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D.1.3 Critical water infrastructure's vulnerability and weaknesses assessment report

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Report Information

Grant Agreement / Proposal ID	101157447
Project Title	Geologically Enhanced NaturE-based Solutions for climate change resiliency of critical water InfraStructure
Project Acronym	GENESIS
Project Coordinator	IGME-CSIC
Project starting date / end date	1 September 2024 / 31 August 2028
Related Work Package	WP1: Macaronesia Water Climate Risk Observatory
Lead Organisation	Universidad de La Laguna
Document title	D.1.3 Critical water infrastructure's vulnerability and weaknesses assessment report
Submission Date	31 October 2025
Dissemination level	Public
DOI	10.5281/zenodo.17491717

Quality verification

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Revision History

Revision	Revision Date	Changes	Authorised	Function
1	11/07/2025	Draft	Jelena Koritnik	PhD Candidate
2	14/07/2025	Internal revision	Noelia Cruz Pérez Juan Carlos Santamarta Cerezal	WP Partner
3	10/09/2025	Improvements	Megan Expósito Brazier	WP Partner
4	20/10/2025	Full revision Full revision Focus on Gran Canaria	Daniel Reyes Parrilla Mercedes Díaz Bueno Gilberto Martel Rodríguez	WP Leader WP Partner WP Partner
6	24/10/2025	Full revision, focus on Faial	Ana Hipólito	WP Partner
7	28/10/2025	Full revision, focus on Canary Islands	Iván Hernández Ríos	WP Partner

Executive summary

This report presents a vulnerability assessment of critical water infrastructure across six volcanic islands in the Macaronesia region: La Palma, Gran Canaria, and El Hierro (Canary Islands, Spain); Madeira (Portugal); Faial (Azores, Portugal); and Santiago (Cape Verde). These islands serve as demonstrator sites within the GENESIS project, where the resilience of essential service systems is evaluated under compound hazard conditions. The assessment identifies key vulnerability drivers and supports the development of integrated adaptation strategies.

The assessment focuses on infrastructure components supporting potable water supply, irrigation, and wastewater management, namely desalination plants, groundwater and surface water abstraction points, conveyance and distribution networks, storage reservoirs, wastewater treatment facilities, and other associated energy-dependent assets such as pumping stations. Hazards considered include volcanic eruptions, earthquakes, landslides, flash floods, coastal storms, droughts, wildfires, and climate-driven pressures such as temperature rise and altered precipitation patterns.

While each island presents distinct environmental, demographic, and infrastructural characteristics, the analysis identifies several recurrent vulnerabilities across systems. These include aquifer overexploitation, groundwater salinization, limited surface storage, energy-intensive water transport, exposure of infrastructure to geologically unstable terrain, and strong operational interdependencies between water and energy systems. At the same time, various resilience-enabling features were observed, such as decentralised gravity-fed conveyance, aquifer compartmentalisation, infrastructure enabling redistribution from resource-abundant to high-demand areas, and the spatial proximity of supply sources to demand zones in less urbanised settings.

The application of the GENESIS cascading-effects engine enabled scenario-based modelling for La Palma, Gran Canaria, and El Hierro. Results underscore the disproportionate impact of indirect service disruptions, particularly in irrigation and energy, often exceeding the spatial or functional footprint of direct physical damage. Simulated earthquake, fire, flood, and eruption scenarios under both current and projected GENESIS climate conditions revealed cross-sectoral disruption pathways and the amplification of systemic vulnerabilities. These insights support the identification of high-criticality infrastructure nodes and inform the prioritisation of targeted preventive measures.

The analysis was shaped by notable differences in data availability and institutional collaboration across the study areas. In the Canary Islands, cooperation with local water authorities enabled the development and use of detailed geospatial datasets and infrastructure inventories, supporting full integration with the GENESIS cascading-effects engine. In contrast, assessments for Madeira, Faial, and Santiago relied more extensively on literature review and the generation of new cartographic datasets based on available documentation and partner inputs. These disparities underscore the importance of harmonised infrastructure inventories, strengthened monitoring systems, and enhanced institutional coordination, particularly in outermost and resource-constrained territories, to support consistent scenario modelling and risk-informed decision-making.

