GENESIS–La Palma platform for cascading-failure simulation in water–energy systems

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This document is a public summary prepared for DOI dissemination, excluding information of a security sensitive nature. It presents the platform scope, methodology, and aggregated results, while omitting asset-level operational detail for security reasons. Sensitive asset-level and operational details (including exact locations, facility-specific capacities, interdependency mappings at asset level, and parameters that could enable misuse) have been removed or generalized for critical infrastructure security reasons.

Disclaimer: Cascading Failure Simulation Platform (GENESIS Project)

This simulation platform has been developed within the framework of the European project GENESIS as a decision-support tool intended to explore vulnerability and resilience patterns in interdependent critical infrastructure systems, particularly in island environments.

Access to the platform is restricted to authorized public entities operating under a formal cooperation agreement with the University of La Laguna. It is not designed for open public release, commercial exploitation, or redistribution outside the scope of such institutional arrangements.

The outputs generated by the simulation engine are exploratory representations of scenario-based interactions between infrastructure systems. They do not constitute deterministic forecasts, official risk assessments, engineering certifications, regulatory determinations, or legally binding planning instruments. They should not be interpreted as operational instructions.

The modelling framework relies on network-structure assumptions, interdependency matrices, and datasets available at the time of development. As with any system-level model, results are conditioned by data quality, completeness, updating frequency, and by the parameters selected for each scenario. Uncertainties are inherent and may affect outcome sensitivity.

This platform does not replace the technical analyses, statutory procedures, or formal risk assessments required under applicable legislation concerning civil protection, infrastructure safety, land-use planning, emergency management, or public-service regulation.

Users are responsible for verifying the adequacy and contextual applicability of the input data used in each simulation and for independently assessing the relevance of the results within their institutional and regulatory framework.

Any operational, administrative, strategic, or policy decision informed by this platform must be evaluated and validated by the competent authorities in accordance with their own technical criteria and legal obligations.

The developers, researchers, and participating institutions assume no liability for decisions derived from, informed by, or based upon the outputs produced by this simulation tool.

Contents

1. The GENESIS project

GENESIS (Geologically Enhanced NaturE-based Solutions for climate change resiliency of critical water InfraStructure) is an EU-funded Horizon Europe project focused on making critical water infrastructure more climate-resilient in island territories, especially in Macaronesia, where groundwater is the main freshwater source and is highly exposed to climate stress.

What makes GENESIS distinctive is the mix of Macaronesian, geology-informed nature-based solutions, such as dry galleries and underground dyke-impounded dam systems, combined with more "standard" NbS like rainwater harvesting and wetland restoration. The idea is to create synergies and test what really works under non-linear, island constraints.

At its current stage (TRL ~7), GENESIS operates as a demonstration framework across several Macaronesian islands, with multiple pilots including La Palma, El Hierro, and Gran Canaria, and it aims to deliver a deep demonstrator in La Palma, with a long-term goal of producing approaches that can be replicated in other islands and vulnerable mainland areas.

GENESIS is not limited to abstract NbS concepts. It focuses on the capture, storage and protection of freshwater from different sources, the improvement of use and reuse efficiency, and the strengthening of system resilience to drought, flooding and wildfire. These objectives are pursued through technically grounded measures in island hydrogeology and are evaluated under real operating conditions.

Link to the project: https://genesisnbs.eu/

2. Executive summary

This report describes the GENESIS–La Palma platform, a cascading failure simulation tool designed to simulate impacts induced by natural processes in La Palma's (Canary Islands) hydraulic systems and critical infrastructure. Developed within the EU-funded Horizon Europe project GENESIS, the platform models the interdependencies between different essential services, including water, energy, healthcare, transport and communications. This platform enables to evaluate how a localised disturbance may propagate across the island-wide network.

La Palma is a volcanically active island and the northwesternmost island of the Canary archipelago, with a population of about 86,000 inhabitants. Its steep volcanic relief, strong spatial climatic variability and uneven distribution of available water resources shape water management across the island. The island's water infrastructure forms a complex and interconnected system designed to transfer and redistribute water from the main producing areas in the northern sectors of the island, together with additional sources incorporated along the network, toward areas with more limited local availability or higher demand for drinking water and irrigation. Groundwater is the island's primary water source, accounting for 96% of total water production through galleries, wells and springs operating predominantly under gravity. However, this apparent robustness coexists with structural vulnerabilities, including the concentration of electricity generation (90% diesel) in coastal infrastructure; dependence on critical nodes such as the Aduares–Hermosilla pumping system; the routing of water conveyance corridors across steep volcanic terrain prone to slope instability; and the legacy impacts of the 2021 Tajogaite eruption.

The model includes 2454 nodes corresponding to 37 categories of critical services. It represents interdependencies between water supply, energy generation and distribution, transport infrastructure, telecommunications, and essential public services.

The island depends heavily on fossil fuels, diesel generators supply 90% of the energy, while only 10% are produced by renewable energy (wind 7% and solar 3%) (Santamarta et al., 2026; REE, 2025).

To demonstrate the platform's functionality, three scenarios are presented: an island-wide volcanic eruption, coastal flooding in the Santa Cruz–Breñas eastern sector, and wildfires in the central-western sector of La Palma under the 2100 GENESIS climate projection. The simulated scenarios allow for the assessment of potential cascading effects on infrastructure integrity and service continuity. They also provide indicative estimates of impacts on population groups, workforce availability due to school closures, and agricultural areas affected by interruptions to irrigation supply.

Main findings

1. **The main risk is not water scarcity, but the spatial concentration of critical infrastructure.** The 19 fuel tanks supporting the diesel power generation, are located along the coastal front between Breña Alta and Santa Cruz, where they are exposed to coastal flooding.

2. **The Aduares-Hermosilla pumping station is a critical water conveyance node.** After the Tajogaite eruption, several conveyance channels were disconnected by lava flows, and the channel LP-III experienced flow reductions. As a result, the role of the Aduares-Hermosilla pumping station in maintaining supply was reinforced, especially for the south-western sector of the island.

3. **Hydrogeological compartmentalisation is both a source of vulnerability and resilience.** Geological heterogeneity, with dyke-impounded volcanic aquifers, restricts groundwater flow connectivity, but can also limit disturbance propagation and enable some operational redundancy between compartments.

4. **Selective protection of the fuel tanks can substantially reduce cascade propagation.** The simulation demonstrates that protecting the 19 fuel tanks located between Breña Alta and Santa Cruz against coastal flooding can limit cascading failure spread across the system.

5. **Real-time operational data is lacking**. Water abstractions, managed by several parties, including irrigation communities, municipalities, private operators and La Palma's Water Council, don't have a unified control or telemetry system. This lack of information limits the systematic integration of flow and piezometric data into a centralised monitoring platform, reducing the overall observability of the system.

3. Introduction

A brand-new high-performance simulation engine modelling the cascading failure of critical infrastructure services has been developed from the ground up using a new proprietary algorithm by the contractor "*Ramparts & Light limited*" in the Rust programming language (a new language known for its safety and performance, as it reduces loading times and consequently improves user experience) and applied to three complete case studies (Canary Islands of El Hierro, La Palma and Gran Canaria).

The proprietary cascading failure engine uses complexity science coupled with network science, as well as principles akin to economics and disease propagation modelling to introduce a co-dependency between population and critical services, where the nodes represent infrastructures whose disruption could propagate through interdependencies, potentially triggering cascading failures across connected sectors.

Specific and relevant demography and employment data are applied for each smallest electoral district in order to obtain sufficient granularity when capturing the feedback loop between critical service disruptions and population e.g. when a disruption to critical services impacts the population and workforce availability, that in turn impact critical services again. The introduction of a co-dependency between population and critical services is extremely important for the accuracy of the model because demography can amplify or absorb disruptions to critical services up to a considerable degree. One common example is how one particular industry can be disproportionally impacted if most of its workforce is composed of working parents of young children – in that case, closure of primary schools will have a significant impact on productivity in that sector.

