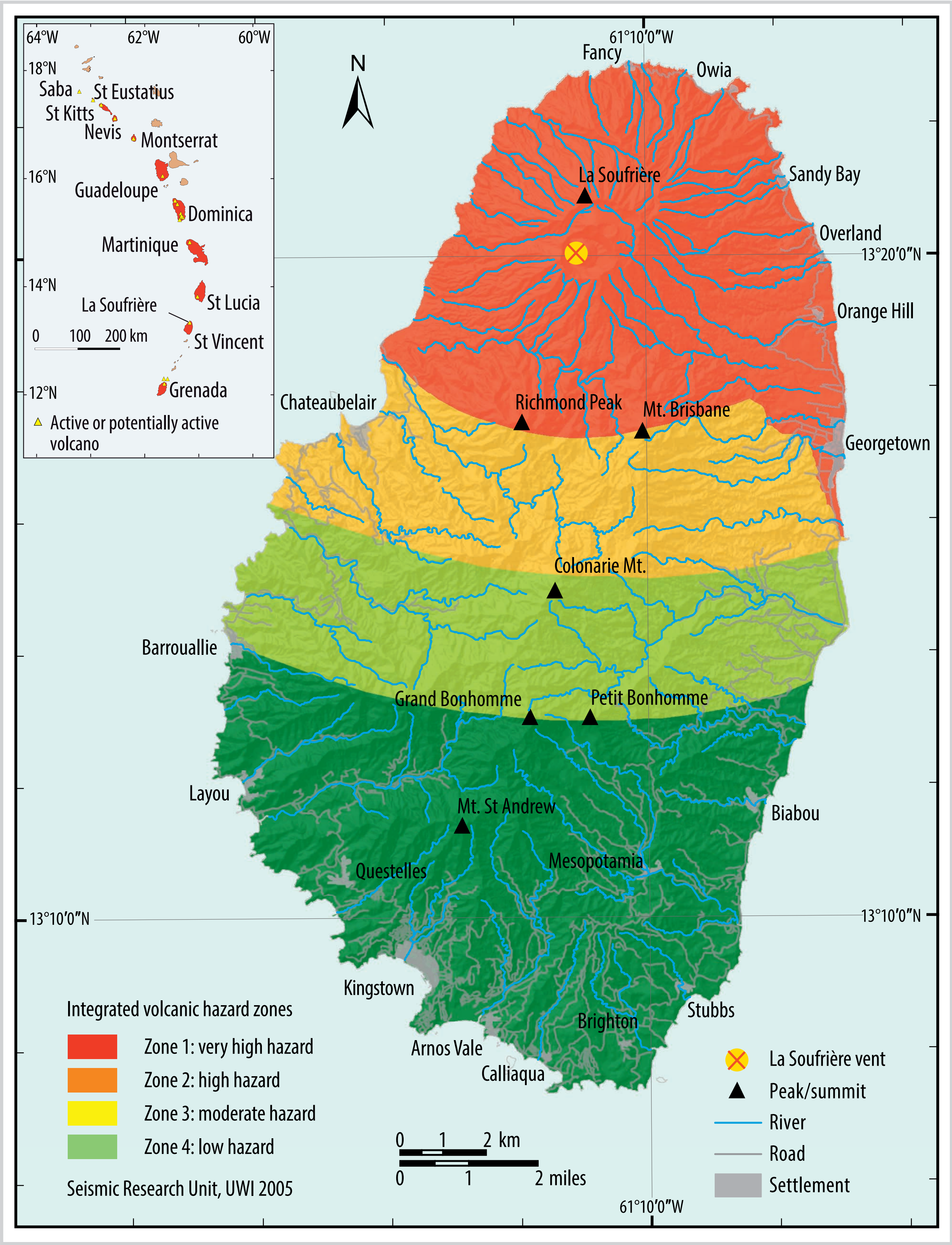
Here we demonstrate some complexities associated with volcanic risk management in the Caribbean using the recent explosive eruptions at LSV as an example to evaluate the University of the West Indies Seismic Research Centre (UWI-SRC; Box 1) volcanic monitoring approach. We also present reflections on the United Nations (UN) response mission regarding collaborations with local and international scientific actors to identify, assess, and mitigate the negative environmental impacts caused by the volcanic eruption. We present a case study that was undertaken to analyze the current lahar hazard around LSV, because of the source material deposited during the recent eruptive activity, as a component of this technical advice and highlight some of the most vulnerable areas that could benefit from best practice mitigation strategies and greater community awareness to better live with lahars and their impacts.