Based on the assessment findings, this report identifies key implementation priorities to support adaptive and resilient management of water infrastructure across the Macaronesian islands. These include: ensuring appropriate siting and protection of coastal infrastructure such as desalination plants; maintaining and, where necessary, enhancing potable and contingency storage capacity; ensuring continuity of energy-dependent water infrastructure through backup generation and protected transmission systems; verifying and reinforcing pipelines and pumping stations in landslide- and erosion-prone areas; expanding and maintaining automated monitoring of aquifer levels, salinity, and flow variability to support adaptive abstraction management; and applying hazard-informed design standards in infrastructure planning, construction, and rehabilitation. These recommendations should be tailored to the specific environmental, technical, and institutional contexts of each island.

Overall, the findings of this report underscore the interdependence of water, energy, and environmental systems in volcanic island settings. As climate-related and geophysical hazards increase in frequency and intensity, maintaining the continuity of essential services, particularly those related to potable water supply and irrigation, requires coordinated strategies that combine physical protection, institutional preparedness, real-time monitoring, and risk-informed investment. The GENESIS methodology, through scenario-based modelling and cross-sectoral analysis, offers a transferable foundation for supporting infrastructure resilience and adaptive planning in multi-hazard environments.

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1- INTRODUCTION

1.1. Water infrastructure challenges in small volcanic islands

Water supply infrastructure plays a critical role in safeguarding public well-being and enabling socio-economic development, and must be protected as part of critical infrastructure planning against future threats associated with the environmental impacts of climate change[1]. Critical infrastructures are those assets, systems or networks whose functioning is indispensable and can't be substituted, such that any disruption or destruction would have major consequences for the provision of essential services[2]. This need for protection is particularly urgent in island regions such as Macaronesia, where water-related vulnerabilities are intensified by volcanic terrain, limited resources, and geographic isolation[3].

The Macaronesian region comprises four volcanic archipelagos in the North Atlantic: the Azores (Portugal), the Madeira archipelago (Portugal), the Canary Islands (Spain), and Cape Verde (Figure 1). These island groups share similar climatic, geological, and environmental characteristics shaped by their volcanic origin, which directly affect water resources, groundwater availability, surface runoff dynamics, and the vulnerability of water infrastructure.

Figure 1 Location of the Macaronesia region and its constituent archipelagos.

Water management across Macaronesia is shaped by the combined pressures of high-demand sectors, particularly agriculture and tourism, and the increasing impacts of climate change, including more frequent and prolonged droughts[4]. Water availability generally increases from south to north, with the Azores receiving higher rainfall than the Canary Islands or Cape Verde, but each island's conditions are primarily determined by its specific orography and morphology. Key characteristics of these volcanic islands include[3]: limited surface water, widespread groundwater overexploitation, salinization processes, especially saline intrusion, coastal population concentration, water-intensive agriculture, massive tourism demand, and a pronounced water–energy dependency due to energy requirements for water extraction and distribution. Except in the Azores, where continuous flows exist in some basins, permanent surface watercourses are largely absent. These constraints require island-specific water governance and management strategies, as continental models often prove unsuitable for small, environmentally heterogeneous volcanic systems.

1.2. Institutional and policy frameworks for outermost regions

Macaronesia forms part of the European Union's outermost regions (OR), a group of nine territories situated far from continental Europe: the Azores and Madeira (Portugal), the Canary Islands (Spain), and six French territories: French Guiana, Guadeloupe, Martinique, Mayotte, Réunion, and Saint-Martin. Although geographically remote, these regions are fully integrated into the EU, with the entirety of EU law applying. Article 349 of the Treaty on the Functioning of the European Union (TFEU) provides a legal basis for specific measures addressing structural constraints such as remoteness, insularity, small size, complex topography, and climate-related vulnerabilities[5]. These territories are also recognised for their strategic potential in biodiversity conservation and renewable energy development. Since 2004, tailored EU strategies have supported their sustainable development, with the 2022 framework placing renewed emphasis on improving living conditions and systematically incorporating OR-specific considerations into EU policy design[5].