Simulated results display the state of critical services as well as the impact on the population at a generic level down to the smallest electoral statistical area level (akin to a neighbourhood size wise). This level of precision allows not only to think in terms of emergency reactive planning, but also in terms of pre-emptive strategic thinking.

Some defining exploratory features of the simulation engine are the ability to simulate what would happen if certain critical nodes were shielded from a specific type of damage (i.e. if a node is protected from flood damage), what would happen if some critical nodes were undisturbed by disruption to some input services (e.g. a backup generator will make the node impervious to a decrease in power input service), and what would happen if some infrastructure node could be switched from providing one type of service to providing another, effectively changing the topology of the interconnected networks to manipulate the resilience of the system as a whole. Another notable feature is the possibility to introduce additional layers of factors impacting critical services interdependencies e.g. adding hydrology areas where reservoirs depend more on a certain type of input source than another.

Finally, from the disruption to critical services, additional impacts derived from GENESIS climate scenarios can be calculated e.g. how an increase in the predicted number of high temperatures and extreme wind alerts can increase expected damages from forest fires to crops for example. For more detailed information on the GENESIS Climate Projections, refer to Reyes Parrilla (2025).

Models capturing the interdependencies between critical infrastructure services were created and tailored for each one of the three islands. These models show significant differences regarding the way critical infrastructure services relate to water and energy between El Hierro, La Palma, and Gran Canaria.

The presented work is not just an evolutionary but a qualitative step up from exploratory proof of concepts of cascading failure engines developed within other HORIZON projects such as ARSINOE and NATALIE in the sense that the new proprietary simulation engine can deliver comparable results a hundred to a thousand times faster, with fundamentally new groundbreaking features such as real-time GIS based network topology reconstruction when switching critical node roles. The implications are that:

(i) It is possible to prepare for disruption and improve resilience in advance by prioritising limited resources to identify and protect critical assets.

(ii) It enables the identification of what type of input service vulnerabilities can be protected by which appropriate backups.

(iii) It facilitates the identification of critical infrastructure nodes that can switch roles to create an adaptable resilient network akin to the human brain (where plasticity allows other neurons to take over the function of a damaged neuron to keep the overall system able to perform critical tasks).

In this work, the critical infrastructure services are exposed to different types of disruptions. The RIESGOMAP project ("Prevention of Natural and Technological Risks in Territorial and Urban Planning - RIESGOMAP", 2013) belonging to the Madeira-Azores-Canarias Transnational Cooperation Program is used to provide six different types of disruptions: volcanic eruptions, earthquakes, forest fires, landslides, coastal floods, and fluvial floods.

Work developed in GENESIS adds a climate-based modifier to these baseline disruptions, using the projected number of alerts per year (+1% damage per alert). This modifier is applied for three future periods: 2050, 2075 and 2100; which represent near-, mid- and long-term climate conditions relative to the present baseline.

(i) For forest fires, the damage is increased by 1% for each wind alert and each high temperature alert that impacts a critical infrastructure node. E.g. if you have a node that would normally have a health of 50% after disruption in a normal RIESGOMAP scenario, you will subtract 1% x 10 wind alerts and 1% x 5 high temp alerts, which amounts to subtracting in total 15% to the integrity of the node.

(ii) For landslides, the damage is increased by 1% for each precipitation alert.

(iii) For coastal floods, the damage is increased by 1% for each storm alert, wind alert (wind has a significant role in these), and coastal alert.

(iv) For pluvial floods, the damage is increased by 1% for each precipitation alert, and storm alert.

Users can apply these scenarios to a chosen area or several of them and see the consequences on critical infrastructure services in general, look at the impact on services per area on the map, check workforce availability for the area, examine impact on the population, and see the state of different crops after disruption. Details on the nodes used for each island, the hazards encountered, and the resulting cascading failures are provided below.

4. Cascading-failure platform: operational definition

A cascading-failure simulation platform can be described as a computational framework used to represent interdependencies between critical infrastructure systems. Its purpose is to examine how an initial disturbance may propagate across connected services and generate indirect impacts beyond the directly affected assets. In La Palma, this approach is especially relevant due to the inherent energy dependence of the water supply system. Water distribution to the southern areas of the island relies on pumped conveyance over steep volcanic terrain, which increases vulnerability to service interruptions.

What it simulates and what it does NOT simulate

The platform simulates:

(i) the topology of the critical infrastructure network (2454 nodes, 37 service types);

(ii) functional dependencies between interconnected systems (water, energy, transport, telecommunications);

(iii) temporal propagation of service degradation;

(iv) progressive reduction of functional integrity under defined hazard scenarios.

The platform does not simulate:

(i) detailed hydraulic behaviour (head losses, pressure transients up to 50 kg/cm²);
(ii) price dynamics;
(iii) real-time human decisions;
(iv) physical evolution of hazards.

Minimum input components

(i) **Geospatial inventory of critical infrastructure and service assets:** location, function and operational capacity (e.g., groundwater abstractions for drinking water and irrigation, desalination plants, transmission pipelines, pumping stations, storage tanks and reservoirs, energy generation and distribution nodes, transport facilities and essential service nodes).

(ii) **Interdependency matrix:** defining functional dependencies between infrastructure and service sectors, with energy-source weighting included as a system parameter (for La Palma: diesel 0.9, renewable 0.1).

(iii) **Spatial hazard or disruption layers:** used to define scenario-based initial disturbances.

(iv) **Failure propagation logic:** based on service-dependency thresholds, where node functionality degrades or fails when required input services fall below defined operational levels.

Model output metrics

These indicators are derived from demographic and socioeconomic datasets integrated into the modelling framework and should be interpreted as indicative system-level estimates.

(i) **Global system integrity:** normalized aggregate service functionality (%).

(ii) **Category-level integrity:** functionality percentage relative to maximum capacity within each infrastructure or service category.

(iii) **Workforce availability by industry:** sectoral reduction in workforce participation due to school closures, based on affected parents, differentiating single-parent and two-parent households.

(iv) **Population impact by service type:** number and percentage of people experiencing 10–50% and >50% functionality loss for each essential service, disaggregated for total population, vulnerable groups (aged <5 and >85) and economically deprived groups (income below defined threshold).

(v) **Agricultural integrity by crop type:** cultivated area (descriptive attribute), starting integrity (direct hazard impact) and integrity after cascading failure (reflecting irrigation service disruption).

Assumptions and uncertainty

The platform is intended for exploratory, scenario-based analysis. Results depend on modelling assumptions and on the quality and completeness of the available datasets. For that reason, outputs should be interpreted as system level representations of potential cascading dynamics, not as precise forecasts of specific outcomes.

Principal assumptions and sources of uncertainty include:

(i) **Availability of backup power at pumping stations.** The model presumes that diesel backup generators are both present and operational. In practice, their effectiveness depends on site physical accessibility, equipment condition, start-up reliability, fuel reserves, and the logistics of fuel supply during a disruption.

(ii) **Repair and restoration durations.** Recovery processes are simplified. In areas of steep terrain with limited alternative access, actual restoration times may exceed those assumed, particularly when road access is restricted or multiple assets fail simultaneously.

(iii) **Infrastructure condition and degradation.** The current cascading failure simulation does not explicitly account for asset age, corrosion, material fatigue, or deterioration associated with high-pressure segments in pipelines or coastal exposure. These factors can influence both failure probability and recovery duration.

(iv) **Simplified representation of the water system.** As groundwater accounts for 96% of the island's supply, water distribution is modelled mainly from this source. Surface water and the small desalination plant are yet to be fully integrated into the cascading failure analysis.