The main objectives of the article are threefold: (1) to illustrate and analyze the response activities both before and after the explosive eruptions in April 2021, and the collaboration of different actors in light of comparable operations in the future; (2) to investigate and examine the compounded and cascading hazards and risks in SVG, with a focus on lahars; and (3) to provide scientific solutions and planning perspectives to improve land management practices and lower volcano-induced risks for better and sustainable development through a case study of the lahar hazards around LSV.

Volcanic hazard in the Caribbean

The Lesser Antilles arc spans 850 km, extending from Sombrero in the north to Grenada in the south, and consists of 11 volcanic islands that possess 21 potentially active volcanic centers (Figure 1; Lindsay et al 2005). The Lesser Antilles region is considered the most exposed to volcanic

FIGURE 1 Integrated volcanic hazard map for St Vincent, which illustrates the potential for ground-based volcanic impacts, such as PDCs and surges, tephra fall, ashfall, and lahars, to affect areas around the volcano. A simplified schema from red to green communicates the relative hazard level (modified after Robertson 2005). Inset: Map of the Lesser Antilles Island Arc, with the 21 active volcanoes shown. Of these volcanoes, 17 fall under the monitoring responsibility of UWI-SRC (modified after Lindsay et al 2005).



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hazards in the world (Brown et al 2015). This region is also affected by other natural hazards, in particular a high frequency of impacts from hurricanes and related storm surges, as well as earthquakes, tsunamis, flooding, and landslides. Vulnerability reduction in this multihazard environment is therefore essential to improving the recovery and resiliency of these volcanic islands with a challenging topography.

Volcanic risk management planning and awareness activities are the primary volcanic hazard mitigation strategies implemented by UWI-SRC for the Caribbean. These activities include the preparation of volcanic hazard maps for the Antilles region (eg Figure 1) and the volcanic hazard atlas of comprehensive geological and volcanological data for each volcanic island (Lindsay et al 2005), as well as the development of volcanic alert-level systems for each island (Joseph et al 2022).

La Soufrière eruption, monitoring response, and volcanic impacts

UWI-SRC is the agency responsible for monitoring the seismic and volcanic activity in SVG, with on-island support from the Soufrière Monitoring Unit (SMU) of the National Emergency Management Organisation (NEMO). The National Aeronautics and Space Administration's alerting system, the Fire Information for Resource Management System (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms/about-firms), signaled a hotspot in the summit crater of LSV on 27 December 2020. SMU provided visual confirmation of a new lava dome growing in the southwest sector of the existing dome in the summit crater of LSV (13°51′22.18″N, 61°03′23.76″W) on 29 December 2020, resulting in the immediate change in the alert level for the volcano from green to orange (Figure 2). This dome growth was preceded by a short period of low-level volcanic seismicity at the volcano from November 2020. SMU uses an alert system that consists of 4 levels, with green indicating normal background volcanic activity with no or minimal risk and red indicating eruptive activity with high or impending risk that may potentially have negative impacts on communities, agriculture, and structures near the volcano (Joseph et al 2022).

The immediate response by UWI-SRC upon the confirmation of effusive activity was the mobilization of a team to SVG to reactivate the Belmont Observatory and begin network strengthening. This was followed by a continuous 24/7 standby rotation of on-island monitoring teams (January–November 2021), with support from the local SMU and UWI-SRC staff in Trinidad and Montserrat. The seismic and ground deformation networks were significantly strengthened by February 2021, with 8 seismic stations and 4 continuous global positioning system (GPS) sites in operation. A regular program of gas measurements (sulfur dioxide [SO_2] flux and soil carbon dioxide [CO_2], measured using a multicomponent gas analyzer system [MultiGAS]), ground deformation monitoring (electronic distance measurements, remote sensing, and campaign GPS surveys), and dome growth measurements (satellite images and drone surveys) was undertaken throughout the effusive phase. UWI-SRC also provided support to NEMO through participation in virtual public awareness campaigns targeting the northern communities, in the provision of regular scientific advisories to the SVG government and relevant authorities, in the provision of updates on the volcanic activity to the public and media, and on various social media platforms.

This newly formed dome underwent a significant increase in growth rate, with increased venting and visible incandescence observed 6–8 April 2021 (Joseph et al 2022). UWI-SRC issued a warning on 8 April based on heightened seismicity and visual observations that were indicative of an imminent explosive eruption. The SVG government subsequently raised the volcanic alert level to red and ordered an immediate evacuation of the people living in the most exposed areas (Figure 1, red and orange zones). This provided crucial time for the evacuation of thousands of people from these northern zones of the island, which undoubtedly saved many lives.