1.3. Climate change impacts on water security

The IPCC's Sixth Assessment Report identifies small islands as among the most vulnerable regions globally with respect to freshwater resources, stating that freshwater systems on small islands are exposed to dynamic climate impacts and are among the most threatened on the planet[6]. In Macaronesia, projected climate change impacts include increased water demand during warmer periods, reduced freshwater availability due to altered

precipitation regimes, and more frequent extreme events such as storms and floods[7]. Sea-level rise further threatens water security through saltwater intrusion and potential disruption of water treatment infrastructure.

These vulnerabilities are compounded by maintenance difficulties, and the high energy demands of water infrastructure[8]. While high-altitude water galleries in the Canary Islands operate by gravity and enhance energy efficiency[9], wells, boreholes, and desalination plants require energy-intensive pumping systems[10,11]. As temperatures rise and rainfall decreases, managed aquifer recharge may be required to sustain groundwater levels[12–14]. Groundwater quality is further threatened by marine intrusion[15], nitrate contamination[16–18], volcanic leachates[19], and emerging contaminants[20]. The progressive salinization of coastal aquifers remains a critical long-term management concern[21,22].

1.4. Hydrogeological constraints and water quality risks

Volcanic islands such as those in Macaronesia face structural and hydrogeological constraints due to steep topography, highly permeable soils, and limited capacity to capture and store rainfall. Climate-driven rainfall variability produces alternating droughts and intense precipitation events, which may exceed system capacity and affect infrastructure performance[23]. Population growth, tourism, and intensified land use further increase pressure on groundwater resources, contributing to overextraction, salinization, and ecosystem degradation[22,24]. Although basaltic aquifers often provide high-quality groundwater[25–27], they remain vulnerable to marine intrusion, volcanic and seismic activity, and complex flow dynamics shaped by heterogeneous geological structures[28–32]. Sustainable management under these conditions requires hydrogeologically adapted strategies that account for structural complexity and evolving water quality risks.

1.5. Nature-based solutions and GENESIS project scope

The GENESIS project addresses the structural and environmental challenges facing small volcanic islands by developing and implementing nature-based solutions (NbS) tailored to their hydrogeological and climatic contexts. These include dike-impounded underground dams, dry galleries, rainwater harvesting systems, infiltration systems and wetland restoration, aimed at enhancing storage capacity and safeguarding water quality[7]. Nine demonstrator sites have been established across Macaronesia: La Palma, Gran Canaria, and El Hierro (Canary Islands); Faial (Azores); Madeira; and Santiago (Cape Verde), with five replicator sites: Santa Maria and Graciosa (Azores), Martinique, Guadeloupe, and Réunion. The project integrates field characterisation, hydrological modelling, and digital tools,

including smart monitoring systems and a digital twin platform, to strengthen infrastructure management and long-term system resilience.

1.6. Objectives, data approach, and evaluation criteria

This report presents a vulnerability assessment of critical water infrastructure across the GENESIS demonstration sites in Macaronesia. It aims to identify infrastructure components most exposed to natural hazards and system weaknesses, while supporting the development of tailored adaptation strategies. The assessment focuses on key infrastructure elements, including desalination plants, potable water supply and distribution networks, irrigation systems, galleries, wells, reservoirs, dams, and wastewater treatment facilities. This analysis supports the project's success, as it provides a solid evidence base to design and implement NbS for climate adaptation, helping to reinforce the resilience of critical water infrastructure. With this data, further decisions can be made to better withstand climate impacts, ensure the continuity of services and protect the communities.

The hazards considered in this assessment include both geological and climatic risks, as these directly shape the vulnerabilities of water supply systems. Volcanic risk is unevenly distributed across the region: while some islands have remained inactive for millennia, others, such as Fogo, São Miguel, La Palma, and Tenerife, present elevated risk due to active volcanism and high population exposure[33–37]. Seismic activity, particularly in the Azores, has resulted in major disasters, including damaging earthquakes in 1522, 1939, and 1980[38]. Landslides have also affected multiple islands, with notable events documented in São Miguel, Gran Canaria, and Madeira[39,40]. Climatic hazards, including extreme rainfall, flash floods, heatwaves, tropical storms, and wildfires, are more frequent and geographically widespread. Severe events such as the floods in Madeira (2010) and Tenerife (2002), and wildfires in Madeira (2010, 2016) and Gran Canaria (2007), underscore the exposure of water infrastructure to climate-related impacts[35]. The increasing frequency and intensity of such events highlight the accelerating influence of climate change across the region.