(v) **Hazard scenarios.** Hazard disturbance layers represent scenario impacts in a simplified form. They do not reproduce the physical progression of hazards or fine scale spatial variability, both of which can condition direct damage and site accessibility.

(vi) **Dependency thresholds and propagation rules.** Cascading dynamics development is determined by the adopted dependency configuration, threshold values, and criticality weighting. Alternative parameter settings can produce different propagation sequences; results are therefore sensitive to these modelling choices.

Where feasible, uncertainty should be reduced through progressive refinement of input data, including updated asset inventories, operating parameters, telemetry integration, and confirmed backup characteristics, together with targeted sensitivity analysis of influential variables.

5. La Palma: socioeconomic profile and natural constraints

La Palma is the northwesternmost island in the Canary Islands (Figure 1). It forms the emergent portion of a large volcanic edifice that rises approximately 6,500 m from the Atlantic abyssal plain, reaching an elevation of 2,426 m a. s. l. (Carracedo, 2011). The island covers an area of 708 km^2 and has a population of 86297 inhabitants (INE, 2025). The island's hydrogeology reflects its volcanic origin, comprising a complex system of dyke-impounded aquifers and highly permeable volcanic formations. La Palma's climate is considered subtropical, with an average annual rainfall of 628 mm, where around 41% of this rainfall infiltrates and recharges the aquifers (CIALP, 2023; Santamarta et al., 2025a). Groundwater generally flows from the summit towards the coast, but the dyke barriers disrupt this movement, producing inland piezometric levels reaching up to 1800 m (Custodio, 2020). The economy in 2023 is largely service-oriented, accounting for 88% of activity, while the primary sector, though accounting for only 4% of the economy, remains important in terms of land use and water demand, particularly for banana plantations and vineyards (ISTAC, 2023) (Tables 1 and 2).

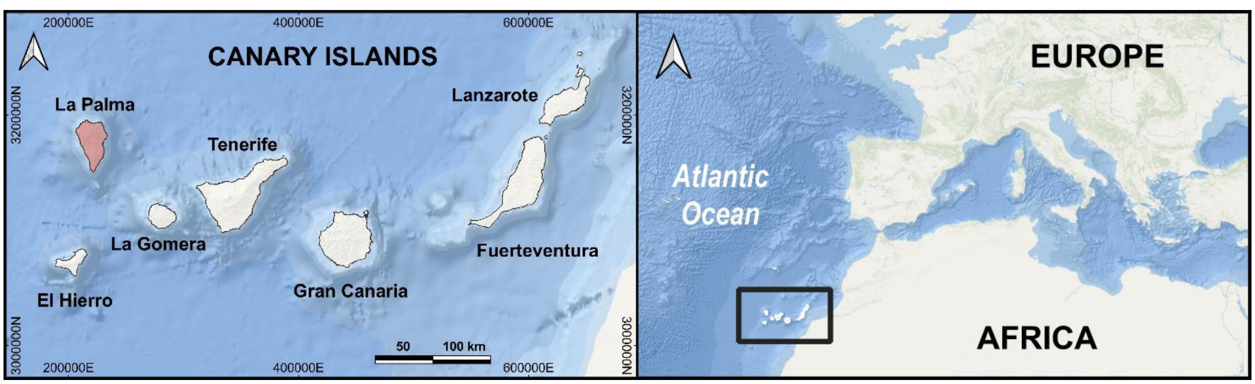

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Figure 1. La Palma's location within the Canary archipelago and wider regional context.

Source: authors' elaboration (2026)

Table 1. Socioeconomic indicators for La Palma. Latest available year shown per indicator; values are not intended to represent the same reference year.

Indicator	Value
Resident population (2025)	86,297
Island GDP (est. 2023)	≈ 1,750 M €
GDP per capita (2020)	≈ 20,000 €
Economic structure (2024)	Services 88%; construction 5%; primary 4%; industry 3%
Passenger arrivals (2023)	233,000 visitors
Cultivated area (2023)	≈ 10,936 ha
Main agricultural uses	Banana (≈ 60% agricultural surface used (SAU)), avocado, vineyard

Sources: Santamarta & Cruz-Pérez, 2025; CIALP, 2023; Instituto Canario de Estadística (ISTAC, 2024).

Table 2. Physical constraints of the water system

Variable	Value / Description
Geological age	≈ 1.8 Ma
Area	708 km²
Maximum elevation	2,426 m a.s.l. (Roque de los Muchachos)
Mean annual precipitation	628 mm/year
Horizontal rain[1]	Up to 150 mm/year at intermediate elevations in the cloud forest belt (600-1200 m a. s. l.)
PET[2]	900-1200 mm/year
Effective recharge	150-180 mm/year in humid zones; 48% evaporates; 41% infiltrates and recharges aquifers (≈ 177 hm³/year)

[1] **Horizontal rain (fog precipitation)** refers to water inputs generated when wind-driven fog or low clouds are intercepted by vegetation (canopy) or collectors; droplets coalesce on surfaces and drip to the ground, contributing to effective precipitation even when rainfall is low (Santamarta Cerezal & Seijas Bayón, 2010).

[2] **Potential evapotranspiration** (PET) refers to the amount of water that can evaporate and transpire from a plant-covered surface when it isn't subject to water stress, whether because of deficit or excess of moisture. It depends on the location, temperature, wind speed and humidity (Santamarta, 2013).

Recent volcanic activity	2021 Tajogaite eruption of Cumbre Vieja Impacts: damage and burial of water infrastructure; ash deposition in open reservoirs; and local geochemical alterations and changes in groundwater flow conditions.

Sources: Santamarta & Cruz-Pérez, 2025; CIALP, 2023.

Operational implications

La Palma has an annual groundwater availability of 253 hm^3, of which only 66 hm^3 are currently abstracted (exploitation index of 0.26). However, the Valle Aridane-Tazacorte groundwater body operates at an index of 0.7, approaching poor quality status (CIALP, 2023). The island is not at risk due to water availability, but rather because of the spatial concentration of vulnerabilities:

- **Critical pumping infrastructure:** Certain pumping systems are essential for water distribution. For example, the Aduares-Hermosilla pumping system has become critical since the Tajogaite eruption, as it now plays a key role in supplying water to the south-western part of the island.
- **Energy dependency:** Around 90% of the electricity produced on the island comes mainly from diesel, which adds an additional vulnerability, not only because of the dependence on an external resource, but also because the fuel is stored along the coastal front, an area exposed to marine storms and coastal flooding.
- **Slope exposure:** Part of the infrastructure is located in gravitational collapse zones. This exposure may affect the physical integrity of the infrastructures and hinder access for repair and maintenance after the disruptive events.
- **Fragmented governance:** Water management on La Palma is shared between municipalities, private operators and the La Palma Water Council. Groundwater management follows a fragmented multi-community structure, with numerous local water communities and a large number of galleries, wells and springs distributed across the island (CIALP, 2023). The lack of a fully unified control system with telemetry limits the systematic integration of flow and piezometric data.

6. La Palma hydraulic system: structure and sources

Water sources

La Palma's water supply system is highly dependent on freshwater resources. Approximately 96% of the island's water production comes from groundwater, which is abstracted through galleries, wells and springs. The remaining 4% is supplied mainly by surface water, with a potential contribution from a small desalination plant located in Los Cancajos (Santamarta et al., 2026; CIALP, 2023) (Table 3).

Table 3. Water sources in La Palma (2020/2021)

Resource	hm³/year	%	Notes
Groundwater	60.8	96%	Water abstraction through galleries, wells, and springs
Surface water	3.7	≈ 4%	From Barranco de Las Angustias and Balsa de Barlovento
Seawater desalination	0.0003	≈ 0%	Small desalination facility in Los Cancajos; contribution negligible in 2020/2021
Reclaimed water	0	0 %	Pilot plant in Los Llanos

Sources: Santamarta & Cruz-Pérez, 2025; CIALP, 2023.

