Supplement of

Quantifying cascading impacts due to road network disruption in an insular volcanic setting: the 2021 Tajogaite eruption of La Palma Island (Spain)

Lucia Dominguez[1], Sébastien Biass[1], Corine Frischknecht[1], Alana Weir[1], Maria Paz Reyes-Hardy[1], Luigia Sara Di Maio[1], Costanza Bonadonna[1] and Nemesio Pérez[2,3]

[1]Department of Earth Sciences, University of Geneva, Geneva, 1205, Switzerland
[2]Instituto Volcanológico de Canarias (INVOLCAN), San Cristóbal de La Laguna, 38320, Spain
[3]Instituto Tecnológico y de Energías Renovables (ITER), Granadilla de Abona, 38600, Spain

Correspondence to: Lucia Dominguez (lucia.dominguez@unige.ch)

Table S1. Historical eruptions of La Palma. Compiled from Brusini Dominguez, 2022 and Carracedo and Troll, 2016.

Eruption	Year	Duration (days)	Lava flows surface (km^2)
Tacande	1480	-	5.43
Tahuya	1585	84	2.25
San Martín de Tigalate	1646	82	4.43
San Antonio	1677	66	2.23
El Charco	1712	56	4.88
San Juan	1949	47	3.70
Teneguía	1971	24	3.11
Tajogaite	2021	85	12.19

Figure S1. Temporal variation of lava geometry. Red dashed lines indicate the main changes on the width and length of lava field.

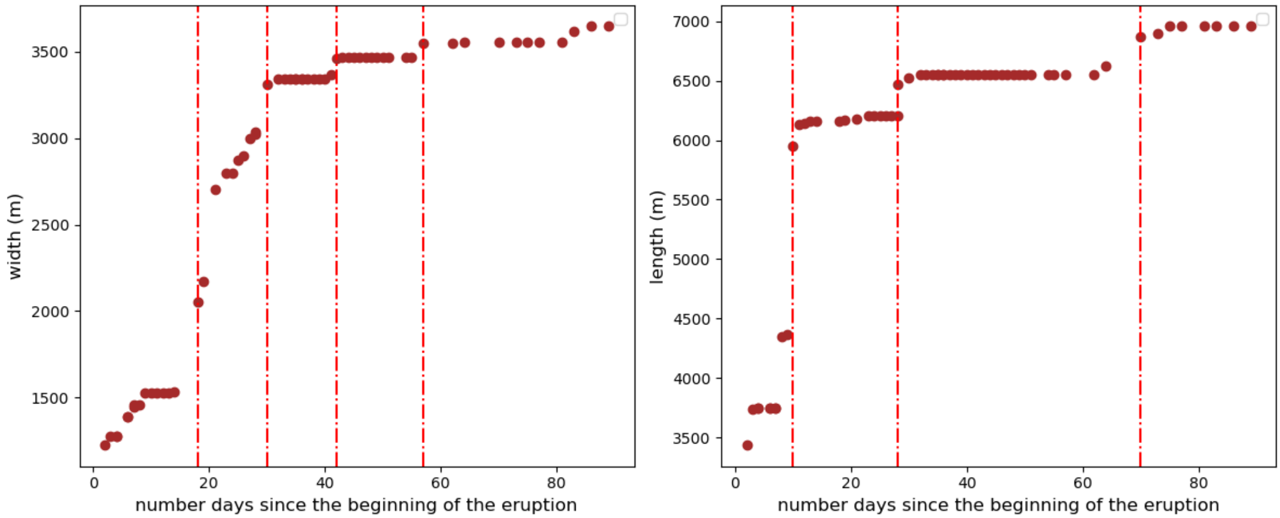

Figure S2. Volcanic alert levels and corresponding phases with Insular and State plans, as specified in the PEVOLCA Plan (https://www.volcanesdecanarias.org/wp-content/uploads/2022/10/PEVOLCA_0908201.pdf). Original version (Spanish) and English version