A central component of this work has been the compilation, organisation, and cartographic representation of critical water infrastructure across the six study islands. As no comprehensive georeferenced datasets were publicly available, significant effort was dedicated to gathering, validating, and processing infrastructure data from institutional partners, technical plans, and available spatial data sources. This task involved extensive coordination and technical processing, resulting in a spatially referenced dataset of key water infrastructure. The compiled data, developed to varying levels of completeness

depending on island-specific availability, will serve as a foundational input for current and future GENESIS analyses.

The evaluation approach is tailored to each island, reflecting differences in environmental setting, system complexity, data availability, and integration within the GENESIS framework (Figure 2). For the Canary Islands (La Palma, Gran Canaria, and El Hierro) extensive data coverage enabled the use of a cascading-effects engine to generate scenario-based vulnerability narratives. This includes creating a platform for modelling interlinked infrastructure failures. For the remaining demonstration sites, Faial (Azores), Madeira, and Santiago (Cape Verde), the assessments draw on available environmental and infrastructure information, supported by cartographic visualisation and literature review. Each chapter presents the island's context and water system characteristics, followed by an analysis of key pressures and system weaknesses based on the data and methodological scope applicable to each case.

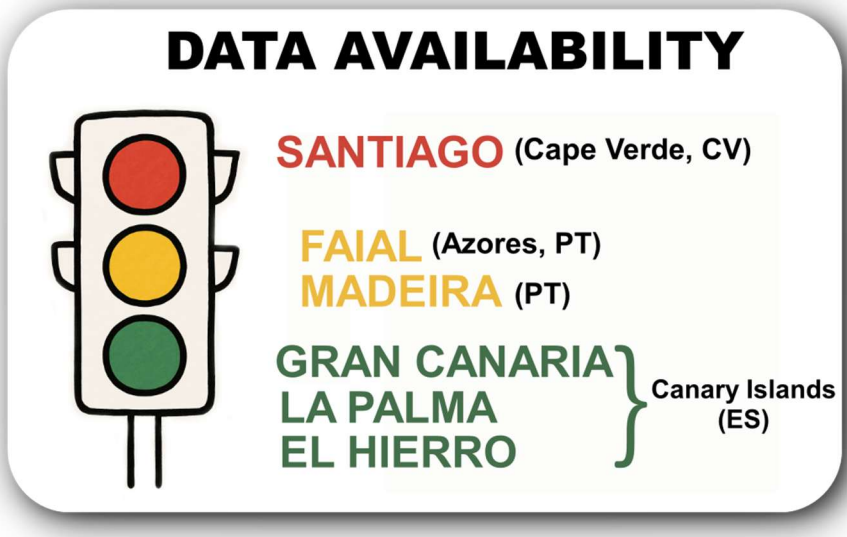

Figure 2 Data availability traffic light assessment across demonstration sites, indicating relative completeness and usability of infrastructure and environmental datasets.

This report follows a context-specific definition of vulnerability as "the degree to which a system is sensitive to threats and limited in its capacity to reduce risk"[41]. The analysis links physical and environmental pressures with technical system characteristics to identify critical points of exposure, sensitivity, and adaptive capacity. Evaluation criteria include the scale of impact, consequences for population, economy, and environment, degree of interdependence, time sensitivity, and system redundancy. Where relevant, the report also highlights established mitigation and prevention strategies to strengthen resilience, particularly for infrastructure near the coastline or exposed to compound hazards.

1.7. Simulation engine modelling the cascading failure of critical infrastructure services

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 term 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 Deliverables 1.1 and 1.2.