The fact that most of the island's water supply relies on groundwater can be considered both a strength and a risk. It represents a strength because it implies that recharge conditions are favourable, and because in many areas this resource can be abstracted by gravity. However, it also represents a risk, as the entire demand depends on a single resource. In addition, at the time represented in Table 3 (2020/2021), desalination played a negligible role in La Palma's water balance. However, following the 2021 Tajogaite eruption, small-scale desalination units gained relevance as emergency backup resources within the island's supply strategy. Furthermore, unlike other Canary Islands, La Palma doesn't yet reuse treated wastewater for agricultural irrigation, using its freshwater resources for both drinking water and agriculture (CIALP, 2023; Santamarta, et al., 2026).

Consumption by sector

Table 4. Water consumption by sector (2021)

Sector	Demand (hm³/year)	%	Source and notes
Agricultural	69.1	86.7%	Primarily banana and avocado; under drip irrigation.
Urban-domestic	8.8	11%	Disperse population, accounts for ~15% distribution network losses.
Industry and services	0.5	0.6%	Small agro-industrial sector oriented toward export markets.
Recreational uses	1.3	1.7%	Rural tourism, hiking, spa resorts.

Sources: Santamarta & Cruz-Pérez, 2025; CIALP, 2023.

Note: The apparent difference between total water production (Table 3, reference year 2020/2021, ~64.5 hm^3/year) and total water demand (Table 4, reference year 2021, ~79.7 hm^3/year) reflects several compounding factors. The 2020/2021 production figure corresponds to a period of reduced groundwater abstraction, partly associated with the disruption caused by the 2021 Tajogaite eruption and pre-eruption conditions. Additionally, distribution network losses (estimated at ~15% in the urban sector, and likely significant in open-channel irrigation infrastructure) are not deducted from demand figures. Finally, a proportion of groundwater abstractions managed by private water communities may not be fully captured in official statistics. These factors together account for the observed gap and do not indicate a structural water deficit under normal operating conditions.

Agriculture's significant water demand means that any disruption to irrigation can have a direct economic impact, potentially extending beyond the physically affected area. Regarding industry, water use is limited, restricted to small agri-food facilities and auxiliary services. At present, tourism doesn't play a significant role in the island's water consumption. However, projections of increased demand highlight the need to integrate water efficiency and reuse measures in the future to protect the island's water sources (Santamarta & Cruz-Pérez, 2025).

Main groundwater abstraction points

La Palma has five groundwater bodies (CIALP, 2023):

- **Insular slopes (ES70LP001):** The main water reservoir, with good quality and abstracted through several galleries.
- **Coastal (ES70LP002):** Where most operational wells are located.
- **Basal complex (ES70LP003):** Mass associated with the impermeable materials of the basal complex, where water flows through fractures and discontinuities. It has limited potential as an aquifer due to its low water quality, with high sulphate concentrations.
- **Southern ridge (ES70LP004):** Aquifer associated with the residual volcanism on La Palma, characterised by the presence of volcanic CO_2, and not suitable for drinking or irrigation use.
- **Valle de Aridane–Tazacorte (ES70LP005):** Groundwater body delineated and classified as vulnerable to nitrate contamination from agricultural sources, including domestic and livestock contributions.

Groundwater status

Quantitative status. The mean exploitation index is 0.26 but rises to around 0.70 in the Valle de Aridane–Tazacorte groundwater body, indicating localised stress points within the island's system.

Qualitative status. Available information from hydrological planning indicates that water quality varies between groundwater bodies. The best water quality is generally found on the island's slopes, whereas in the coastal groundwater body, quality can vary. The southwestern coast has chloride concentrations above 600 mg/L due to seawater intrusion. Nitrate concentrations are generally below 25 mg/L, except in the Valle de Aridane–Tazacorte groundwater body, where values can exceed 50 mg/L. In addition, diffuse CO_2 emissions associated with residual volcanism have long been documented in the southern sectors of the island, which has limited the use of the corresponding groundwater body and requires water to be conveyed from other parts of the island (Jiménez Sánchez et al., 2022). Following the 2021 Tajogaite eruption, additional geochemical changes linked to volcanic activity have been recorded in the central and southern sectors (García-Gil et al., 2023; Jiménez et al., 2024); however, no significant impact on drinking water quality has been observed across the island (Koritnik et al., 2025).

Water conveyance and storage infrastructure

Water transport on La Palma is based primarily on gravity conveyance through a system of pipelines and narrow open channels organised around three main transport lines (LP-I, LP-II and LP-III). These channels collect flows from galleries, springs and storage reservoirs and distribute water progressively along the eastern and western slopes of the island, supplying both irrigation and urban demand (Figure 2). Closed pipeline sections are mainly used to convey water to drinking water reservoirs, while open channels predominantly distribute irrigation water. In addition to the gravity system, the Aduares pumping station transfers water from the eastern side of the island to Hermosilla on the western side, supporting supply to several western sectors and gaining importance following the Tajogaite eruption.

Drinking water is stored in closed tanks where it undergoes disinfection, typically through free chlorination, before being distributed through municipal distribution networks. Each municipality operates its own storage facilities, which can also be managed manually when required. Irrigation water is stored in open reservoirs dedicated to agricultural use. While conveyance may be shared along parts of the system, drinking water and irrigation water are distributed separately, ensuring that potable water undergoes regulated treatment and storage before consumption.

Groundwater management follows a multi-community model. According to the La Palma Hydrological Plan for 2021-2027, the water conveyance network will be modernised through the digitalisation of flow meters. In addition, drought conditions will be identified when spring discharge falls below 200 L/s, and when total reservoir storage drops below 2 hm^3. The La Palma Water Council (CIALP) manages a total of 12 reservoirs across seven municipalities. These have a combined storage of 10 hm^3, of which approximately 5 hm^3 are currently stored (49%) (Table 5). Wastewater is managed separately through dedicated sanitation infrastructure for collection, treatment and discharge.

Table 5. Reservoir storage in La Palma (2026)

Municipality	No. of reservoirs	Capacity (hm^3)	Storage level (March 2026)
Barlovento	1	1.76	25%
San Andrés y Sauces	4	0.74	≈77%
Puntallana	1	0.13	44%
Los Llanos de Aridane	2	0.50	≈74%
Tijarafe	1	1.39	47%
Puntagorda	2	0.21	≈83.5%
Fuencaliente	1	0.11	46%

Source: CIALP, 2026.