The eruption transitioned to an explosive phase on 9 April 2021, with multiple Vulcanian and Sub-Plinian explosions occurring. The explosive eruptions consisted of 32 discrete events that generated plumes of 15 km or more above the volcano (Joseph et al 2022), which deposited ash over the entire island of St Vincent and extended to the neighboring islands, particularly Barbados.

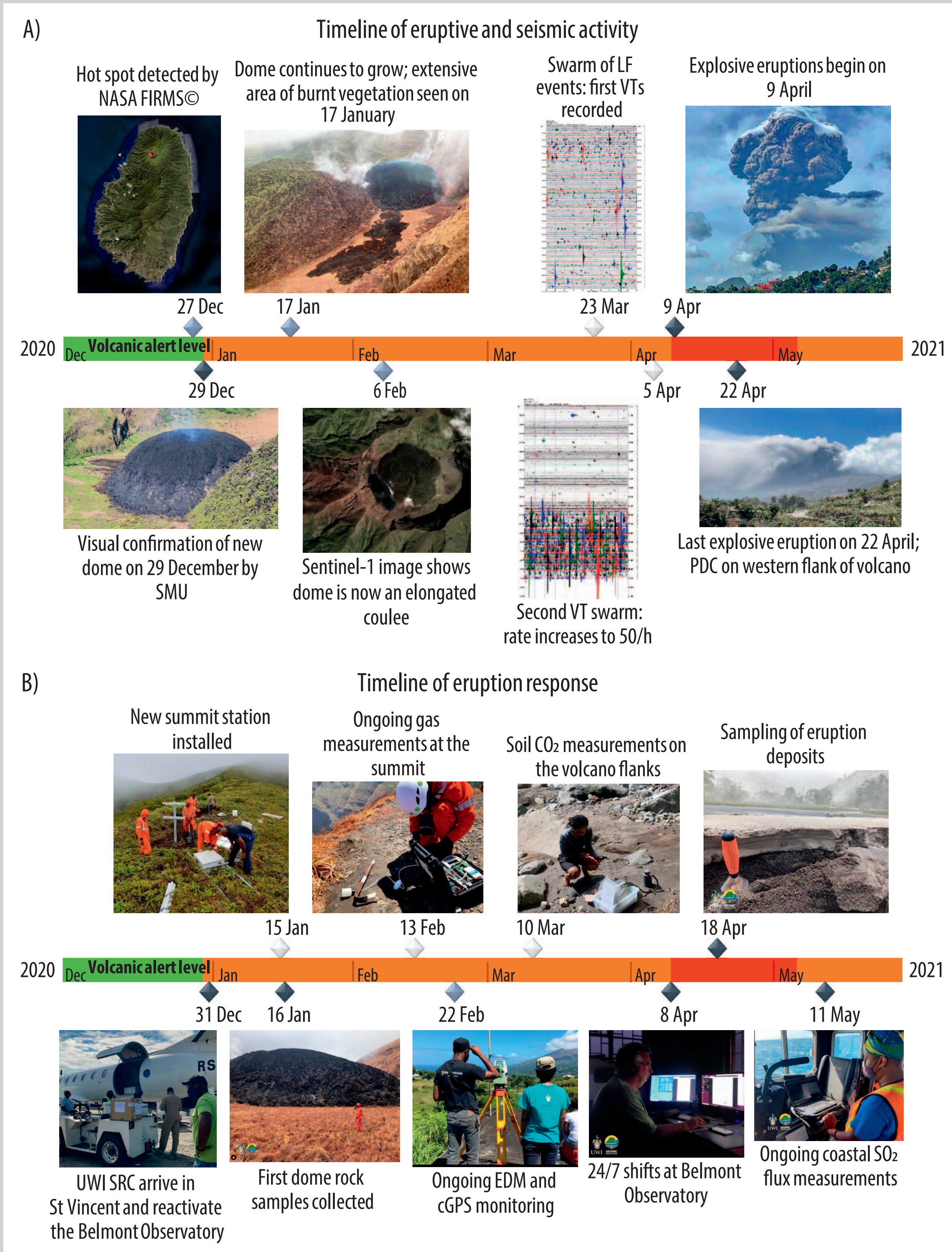
These explosive eruptions created a series of compound hazards, with ashfall and pyroclastic density currents (PDCs) providing extensive amounts of source material that have since cascaded into lahar hazards. The resultant ash thickness was up to ~15 cm across the island, with the weight of the ash collapsing roofs and causing structural damage, and areas with less ash deposition experienced corrosion to metal roofs. Ash also damaged agricultural crops and disrupted livestock production in the area. The PDCs that were generated during the explosive eruptions primarily traveled to the south and west of the summit crater, avoiding the highly populated areas, although PDCs and surges heavily affected the vegetation in these areas. Lahars were also generated during the explosive phase and continue to remobilize ash and/or PDC deposits during and shortly after heavy rainfall events. These lahars have affected settlements along the river channels, including causing heavy damage to buildings, which has been observed in the Sandy Bay area. Rainfall-induced lahars have affected virtually all valleys leading from the summit crater at some point to date. This hazard is amplified during heavy rains, which is a particular concern during hurricane season.