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[42] and NATALIE[43] 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:

- It is possible to prepare for disruption, and improve resilience in advance by prioritising limited resources to identify and protect critical assets;
- It enables the identification of what type of input service vulnerabilities can be protected by which appropriate backups;
- 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 European project ("Prevention of Natural and Technological Risks in Territorial and Urban Planning - RIESGOMAP", 2013)[44] 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 within GENESIS adds on top of these base disruptions a climate projections related modifier based on the number of alerts per year (+1% damage per alert) in three scenarios (2025, 2050, 2075 and 2100).

- 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.
- For landslides, the damage is increased by 1% for each precipitation alert.
- 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.
- 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[45–47]. Details on the nodes used for each island, the hazards encountered, and the resulting cascading failures are provided below.

2- LA PALMA ISLAND

2.1. Introduction and environmental setting

La Palma, the northwesternmost island of the Canary Islands (Spain) (Figure 3), covers an area of 708 km² and has a population of 85 104 residents[48], primarily concentrated along the coast and within the central valleys. Its economy relies heavily on agriculture, especially banana cultivation, and on tourism, both of which exert considerable pressure on the island's water resources and infrastructure[49].

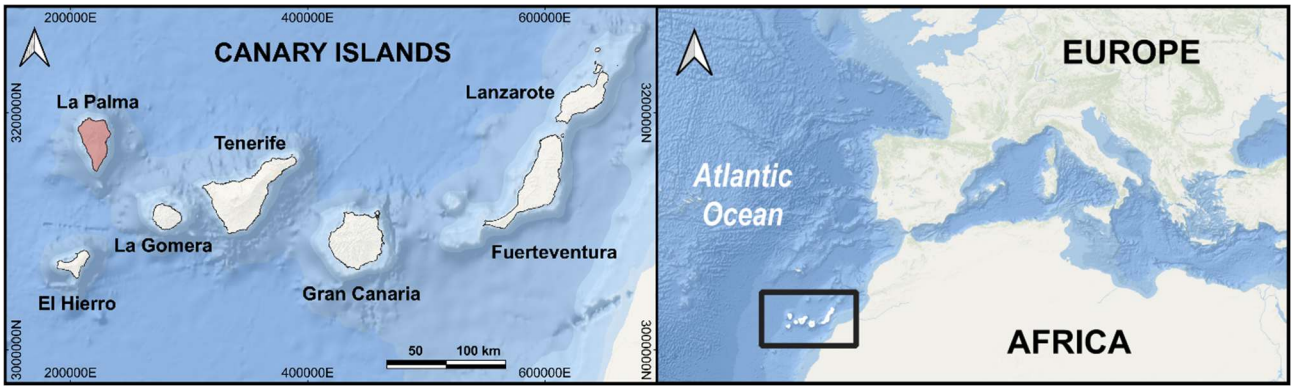

Figure 3 La Palma's location within the Canary archipelago and wider regional context. CRS: EPSG:32628 WGS 84 / UTM 28N.

La Palma is the emergent part of a large volcanic structure that rises approximately 6500 m from the Atlantic abyssal plain. It is built upon Jurassic oceanic lithosphere located at the western edge of the African plate[50]. The island's topography features two principal mountainous areas: the older northern shield volcano, which includes the Caldera de Taburiente (7 km wide caldera with ridges exceeding 2000 m and a central depression between 600–800 m a.s.l.), and the younger, active Cumbre Vieja ridge, which extends 21,5 km north to south and hosts numerous volcanic cones and craters[51].

La Palma's climate is subtropical, with an average annual rainfall of 628 mm[49]. Precipitation distribution varies significantly across the island due to the orographic effect and the trade winds. Approximately 41% of this rainfall, amounting to 177 hm³ per year, recharges the aquifers[49].

The island's hydrogeology reflects its volcanic nature, comprising a complex system of dike-impounded aquifers and porous lava formations that control groundwater storage and flow. Basaltic lava flows interlayered with pyroclastic deposits and intersected by dikes create hydrological barriers and impoundments. In rift zones, dense dike swarms form sealed compartments with steep hydraulic gradients. Groundwater generally flows from the summit towards the coast, but dike barriers disrupt this flow, producing inland

piezometric levels reaching up to 1800 m[22]. Additionally, debris avalanches have contributed to the formation of confined or semi-confined aquifer zones[52]. Vertical permeability exceeds horizontal permeability, allowing rainwater to reach high-altitude aquifers within 2–3 months[52]. Overall, precipitation is the primary source of aquifer recharge, with minimal contribution from irrigation returns[51].