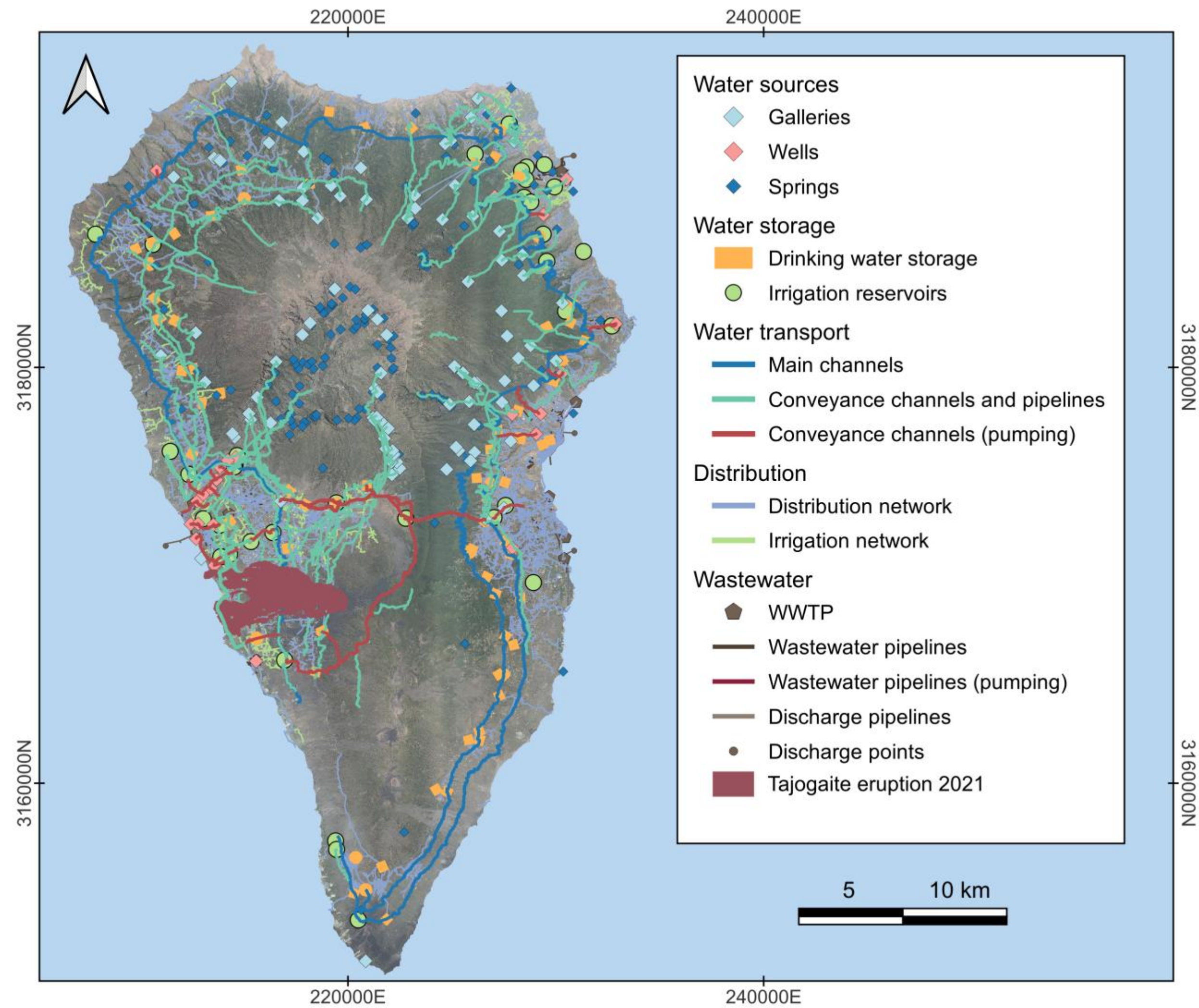

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Figure 2. La Palma's water supply system and infrastructure. Tajogaite eruption 2021 denotes the mapped extent of lava flow hazard.

Source: authors' elaboration based on data from CIALP and IDECanarias (2026).

Lessons from the Tajogaite eruption (2021)

The Tajogaite eruption of Cumbre Vieja, which lasted from September to December 2021, caused significant disruption to the island's water and energy infrastructure (García-Gil et al., 2023; Koritnik et al., 2025). The main impacts included:

- Hydrogeological and hydrogeochemical changes in the island's groundwater system (García-Gil et al., 2023; Jiménez et al., 2024).
- Burial and damage of water conveyance infrastructure and storage reservoirs.
- Localized disruption of road connections due to lava flows, temporarily isolating parts of the inhabited area. The eruption also generated cascading impacts across the road network (Dominguez et al., 2025).
- Damage to underground electricity lines.
- Shift of the Aduares-Hermosilla pumping system from an auxiliary to a critical supply role.
- Deployment of portable mini-desalination capacity as part of the island's emergency water supply system.

These events highlighted that resilience can't be assessed only through water balance, but rather through the functional redundancy of critical nodes within the system (Santamarta et al., 2026).

7. GENESIS–La Palma cascading-failure simulation platform

Factsheet: size and complexity

The model includes 2,454 nodes distributed across 37 categories of interdependent critical infrastructure services (Figure 3). The assessment of agricultural impacts takes into account about 51,450 fields. In this public summary, in which security sensitive information is not included, asset categories are described at a generalized level; site-specific identifiers and operational details are omitted. The scope encompasses the principal systems that determine service continuity on the island:

- **Water system:** groundwater abstraction (water galleries, wells, springs), pumped and gravity conveyance, main water conveyance channels LP-I/II/III, drinking water storage and distribution, irrigation storage and distribution, and wastewater treatment and distribution.
- **Energy system:** electricity generation (diesel and renewable energy), fuel storage and supply, and electricity distribution.
- **Transport and telecommunications:** key transport nodes and functional connectivity, together with radio/TV, broadband, and mobile network infrastructure.
- **Essential services:** health and emergency services, public administration functions, food supply, and primary/secondary education, represented as service categories rather than as operational guidance.
- **Agriculture:** agricultural areas classified by crop type, used to explore irrigation-related impacts under service disruption.

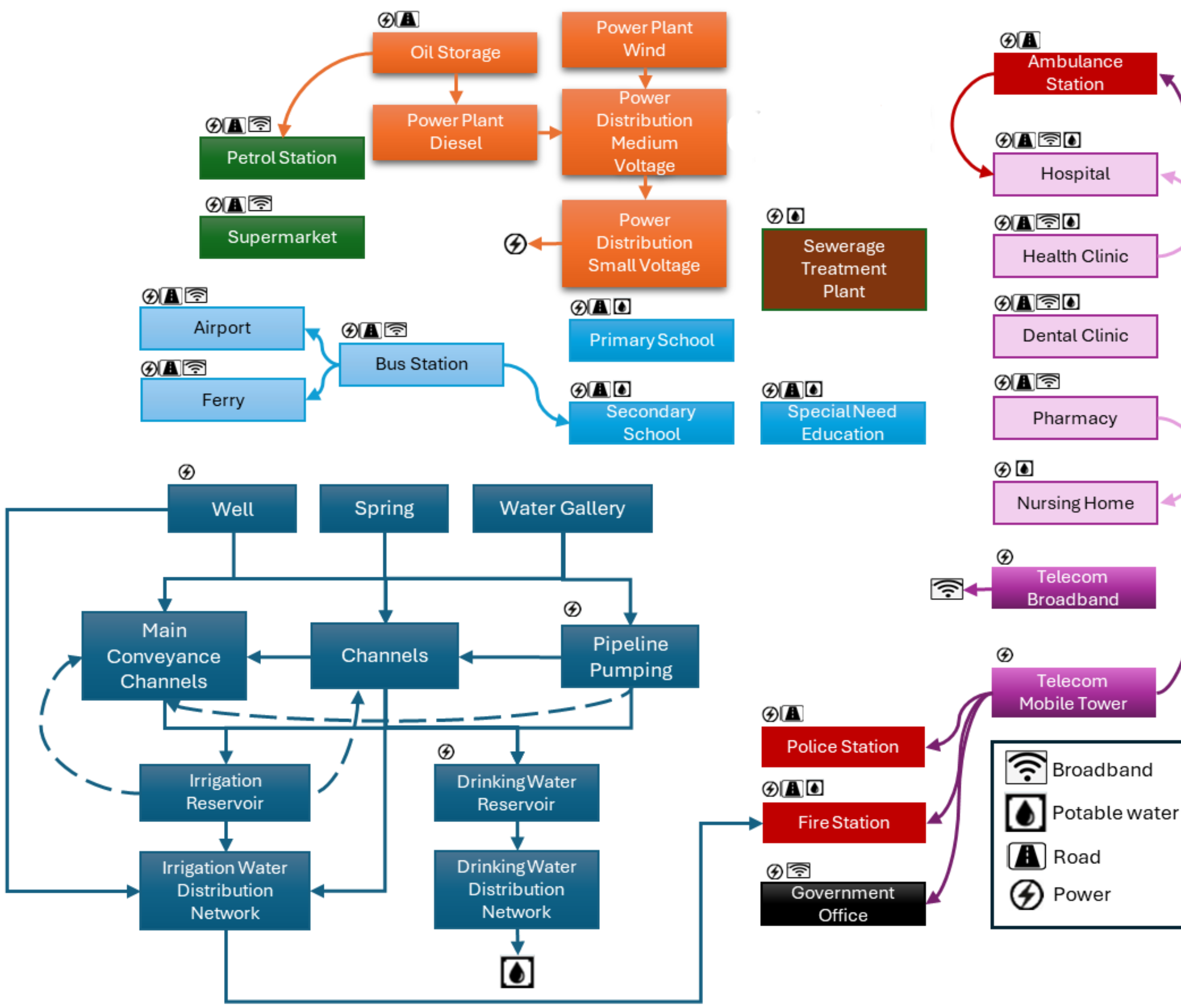

Figure 3. Simplified view of service dependencies between the 37 types of Critical Infrastructure nodes in La Palma.