National and international response, including humanitarian relief

The region was still recovering from the 2020 hurricane season and grappling with the ongoing COVID-19 pandemic when the effusive eruption commenced in December 2020. These factors directly affected the status of the volcano-monitoring network on SVG, with regional travel restrictions limiting network maintenance and a significantly reduced budget hampering the necessary acquisition of on-island monitoring equipment such that there was only one operational seismic and continuous GPS station on SVG at the start of effusive activity.

UWI-SRC embarked on collaborations with several international institutions in January 2021 because of the

FIGURE 2 Timeline of the 2020–2021 eruption of LSV, SVG. (A) Time of eruptive and seismic activity, with changes in dome growth, periods of volcano-tectonic (VT) earthquake swarms, and the transition to explosive activity identified. (B) Timeline of the eruption response by scientists, with on-island occupation, networking strengthening, and fieldwork and monitoring. LF, low frequency; EDM, electronic distance measurement; cGPS, continuous global positioning system.



potential for volcanic activity to enter an explosive phase with little warning and the limited monitoring capacity at the start of the effusive phase of the eruption. These collaborations facilitated the acquisition of satellite imagery to monitor the state of the summit crater, survey the dome, provide preliminary PDC models to identify vulnerable areas, provide helicopter support to conduct dome measurements and sampling, install monitoring equipment at the summit, and acquire additional monitoring equipment and emergency supplies in the event of an evacuation in the high hazard zones. Once LSV became explosive and the safety of the residents surrounding the volcano was ensured, UWI-SRC shifted some of its attention to better understanding the short- and long-term impacts of the volcanic hazards. However, the ongoing COVID-19 pandemic inhibited direct in-person involvement by some institutions, thereby increasing the importance of effective communication networks and remote-based support systems even after the explosive events. This situation also highlighted that regional and broader international collaborations are vital to incorporate the best available datasets, methods, and scientific knowledge to respond to the rapidly developing crisis. These collaborations were mostly undertaken via remote communications and online meetings with partners located across many time zones. Furthermore, contributions from both the donor agencies who responded to the monitoring needs and the authorities who facilitated the evacuation and recovery preparations were significant.

UWI-SRC created subgroups based on the necessary volcanic disciplines and identified team leads to coordinate the international scientific support response (Joseph et al 2022). This approach greatly improved access to available data and resources in a timely manner. However, there were still challenges in managing such a large number of collaborators across all sectors (ie academia, government, and private sectors) using multiple communication platforms and concurrently managing, processing, and interpreting the monitoring data in nearly real time. UWI-SRC was working in direct collaboration with 21 university partners, 17 regional agencies and donors, and 14 additional scientific partner agencies during the height of the explosive activity.

The UN Office for the Coordination of Humanitarian Assistance (OCHA; Box 1) Geneva Office received a request for international assistance from the SVG government after the initial major explosive phase. This gave clear instructions to only address the environmental aspects and impacts of the volcanic eruptions. All aspects related to disaster response coordination were exclusively in the hands of NEMO and the regional Caribbean Disaster Emergency Management Agency. The UN Environment Programme/OCHA Joint Environment Unit (JEU) in Geneva, in close coordination with the UN resident coordinator in Barbados, subsequently dispatched a team of 12 environmental experts to Kingstown to provide technical advice on the impacts on nature and ecosystems, environmental toxicology and pollution, geology, ash management (cleanup and disposal), environmental pollution, ecology, and green humanitarian response. The mission team in SVG received remote support from Bonn through a scientific team of Global Mountain Safeguard Research (GLOMOS), UN University Institute for Environment and Human Security. In view of the growing number of complex disasters worldwide, such so-called remote environmental assessment and analysis cells are becoming more important as the international response system reaches the limits of its capacity.