2.2. Water supply system and infrastructure

La Palma's water infrastructure is a complex and interconnected system designed to transport water from abundant northern and high-altitude sources to drier areas with higher demand for drinking and irrigation purposes. The system comprises four main components: water sources, transport networks, reservoirs, and distribution systems (Figures 4 and 5). Wastewater is managed separately through dedicated sanitation infrastructure for collection, treatment, and discharge.

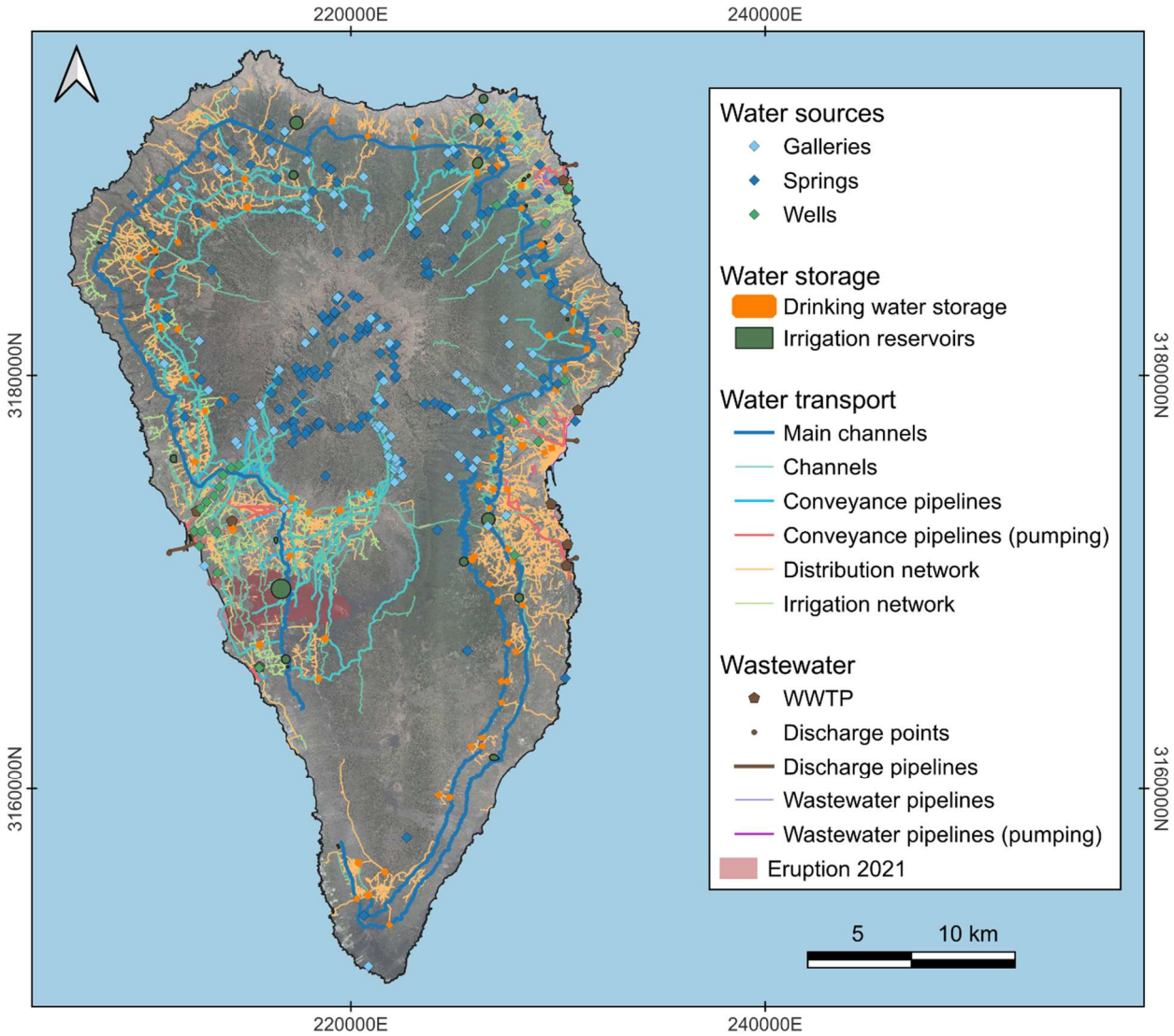

Figure 4 La Palma water supply system and infrastructure. Data sources: CIALP[49,53]; IDECanarias[54]. CRS: EPSG:32628 WGS 84 / UTM 28N.

2.2.1. Water sources

The island's primary water source is its network of water galleries, or water mines. Galleries are horizontal tunnels excavated into the rock to drain groundwater from aquifers. Each gallery has a single entrance and typically features a cross-section of around 2 x 2 meters to allow maintenance access. Over time, infiltrating rainwater accumulates underground to form a saturated aquifer zone. Galleries are drilled with a slight incline to intersect this zone, enabling water to flow out naturally by gravity without the need for pumping.

Gallery development began in La Palma at the end of the 19th century, initially with manual excavation targeting areas indicated by natural springs. Later, the use of explosives facilitated deeper and longer excavations. Upon reaching the aquifer, galleries often yield a strong initial outflow that stabilises as reserves are depleted within their zone of influence, prompting further excavation to restore production. Some galleries reach lengths of 5–6 km[49]. Production rates vary widely, from a few litres per second to several hundred, depending on geological and recharge conditions. A notable example is the Water Transfer Tunnel (*Túnel del Trasvase)*, initially planned as a single east–west gallery but later constructed with separate East and West mouths due to high flows.