Criticality weights

Criticality weights are applied to indicate the degree of dependence of certain service categories on specific upstream inputs. In this model, weights were defined on the basis of reported production shares, the mapped dependency structure of the infrastructure inventory, and expert assessment. They represent modelling parameters intended for scenario analysis and can be adjusted as required.

- **Energy.** Weights assigned to the electricity distribution nodes reflect the island's generation mix: diesel 0.9 and renewable energy (wind) 0.1.
- **Drinking water distribution.** Weights for the water distribution are designed according to the hydrogeological area, the source of the water (main conveyance channels, local conveyance channels, or municipal water storage reservoirs), and whether it's delivered by pumping or by gravity.
- **Irrigation reservoirs.** Irrigation storage and distribution are modelled as systems supplied by multiple inputs, depending on each hydrogeological area and the origin of the water (local conveyance channels, main conveyance channels, or pumped conveyance). In the case of the irrigation distribution network, supply also depends on additional sources, including wells and irrigation water reservoirs.

These weights do not constitute audited operational fractions. They provide a practical way to explore how changes in dependencies influence cascading dynamics in the simulated scenarios.

Demonstrative simulated scenarios

Three scenarios are included to demonstrate how the platform functions under different types of disturbance:

- **Coastal flood in Las Breñas and Santa Cruz.** A coastal flood scenario in Breña Alta, Breña Baja and Santa Cruz de La Palma, was simulated. Results show how despite being a quite localised coastal flood, the impact goes well beyond the main impacted area, as it affects the diesel power generator that provides 90% of the energy for the whole island. This scenario also includes the simulation of what could happen if the impacted oil tanks were shielded from flood damages.
- **Forest fires in El Paso, Breña Alta and Los llanos under the 2100 climate projection.** This experiment shows the consequences of wildfires taking place in the regions of

El Paso, Breña Alta and Los Llanos de Aridane, with increased disruption from wind alerts, and high temperature alerts (+1% damage to an already impacted node per alert) estimated for 2100 over the area.

- **Island-wide volcanic eruption.** An island-wide volcanic eruption in La Palma. Results show that the impact can be higher because of the cascading failures. Crops aren't only affected by the direct damage, but also by indirect damage as the irrigation network fails to supply water (Santamarta et al., 2026).

Use for prioritizing interventions

The platform is intended to support exploratory comparison of resilience options. In practice, it can be used to:

(i) highlight candidate high-centrality nodes and functions (e.g., major abstraction points, pumped conveyance corridors, and strategic reservoirs);

(ii) test how targeted protection measures may change failure propagation pathways under different scenarios;

(iii) compare configurations with and without contingency measures, such as backup energy generation, backup water storage, or telecommunications redundancy;

(iv) support prioritisation discussions by using various criteria (for example, reduction in the exposed vulnerable population and reduction of agricultural area affected by irrigation disruption), rather than relying on a single metric.

8. Cascading failure examples in La Palma

Experiment 1: Coastal flood in Breña Alta, Breña Baja and Santa Cruz de La Palma

This experiment shows the consequences of a coastal flood taking place in the coastal area of these three municipalities, and what could happen if impacted oil tanks (linked to the diesel power generator that provides 90% of the energy for the whole Island) were shielded from flood damages. Figure 4 shows the integrity scores for each critical service (these percentage scores represent the sum of all services produced by all nodes per category over their maximum possible combined output) without protecting the oil tanks (left) and applying a shield on these tanks (right). Figure 5 shows an estimation of the number of people facing a critical service loss where these services are impacted by 10-50% service loss, and above 50%. Figure 6 shows an estimation of how workforce availability per type of industry is impacted by the fact that services such as primary schools and secondary schools are closed, preventing some parents from going to work. Figure 7 shows how crops are affected by the coastal flood scenario.

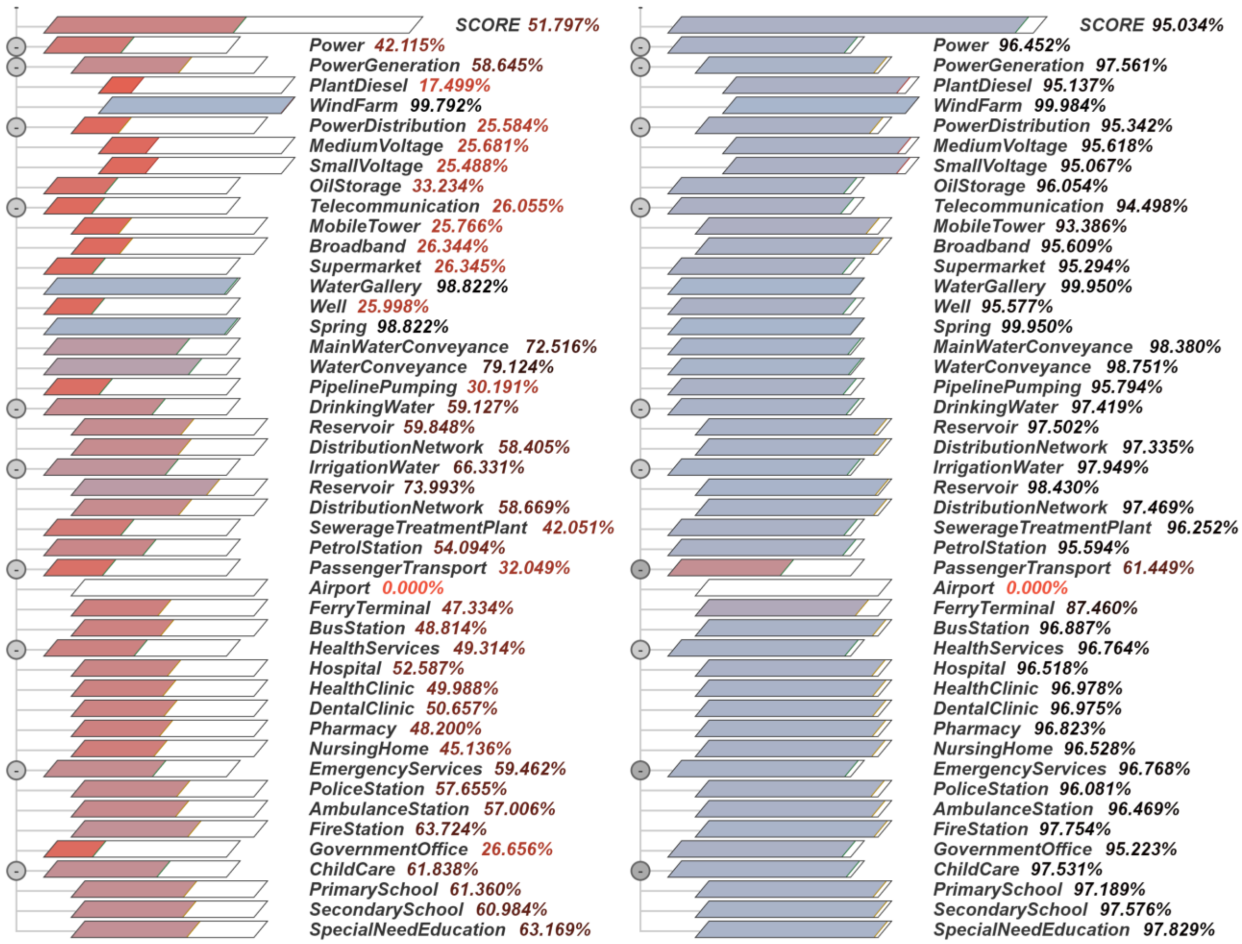

Figure 4. Simulated effects of a coastal flood on critical infrastructure services in La Palma (left) vs the same coastal flood where 19 oil tanks linked to the diesel power generator that supplies 90% of the electricity in the island are shielded from flood damage (right).