The mission team in SVG worked directly with NEMO, as well as other local authorities, line ministries, and institutions involved. Meanwhile, the GLOMOS team was tasked with remotely facilitating and supporting the communication and information exchange between the field team and a larger group of regional and international scientific institutions, including UWI-SRC. The team established a dashboard information management system to collect, analyze, update, and present information relevant to the disaster response and recovery. This dashboard was fed with available maps and the most recent satellite imagery, as well as news and situation reports, scientific data, and information received directly from the field. The team also collected information on ecological restoration for postdisaster early recovery and reconstruction.

There was a critical need to restore the lost monitoring capacity once the explosive phase of the eruption ended in April 2022, because all monitoring infrastructure at the summit station was destroyed. Furthermore, disrupted power and communications to the northern and eastern seismic and ground deformation monitoring stations led to long-term intermittent acquisition at these sites. This amounted to a 40–60% reduction in the event detection and location thresholds and a resulting reduction in ability to recognize early-warning cues of a possible restart of volcanic activity. Therefore, it became critical for UWI-SRC to obtain additional monitoring equipment, find alternative sites for station deployment, reestablish power and communications, and build new monitoring infrastructure. This effort required significant financial and human resources, which were limited posteruption.

Socioeconomic and environmental impacts of the eruption

Approximately 22,240 people, or about one fifth of the total number of inhabitants in SVG, were displaced, with 4456 living in shelters, because of the volcanic activity (29 April 2021 status; CDEMA 2021). PDCs, lahars, and volcanic ash damaged critical infrastructure and rendered unusable roads that were urgently needed to move people and goods within the northern area. SVG had limited access to clean water and electricity, and the airports and seaports had to close for several days. The eruption also affected the livelihoods of the already vulnerable population in SVG and will have a strong negative impact on the economy for months and potentially even years to come. The large volcanic ash deposits could generate cascading and compound multihazards. The ambient air quality has been severely affected by fine particles within the volcanic ash that may cause acute respiratory conditions, such as asthma and bronchitis symptoms (Horwell and Baxter 2006; Jenkins et al 2015). Air quality is not monitored in SVG, even though it can directly affect human health; however, the Pan American Health Organisation is developing monitoring systems for the region, subject to funding. The terrestrial and aquatic–marine ecosystems have also been heavily affected by ash deposits. Ash can cause acid damage or physical abrasion to vegetation, leaves, and fruits, with damage to agricultural crops potentially leading to food insecurity (Jenkins et al 2015). Ashfall can also affect the aquatic environment, particularly through the physical effects of suspended particles that threaten local fish populations (Di Prinzio et al 2021). From the perspective of the UN-led environmental emergency mission, further environmental concerns resulting from the eruption included volcanic ash management in terms of its cleanup, storage, utilization, and disposal, with particular consideration of its physical and chemical properties, as well as the management of waste from other sources, such as home and building damage, the loss of electronics and electrical appliances, and waste stemming from the humanitarian response (ie food packaging waste; JEU 2021). Lahars have continued to affect the roads, bridges, and culverts on the eastern slopes of the volcano, disrupting access to the settlements on the eastern coast. The structures in the river valleys are particularly vulnerable, as are the utilities that transect these affected areas to serve the communities in the north.

After an extended period of declining posteruption activity with hot degassing vents observed in the summit crater, declining daily seismicity, and SO_2 flux, LSV returned to near background levels of activity in March 2022, with the alert level being officially lowered to green on 16 March 2022. However, the significant amount of material deposited on the flanks and in the valleys of the volcano makes lahars an ongoing concern that can continue for an indefinite period (Gran et al 2011).

Lahar hazard modeling for risk assessment and planning: case study

Lahar hazard modeling used the LAHARZ software package (Iverson et al 1998; Schilling 2014) to assess the inundation extent of the potential lahars traversing major drainages and affecting downstream settlements. This was necessary because the current hazard map for SVG (Robertson 2005) only incorporates a simplified method for determining lahar footprints that does not consider the wider spatial extent of this hazard in low-lying areas (Lindsay and Robertson 2018). LAHARZ has been widely implemented because it can rapidly generate first-order inundation models with multiple user-defined lahar volumes simultaneously (eg Darnell et al 2012; Castruccio and Clavero 2015). The uncertainties in the inundation extents and their runout lengths are primarily a function of the digital elevation model (DEM) and chosen input lahar volumes. Four input volumes (5000, 50,000, 100,000, and 500,000 m^3) were chosen, and 37 initiation points (out of 307 that were automatically generated by the toolkit) were selected to optimize the coverage of all major drainages surrounding LSV via a user-defined approach (Figure 3). The lahar inundation extent from a specific initiation point requires the mobilization of volcanic material via a minimum amount of localized rainfall; therefore, a given rainfall event is not expected to generate lahars from each of the 37 identified initiation points. See Appendix S1 (*Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-22-00001.1.S1) for further details on the modeling parameters and LAHARZ steps that were implemented in this study.