Overall, galleries provide the largest share of La Palma's water, mainly for drinking, with surplus used for irrigation. In 2018 there were 78 active galleries totalling 264,3 km in length. In 2019, galleries extracted around 46.6 hm^3 annually, and when combined with boreholes, extraction reached 66 hm^3 per year, the equivalent to roughly 26% of the island's annual recharge[49,55]. Natural springs now play a smaller role due to gallery development, though the *Marcos and Cordero* springs in the north remain significant. Traditional coastal wells, primarily used for irrigation, face salinization risks and are of limited use for drinking water.

2.2.2. Water transport

Water is transported mainly by gravity through pipelines and open channels, supported by three main channels:

- LP-I: Transports water along the eastern slope, including to the south where the volcanic aquifer is unsuitable for extraction.
- LP-II: Supplies water to the western slopes for irrigation.
- LP-III: Runs along the southeastern slope above LP-I, providing irrigation water at higher elevations.

These main channels supply both irrigations and urban demand and merge flows from galleries, springs, and reservoirs, with water mixing occurring progressively along the route.

Closed pipeline segments convey water to drinking water reservoirs, while open channel segments mainly distribute irrigation water.

In addition to these channels, there's a pumping station at Aduares (East) that transports water to Hermosilla (West). It has gained more relevance in recent years, as it has helped mitigate the decrease in flows from the LP-III and to supply the areas south of the lava flow after the Tajogaite eruption[56].

2.2.3. Storage and distribution

Drinking water is stored in closed tanks where it undergoes disinfection (free chlorination) before being distributed via municipal distribution networks. Each municipality operates its own storage facilities, which can also function manually if needed. Irrigation reservoirs are open structures dedicated exclusively to agricultural use. Drinking and irrigation water are delivered through separate systems, ensuring that potable water always undergoes regulated treatment and storage before consumption.

2.2.4. Sanitation and wastewater management

Wastewater is collected through gravity-fed and pumped sewer networks, treated at *EDAR/EBAR* facilities, and discharged via emissary pipelines to designated marine outfalls. The sanitation network operates independently from the water supply system, maintaining clear separation between potable, irrigation, and treated effluent flows.