Service	People Facing 10-50% Service Loss	People Facing (+50%) Service Loss
Pharmacies	34.134 (40.9%)	49.246 (59.1%)
Hospitals	83.380 (100.0%)	0 (0.0%)
Health Clinics	36.130 (43.3%)	47.250 (56.7%)
Dental Practices	55.094 (66.1%)	28.286 (33.9%)
Bus Transport	83.380 (100.0%)	0 (0.0%)
Mobile Telecommunication	0 (0.0%)	83.380 (100.0%)
Clean Water	51.495 (61.8%)	31.885 (38.2%)
Power	0 (0.0%)	83.380 (100.0%)
Total Population		83.380

Figure 5. Simulated effects of a coastal flood on the number of people facing critical infrastructure loss of service between 10-50% and above 50%.

Industry	Workforce (Current / Initial)	Availability (%)
G Comercio al por mayor y al por menor; reparación de vehículos de motor y motocicletas	3694 / 3933	93.93%
I Hostelería	2621 / 2786	94.09%
O Administración Pública y defensa; Seguridad social obligatoria	2617 / 2795	93.62%
Q Actividades sanitarias y de servicios sociales	2434 / 2589	94.02%
A Agricultura; ganadería; silvicultura y pesca	2306 / 2461	93.69%
F Construcción	2247 / 2397	93.75%
P Educación	2178 / 2319	93.91%
C Industria manufacturera	1295 / 1382	93.70%
S Otros servicios	1046 / 1114	93.87%
H Transporte y almacenamiento	1030 / 1100	93.68%
M Actividades profesionales; científicas y técnicas	794 / 847	93.71%

Figure 6. Simulated effects of a coastal flood on workforce availability in La Palma.

Crop Type	Area (m²)	Starting Integrity	Integrity after cascading failure
Hortaliza Otras Mezclas	853,273	100.0%	61.6%
Batata	159,862	100.0%	57.5%
Higuera	153,483	100.0%	63.7%
Tunera	204,478	100.0%	72.1%
Platanera	26,761,245	99.9%	56.0%
Cítricos	1,554,240	100.0%	67.0%
Templado Pepita	341,677	100.0%	75.2%
Viña	8,792,181	100.0%	58.8%
Mango	562,924	97.2%	55.6%
Subtropicales Otras Mezclas	811,345	100.0%	56.8%
Olivo	239,995	100.0%	62.1%
Millo	45,232	100.0%	56.3%
Tagasaste	1,549,673	100.0%	55.2%
Papa	1,023,718	100.0%	67.5%
Aguacate	10,872,876	100.0%	58.6%

Figure 7. Simulated effects of coastal flood in La Palma. Indirect damages due to loss of irrigation are very significant compared to direct damages.

Experiment 2: Forest fires in El Paso, Breña Alta and Los Llanos de Aridane under the GENESIS climate projection for 2100

This experiment shows the consequences of wildfires taking place in the area of El Paso, Breña Alta and Los Llanos de Aridane, with increased disruption from wind alerts, and high temperature alerts (+1% damage to an already impacted node per alert) estimated for 2100 over the area. Figure 8 shows the integrity scores for each critical infrastructure service.

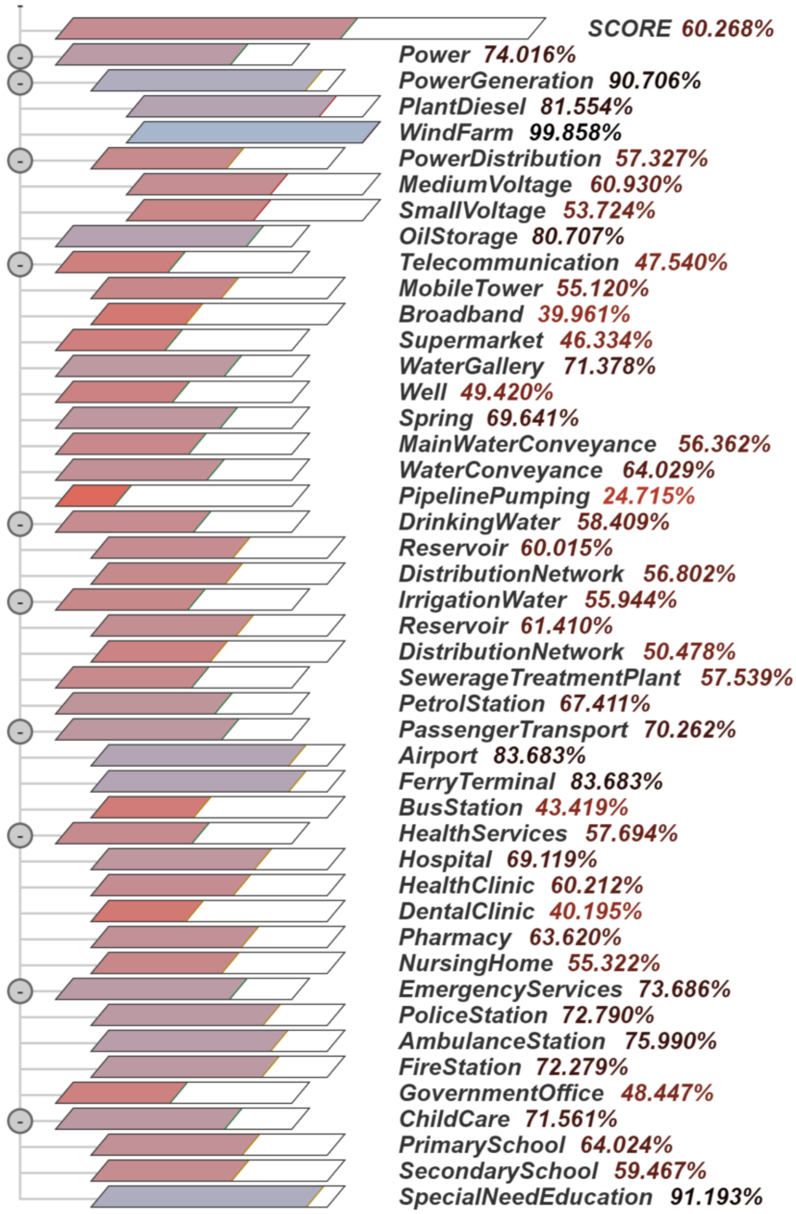

Figure 8. Simulated effects of forest fires taking place in El Paso, Breña Alta and Los Llanos, where the number of estimated wind and high temperature alerts from the 2100 GENESIS climate projection impact critical infrastructure services in La Palma.

Experiment 3: Island-wide volcanic eruption in La Palma

This experiment shows the consequences of an island-wide volcanic eruption for La Palma. Figure 9 shows how the 15 crops with the greatest surface area on the island are impacted after direct damage, and how they are furthermore impacted after indirect damage (when the irrigation service is not available). Figure 10 shows the number of vulnerable people (under 5 or over 85 years old) that face losses of critical services.