SITUACIÓN	SEMÁFORO VOLCÁNICO DE INFORMACIÓN A LA POBLACIÓN	NIVEL DE ACTIVIDAD VOLCÁNICA
PREALERTA	Desarrolle sus actividades normalmente. Conozca su medio físico e infórmese que hacer en caso de actividad volcánico.	Parámetros establecidos en **situación de normalidad.**
ALERTA	Esté atento a las comunicaciones de las autoridades de protección civil. Preparación de la evacuación preventiva.	Aumento de la sismicidad, emisión de gases y deformación del terreno. Erupción sin riesgo para la población.
ALERTA MÁXIMA	Implica el inicio de la evacuación preventiva. Póngase a disposición de las autoridades.	Registros de sismicidad, deformación del terreno y datos geoquímicos advierten de una erupción inminente. Erupción sin riesgo para la población.
EMERGENCIA	Evacuación total de la población que pueda verse afectada.	Erupción Volcánica sin riesgo importante para la población.
	Medidas activas de Protección Civil.	Erupción Volcánica con riesgo importante para la población, infraestructuras y medio ambiente.
	Medidas activas de Protección Civil.	Erupción Volcánica de alta potencia y difícil predicción de comportamiento.

Correspondencia con las fases, niveles y situaciones del Plan Estatal y del Plan Insular

Situación PEVOLCA	Nivel PEVOLCA	Fase Plan Estatal	Situación Plan Estatal	Fase Plan Insular	Situación Plan Insular
				Seguimiento	Normalidad
Prealerta		Intensificación del Seguimiento e Información	Situación 0	Preemergencia	Prealerta
Alerta					Alerta
Alerta Máxima					Alerta Máxima
Emergencia	0-1 Insular	Emergencia	Situación 1	Emergencia	Actuación Progresiva
	2 Autonómico		Situación 2		
	3 Estatal		Situación 3*		Alarma
Fin de Emergencia		Normalización		Fin de Emergencia	Rehabilitación de Servicios Esenciales

* Declarada de Interés Nacional

SITUATION	VOLCANIC ALERT LEVEL TO INFORM THE POPULATION	VOLCANIC ALERT LEVELS
PRE-ALERT	Develop your activities normally Know your own physical state and inform yourself what to do in case of volcanic activity	Parameters established in a **normality situation**
ALERT	Be aware of all communications from Civil Protection authorities Preventive evacuation preparedness	Seismicity increasing, gas emissions and ground deformation Eruption with no risk to the population
MAXIMUM ALERT	Implies the starting of preventive evacuation Collaborate with authorities	Seismicity records, ground deformation and geochemical data warns of imminent eruption Eruption with no risk to the population
EMERGENCY	Total evacuation of population that could be affected	Volcanic eruption with no important risk to the population
	Active measures of Civil Protection	Volcanic eruption with important risk to the population, infrastructures and environment
	Active measures of Civil Protection	Volcanic eruption of high intensity and difficult forecasting behaviour

Correspondence with the phases, levels and situations of the Insular Plan and the State Plan

PEVOLCA situation	PEVOLCA level	State Plan Phase	State Plan Situation	Insular Plan Phase	Insular Plan Situation
				Follow-up	Normality
Pre-alert		Follow-up and information increasing	Situation 0	Pre-emergency	Pre-alert
Alert					Alert
Maximum alert					Maximum alert
Emergency	0-1 Insular	Emergency	Situation 1	Emergency	Progressive action
	2 Authonomous Community*		Situation 2		
	3 State		Situation 3#		Alarm
End of emergency		Normalisation		End of emergency	Rehabilitation of Critical Services

* Spain administrative level 2, corresponding to Departments, Cantons, etc.
# Situation declared of National interest

Table S2. Summary of specific critical sectors, systems and impact data for La Palma.