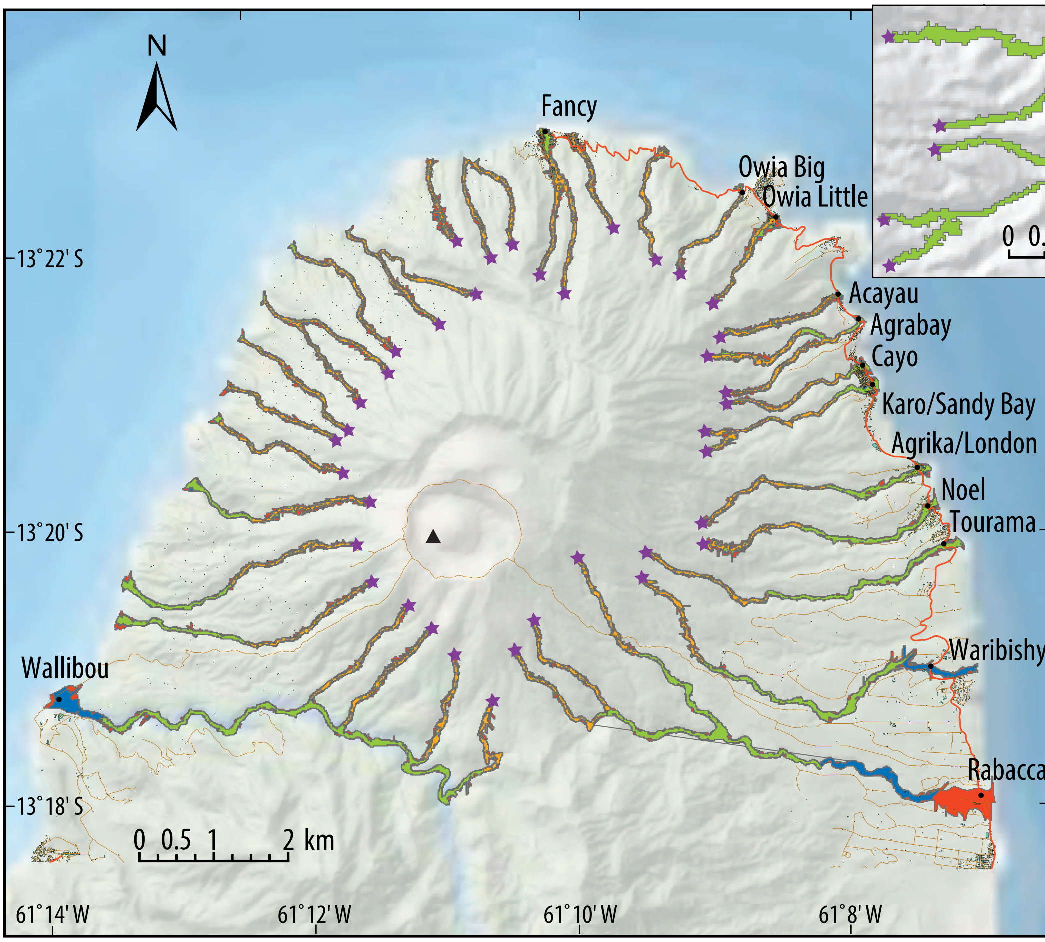
The modeling results highlight that low-volume lahars (5000 m^3) can inundate some drainages, with the northernmost settlements (Fancy and Owia) being the most vulnerable to lahars. The drainages along the western and southern flanks are also susceptible to inundation from low-volume lahars, thereby threatening agriculture production along these flanks, which is one of the primary sources of income in the region (IFRC 2017).

Modest lahar volumes (50,000–100,000 m^3) have the greatest impact on communities and infrastructure along the eastern flank, whereas only high-volume lahars (500,000 m^3) appear to threaten the coastal extents of the larger drainage networks in the south, such as the Rabacca valley. These results suggest that the shorter, more constricted drainage channels in the north are more susceptible to inundation, whereas the longer and broader ones in the south can settle and disperse lahars more efficiently.