Crop Type	Area (m²)	Starting integrity	Integrity after cascading failure
Platanera	26,761,245	50.2%	22.1%
Aguacate	10,872,876	49.8%	21.2%
Viña	8,792,181	42.9%	18.5%
Barbecho	4,443,153	44.9%	21.8%
Huerta Limpia	2,398,780	47.4%	21.6%
Almendro	1,716,105	50.9%	24.0%
Cítricos	1,554,240	45.4%	20.4%
Tagasaste	1,549,673	48.5%	18.8%
Templado Otras Mezclas	1,390,610	49.0%	22.9%
Papa	1,023,718	47.0%	21.5%
Hortaliza Otras Mezclas	853,273	49.2%	20.6%
Subtropicales Otras Mezclas	811,345	52.6%	22.3%
Mango	562,924	54.0%	20.6%
Templado Pepita	341,677	55.5%	25.0%
Huerto Familiar	302,971	51.1%	21.3%

Figure 9. Simulated effects of an island-wide volcanic eruption on crops. Indirect damages due to loss of irrigation are very significant.

Service	People Facing 10-50% Service Loss	People Facing (+50%) Service Loss
Pharmacies	3537 (4.2%)	2803 (3.4%)
Hospitals	1533 (1.8%)	4807 (5.8%)
Health Clinics	3473 (4.2%)	2867 (3.4%)
Dental Practices	802 (1.0%)	5538 (6.6%)
Bus Transport	6340 (7.6%)	0 (0.0%)
Mobile Telecommunication	2526 (3.0%)	3814 (4.6%)
Clean Water	412 (0.5%)	5928 (7.1%)
Power	3209 (3.8%)	3131 (3.8%)

Figure 10. Simulated effects of an island-wide volcanic eruption on the number of vulnerable people that face losses of critical services.

Additional cascading pathways

The following example presents additional experiments that can be conducted using the cascading-failure platform, beyond the standard RIESGOMAP hazard inputs and GENESIS climate projections. These examples establish simplified base conditions by manually adjusting the integrity values of selected nodes in order to explore alternative cascading pathways. They are structured according to the following scheme: trigger; affected nodes; propagation; impact; time to recovery; measures; indicators; and are intended to demonstrate further cascading mechanisms relevant to La Palma.

Example: Operational failure of the Aduares–Hermosilla pumping station

- **Trigger:** The scenario can be triggered by a prolonged interruption of the electricity supply at the Aduares-Hermosilla pumping station.
- **Affected nodes:** This would affect the Aduares station on the eastern slope and the Hermosilla delivery point on the western side, both of which depend on the continued electricity supply.

- **Propagation:** Failure of the east–west pumping system interrupts the transfer of water across the island. This reduces the volume available to several areas of the western side of La Palma, including the south-western sector impacted by the Tajogaite lava flows (although alternative conveyances reconstructed after the eruption also contribute to supplying this sector). During prolonged interruptions, greater reliance on local storage may increase operational pressure on irrigation and drinking water distribution in the Valle de Aridane.
- **Impact:** Although this node had an auxiliary role within the water supply network, after the volcanic eruption it has turned critical. Its failure could place the island's most productive banana cultivation area at risk of significant disruption.
- **Time to recovery:** Recovery time depends primarily on the duration of the electricity supply interruption and the available storage autonomy of drinking water and irrigation reservoirs in the Valle de Aridane. Under normal conditions, drinking water reservoirs provide autonomy of several days. However, if the interruption coincides with low reservoir levels or peak irrigation demand, the effective recovery window may be significantly shorter.
- **Measures:** To mitigate this vulnerability, several measures could be implemented, as maintaining a backup generator at the pumping station, establishing a redundant interconnection within the network, and reinforcing the conveyance infrastructure in the El Paso sector.
- **Indicators:** The impact of this disruption could be monitored through a set of indicators, including the remaining autonomy of storage tanks (in hours), the number of residents left without supply, and the extension of irrigated land affected (in hectares) (Santamarta et al., 2026).

9. System vulnerabilities and mitigation options

Main stress points in the system

The following elements are particularly vulnerable due to their high concentration of dependencies and may therefore become critical in disruption scenarios:

- The primary fuel tanks that supply 90% of the island's electricity, are located on the coast, where they are vulnerable to coastal flooding.
- Electricity generation depends largely on the Los Guinchos thermal power station.
- The Aduares-Hermosilla pumping station is critical for east-west water supply.
- The main conveyance channels LP-I, LP-II and LP-III are key for the intra-island water redistribution.
- The Trasvase galleries are critical sources for supplying the main population centres on both the eastern and western sides of La Palma.
- A limited number of highly productive galleries provide a large share of the island's groundwater discharge, and their flows are transferred through the island's conveyance network.
- The drinking water reservoirs ensure autonomy for several days.
- The access corridors determine repair response times.
- The Valle de Aridane-Tazacorte water body has an exploitation index of 0.7, approaching poor quality, and the southern aquifer remains unusable due to volcanic contamination.
- Small-scale desalination capacity, including the Los Cancajos facility, may provide limited emergency backup under disruption scenarios.

Interventions targeting principal system constraints

Developed scenario experiments suggest that the following interventions may provide comparatively high leverage in reducing cascading-failure impacts:

- Protecting the coastal fuel tanks can reduce the impact of a coastal flood.
- Installing sufficient backup power generators in the Aduares-Hermosilla pumping station to ensure continued water supply.
- Reducing water distribution losses through sectorisation, telemetry, and targeted renewal of priority segments.
- Expanding water reuse where feasible reaching the objective of 60% by 2030, by adding tertiary treatment in the island's waste water treatment plants.
- Improving north–south redundancy through the expansion of the water conveyance network, and strengthening east–west transfer capacity through the renovation and reinforcement of the Trasvase gallery, together with securing water supply to El Paso.
- Hardening and securing access to critical nodes (redundant routes, rapid access planning), in order to reduce restoration delays after potential slope failures or other disruptions.
- Improving integrated monitoring governance (data harmonisation, shared telemetry, and consistent reporting), to support timely decision-making during disruption.

Data gaps for model improvement

Model performance and interpretability would improve with better constraints on recovery dynamics and on operational contingencies. Main data gaps include:

- Recovery times for specific assets and restoration sequences, including delays related to access constraints.
- Verified backup generation data, covering capacity, fuel autonomy, start-up reliability, maintenance status, and fuel logistics during disruptions.
- Implementation of real-time flow monitoring across numerous groundwater abstraction points managed by the local water communities.
- A structured assessment of access vulnerabilities, detailing road criticality, estimated clearance times, and available alternative routes to support realistic restoration planning.
- Operational data for storage reservoirs, including effective storage capacity, operating levels, inflow and outflow regulation, and reserve allocation during supply disruptions.
- Operational and condition data for the water conveyance network, including pipe and channel characteristics, age and maintenance status, and known structural vulnerabilities affecting system reliability.

These elements can be improved progressively without increasing public exposure, provided that asset-level detail remains within restricted documentation delivered only to authorised stakeholders.

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12. Security and access disclaimer

The GENESIS–La Palma cascading-failure platform is not publicly accessible, given the security requirements associated with critical infrastructure and related risk management considerations. This document provides a public summary prepared for DOI dissemination, from which information of a security sensitive nature has been intentionally omitted. Asset-level details are not included, such as precise locations, operational capacities, interdependency mappings on facility level, or other parameters that could be misused. The information herein is provided "as is" for scientific communication only and shall not be construed as operational guidance. Access to the full platform and detailed documentation is restricted to authorized stakeholders, subject to prior approval and applicable confidentiality conditions.

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