Sector	System	Impact data (potential)
Critical Infrastructure (CI)	Transport (aerial, maritime, terrestrial)	✓ Amount of material accumulated (number of trucks, clean-up surfaces, thickness) ✓ Duration (days/weeks of clean-up operations) ✓ Number of trucks ✓ Tephra waste disposal
	Potable water	
	Irrigation water	
	Energy	
	Telecommunications	
Critical services	Public works	✓ Coordination of all operations ✓ Evacuation and follow-up of residents ✓ Clean-up operations ✓ Rapid construction of emergency infrastructures (roads)
	Emergency Military Unit (UME)	✓ Coordination of all operations ✓ Evacuation and follow-up of residents ✓ Clean-up operations ✓ Rapid construction of emergency infrastructures (roads)
	Civil protection, Centro de coordinación Operativa Insular (CECOPIN), fire brigades	
	Police – Civil Guards	✓ Exclusion restricted zones ✓ Evacuation and accompanying ✓ Lava evolution real-time monitoring
	Cabildo	✓ Photogrammetry (drone) and GIS data (https://www.opendatalapalma.es/) ✓ Urban areas: Las Manchas-Jedey-Puerto Naos- Los Llanos
Critical Facilities	Hospital	✓ Service interruption occurrence ✓ Duration and number of affected people ✓ Relocation of users
	Schools	
Economy	Agriculture	✓ Direct physical damage (crop surface, number of farms, number of hotels) ✓ Cascading impacts ✓ Service interruption occurrence ✓ Duration and number of affected people ✓ Relocation and/or alternative ✓ Economic losses (direct and loss of revenue)
	Tourism	

Table S3. Comprehensive questionnaire for impact data collection adapted from Dominguez et al. (2021) for specific sectors and risk context of La Palma.

SECTION 1. GENERAL ASPECTS OF THE INSTITUTION
1. How the system/network work with respect to the government hierarchy? (e.g., private/public, Municipality/Cabildo/Province/Community/State)
2. What areas and/or localities depend on your service?
3. What areas/localities/neighbourhoods/number of people depending on your service?
4. How the system is designed (e.g., network, nodes, edges) – Updated GIS files?
5. Dependency relationships with external institutions or other systems? (e.g., water in electricity, daily activities in road networks, etc.)

SECTION 2. DESCRIPTION AND LOCATION OF IMPACTS
1. Was the institution affected by La Palma eruption?
2. What were the main impacts that the institution suffered?
3. Could we identify what impacts are directly caused by the tephra/lava occurrence? Which are indirectly related to the disruption of other systems? (clearly identify direct and indirect impacts)
4. What are the main components or parts of the network that were damaged by tephra. Lava or both?
5. What were the areas affected: - How many users affected? - How many sectors (e.g., other CI) due to the interruption of services
6. Are impacts georeferenced? Does exist a record of dates, location and intensity of impacts? (e.g., maps, forms, GPS files, tables, reports)

SECTION 3. TECHNICAL ASPECTS
1. Duration and frequency of impacts (systematic record of damages such as supply cuts, closure, destruction). Permanent or intermittent impacts?
2. What were the characteristics of the tephra at the moment of the damage? - Dry/wet - Colour - Approximate thickness - Particle size (e.g., dust, sand, stones)
3. What were the meteorological conditions at the moment of damage (e.g., rain, wind); and air quality conditions (e.g., low visibility, dust (PM) concentrations)
4. Are there evidences of aeolian or water remobilisation of tephra? (e.g., loss of visibility, poor air quality, mud floods).

SECTION 4. EARLY WARNING SYSTEMS (EWS) AND MONITORING
1. In your knowledge, were there volcanic EWS and monitoring in La Palma?
2. Were there EWS and monitoring of failure or impacts in your specific service?
3. With how many hours/days/weeks in advance did you know about the changes on the volcanic alert? (green-to-yellow-to-red)
4. Did your service have time to overtake immediate emergency measures? What kind of measures?