Comparison of these results with the road network indicates that even low-volume lahars (5000 m^3) can potentially affect the Windward Highway along 4 drainages, whereas high-volume lahars (500,000 m^3) can inundate the highway along 19 potential drainages (Table S1, *Supplemental material,* https://doi.org/10.1659/MRD-JOURNAL-D-22-00001.1.S1). This highway, which connects the entire northern region with the closest major business hub (Georgetown), traverses multiple drainage networks and is predominantly constructed of concrete slabs that are placed on the ground-level crossings. Local news updates have consistently highlighted the risk and subsequent disruptions the regional communities face because of frequent flooding and subsequent lahar that engulf these slabs, rendering them unusable until a clearance team is mobilized (iWitness News 2021). Furthermore, the other roads in the region, which are important for regional tourism and trade, are highly susceptible to lahars. A cost–benefit evaluation of replacing the existing concrete slabs along the current regional transportation networks with lahar- and flood-resilient bridges to avert prolonged socioeconomic damages to these lahar-prone areas should be considered.

Residents in the Karo (Sandy Bay) drainages may be exposed to impending lahars at a high frequency and intensity. A comparison of the modeling results and the inundation and building damage already sustained along the Sandy Bay drainages indicates that the lahar volumes in this area have exceeded 5000 m^3. Similarly, lahars, even low-volume ones (5000 m^3), could easily inundate multiple households in Fancy and Owia. These small- to medium-scale lahars require serious attention from the local government, because they can still disrupt livelihoods in the area. The establishment of monitoring stations along the major drainage networks may be advantageous to collect input data for future modeling studies, because lahars could occur across this region over the indefinite future. However, lahar travel times to populated areas in these short drainages mean that lahar early-warning systems are unlikely to be effective or allow timely evacuations. Proper land use planning techniques that delineate lahar-prone areas and identify the underlying risks can be employed to minimize residential and/or commercial development in exposed areas (Hardjosuwarno et al 2015). Buffers should also be created along drainage channels to restrict further residential development, and support should be provided to potentially relocate households to ensure they are not exposed to lahars.

FIGURE 3 Modeled distal lahar inundations (LAHARZ; Schilling 2014) for 4 input lahar volumes. Multiple subdrainages coalesce at the higher lahar volumes, as seen in the Rabacca and Wallibou valleys. Inset: Modeled inundation of the exposed assets within the Sandy Bay and Cayo drainages for an input volume of 50,000 m^3.



This research supplements the preexisting lahar hazard map (Robertson 2005) for LSV and provides a first-order assessment of the most hazardous drainages, which can then be meticulously investigated using more comprehensive lahar inundation models that incorporate the flow mechanics of lahars. Such an analysis can quantify the probabilities of lahar flows based on rainfall patterns across the region. The local communities in these high-risk areas, as well as the disaster response and infrastructure agencies, should be trained, educated, and actively involved in lahar risk prevention, mitigation, and adaptation to abate preexisting vulnerabilities.

Lessons learned and future opportunities: agenda for future research, development interventions, and policy recommendations

The success of the response to the LSV eruption by various stakeholders can be considered a function of the lessons learned from previous volcanic and humanitarian disasters in the region. UWI-SRC has gathered considerable experience from the long-term eruption of the Soufrière Hills volcano, Montserrat, and how volcanic activity affects infrastructure and society at different levels of economic development and vulnerability. Some of the most important lessons learned in relation to UWI-SRC's response to the LSV eruption, both before and after the explosive activity in April 2021, included the importance of a robust monitoring network for the early detection of unrest or activity and continued monitoring throughout the phases of the eruption. This was particularly relevant because there was a considerable lack of seismic and ground deformation monitoring stations on island at the start of effusive activity. It was the strengthened monitoring capacity established within 1 month of detecting the effusive activity that allowed the monitoring scientists to detect the changes in volcanic activity that signaled a transition to an explosive phase. In turn, this allowed them to warn the authorities to evacuate the high-risk zones.

Another important lesson was the rapid development of a harmonized communication strategy between scientists and local authorities early in the volcanic response such that accurate information on the eruption was effectively communicated to all stakeholders clearly and concisely. The collaborative public awareness activities of NEMO and UWI-SRC before the start of the explosive phase in the most at-risk communities played a significant role in the effectiveness of the public's response to the explosive eruptions. This is evidenced by the public's compliance with the evacuation orders issued by the authorities. This highlights the importance of a preexisting volcanic hazard assessment and analysis, as well as the advanced preparedness of the local disaster response officials in responding to a volcanic eruption.

The overall responses to the 2020–2021 eruption illustrate the advantages of incorporating external researchers, sharing resources, and engaging the public to improve the understanding of the volcano and the risks it poses. However, a commitment to invest in monitoring resources and provide effective monitoring services is also critical in such a resource-constrained setting. The combined on-site–offsite model of ground-based personnel supported by larger remote teams was employed by both UWI-SRC and selected UN agencies during their operational responses. This approach is increasingly common for multidimensional hazard response and proved to be of particular relevance when responding to a complex volcanological event during a global pandemic.

Although the immediate explosive hazards generated by the 2020–2021 LSV eruption may have ceased in April 2021, the impacts of the eruption will continue to be felt long after the volcanic crisis is over. This eruption is an example of the importance of long-term land use planning and highlights the need for risk-sensitive sustainable development in hazard-prone areas. Lahars can feasibly continue to affect the region for years to decades following the eruption, as has been the case for several eruptions, including Mount St Helens, Mount Pinatubo (Thouret et al 2020), and Soufrière Hills volcano (James and Miller 2020). It is essential to continue to raise awareness of these ongoing, potentially long-lived volcanic hazards and account for them in planning and decision-making. Lahars can damage buildings situated within active valleys and disrupt distribution networks, such as transportation and critical infrastructure. Therefore, public awareness campaigns and the relocation of at-risk buildings need to be coupled with institutional preparedness and response plans in both the public and the private sectors. Key datasets, including rainfall monitoring on the flanks of the volcano, updated high-resolution topography data (eg recent DEMs), and monitoring of lahar frequency, magnitude, and material properties through seismic monitoring and field studies, need to be considered to further improve lahar hazard assessments.

A compounding factor for effectively managing natural hazards is climate change, which may continue to increase the intensity and frequency of certain hazards, such as hurricanes and rainfall-induced lahars (Glasser 2020). The impacts of associated sea-level rise will put pressure on land use planners to identify and prioritize appropriate land usage, and this will be even more important for island nations that are already feeling these impacts and will continue to do so (Robinson 2020). More people will either choose or be forced to live and work in hazardous environments as the amount of available land decreases. We see the increasing importance of land at higher elevations, such as mountainous regions, thereby placing increasing pressure on land usage in these sensitive zones and a potential increase in exposure to mountain hazards, such as volcanoes and landslides.

The lessons learned through the 2020–2021 LSV eruption apply not only to the Caribbean context but also to international hazard events in which the coordination and collaboration of a diverse range of stakeholders is vital both during an ongoing critical event and for long-term initiatives. Furthermore, the hazard assessment tools used here are transferable to other small-island states that are vulnerable to volcanic hazards and where limited land availability reduces the options for risk-sensitive land use planning.

Humanitarian relief operations within complex environments, such as mountainous small-island developing states, require adaptation strategies that adopt an integrative approach that covers the entire disaster risk cycle, from prevention to recovery. Furthermore, the integration of the environment into the response and recovery process in a way that generates environmental enhancements and facilitates sustainable development is of fundamental importance. Detailed mission results from the UN field team that support these outcomes have been presented to the SVG government (JEU 2021).

Conclusions

Global population growth, coupled with increasing climate change and associated sea-level rise, will ensure that there is continued pressure on land use and increased reliance on mountainous environments. This pressure will be even more pronounced in small-island settings. We could see an increased push to use the volcanic environments on islands for residential and commercial activities, such as agriculture, even though the steep topographies of the volcanic Caribbean islands are at high risk for landslides and lahars. Here we discussed the operational volcano monitoring response of UWI-SRC to the 2020–2021 LSV eruption, the JEU mission to SVG after the initial phase of explosive activity in April 2021, and the international collaborations with various academic and research institutions to better understand the volcanic hazards associated with LSV. Although there was no loss of life associated with the eruption, early limitations of monitoring capabilities, restrictions in a COVID-19 environment, and damaged infrastructure immediately following the April 2021 explosive eruptions introduced challenges. The UN mission to SVG also highlighted the large potential for strengthening the integration of environmental aspects into the response and recovery procedures of this emergency, as well as for future emergencies, generating environmental enhancements and underlining sustainable development. Our lahar modeling study demonstrated that a simple first-order approach can quickly be employed to identify the most vulnerable communities and infrastructures to lahars; more comprehensive lahars models can then be employed to refine the extent of this hazard and model its long-term impacts on the island.

A long-term view for planning and mitigation will be key to ensuring that volcanic hazard is appropriately considered as a component of the multihazard or all-hazard approach undertaken by authorities to ensure the safety of their communities and continued economic development. We need to ensure that a wide assessment of the entire hazardscape is undertaken in at-risk areas to ensure that risk-sensitive sustainable development not only encompasses more frequent hazards but also explores how planning and mitigation decisions might alter the future risk from all hazards.

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Supplemental material

APPENDIX S1 Lahar hazard modeling.
TABLE S1 Total area, building area, and road length affected by lahar inundation.

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