SECTION 5. RESPONSE AND MITIGATION MEASURES	
1.	Did the institution have some action protocol for natural and/or volcanic events prior to Tajogaite event? Do you have response (emergency) protocols for volcanic eruptions or other phenomena? - In the positive case: did you follow the protocol? What were the main difficulties to implement? - In the negative case: what were the immediate response actions overtaken ?
2.	What were the strategies to mitigate the impacts in the short (e.g., closure, maintenance, cleaning) medium (relocation, tephra disposal), long-term (e.g., reconstruction of CI networks)?
3.	What kind of actions could have decreased the duration of disruption and/or reduced the areas of impact? What actions should be previewed?
4.	Are there insurance policies for the built-environment? Do you know about the existence of institutional insurance/budgets in case of natural phenomena disasters (and specifically for volcanic eruptions?)
5.	Were there evacuation plans, shelter availability, and coordination plans before the eruption?
6.	What could be the lessons learnt with Tajogaite eruption? Do you think that population and institutions were prepared considering that last eruption occurred in 1971? What are the similarities and differences with this eruption?

Summary of impacts to other critical infrastructure systems

Aerial transportation

All airport operations were coordinated by the *Ministerio de Transportes y Movilidad Sostenible* of Spain following the national and international aviation protocols for operation during the presence of atmospheric and deposited volcanic ash (ICAO 9691) (e.g., it is recommended that airports close when the onsite threshold of 1 mm tephra thickness is reached). Due to the prevailing NE-SW winds, La Palma airport was not severely affected by tephra. Airport closures occurred 24-26 September and 7-9 October due to ash accumulation on the runways (~250,000 m^2 were cleaned by airport staff, supported by two road sweepers from the airports of Santa Cruz de Tenerife Sur and Lanzarote). Wet ash was extremely problematic to handle due to cementation and runway porosity. 759 flights were cancelled, 256 due to the closure of the airport and 503 due to high ash concentration in the atmosphere (Sara et al., 2024). The *Servicio de Salvamento y Extinción de Incendios* of the airport also participated in the clean-up operations of the heliport of La Palma Hospital and contributed to evacuation process in the impacted area.

Electricity supply

Prior to the eruption, the two agencies responsible for electricity generation and distribution (ENDESA; 20 kV-240 V) and transmission (*Red Eléctrica Española*; 66 kV), started an immediate plan to verify hotspots in the network (overload points) through thermal cameras. Since the La Palma electricity network is characterized by very low network redundancy (only 1 E-W high voltage line from the generation plant to the substation of Los Llanos, Fig. 3B), all annual maintenance works in this unique line were immediately cancelled from Sept. 19 to Dec. 25, 2021. The dynamic pressure and high temperature of lava flows damaged a total of 130 km of electricity lines, 19 distribution centres, 85 medium voltage towers, 1,700 wood and metal poles and 2,200 supply points (PEVOLCA report 25/12/21) (Fig. 5I). However, the electricity supply for inhabited areas was largely mitigated due to the well-coordinated plan to build bypass circuits although the main network was divided by the lava field. In order to mitigate electricity network overload following reconfiguration, two portable diesel generators (9 and 4 MW generators in Los Llanos and Las Manchas, respectively) were stationed to reinforce the supply to the north and the south of the island. Any incidences in the electricity network due to tephra were reported. Given that a common failure caused by tephra accumulation is the insulators flashover, a specialised cleaning truck was rapidly prepared to wash the contaminated insulators. However, this action was not required as wind action was sufficient. Indeed, long chains of composite and glass electricity insulators are designed to withstand high salt and sand concentrations from the Atlantic ocean and Sahara desert in La Palma, which enhanced their resilience to the adverse effects of tephra.

Telecommunications

Since PEVOLCA coordination relies on communications, this system was prioritised during response efforts. The TETRA (Trans European Trunked RAdio) system ensured digital radio communications for critical services (e.g., police, firemen, Civil Protection, Civil Guard). Any impacts to the TETRA or private telecommunication companies were reported.

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Supplementary resources

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