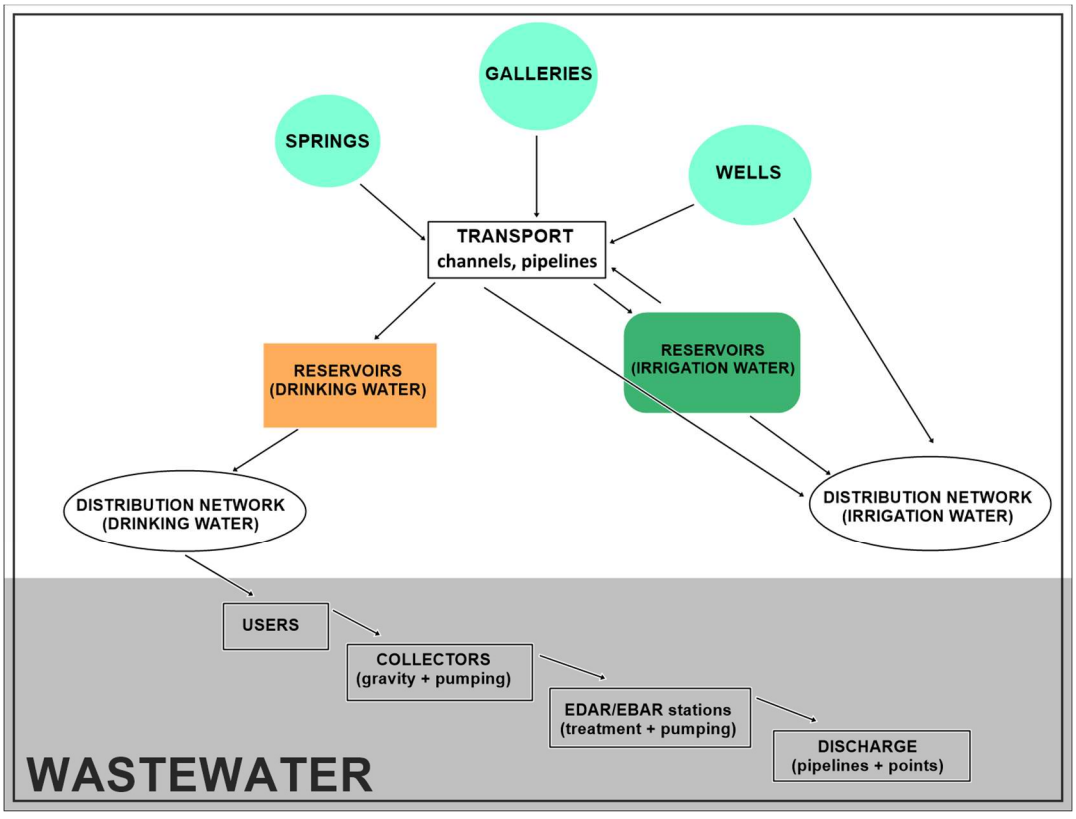

Figure 5 Schematic overview of La Palma's water supply system.

2.3. Vulnerabilities and system weaknesses

La Palma's water supply system, while supported by abundant, low-mineralised, and relatively young groundwater[52], presents significant spatial, geochemical, and logistical vulnerabilities. These arise from the island's complex volcanic geology, spatial heterogeneity in aquifer characteristics, and combined pressures from climate variability, agricultural demand, and volcanic activity.

Recharge on La Palma exceeds current abstractions, an uncommon condition in the Canaries, due to high precipitation and favourable hydrogeological conditions. However, the distribution of rainfall and recharge is unequal in its geographical distribution around the island and exploitable groundwater is compartmentalised across dike-bounded aquifers with steep hydraulic gradients, requiring island-wide transfers and a well-developed distribution network to balance supply and demand[49,52].

The southern aquifer sector remains permanently unexploitable due to diffuse CO_2 emissions and elevated salinity linked to geothermal degassing[49,51]. Coastal wells, traditionally used for irrigation and occasionally for supply, have become less significant due to declining water quality associated with salinization, although no marine intrusion has yet been confirmed. In the Aridane–Tazacorte Valley, agricultural activity further compromises water quality through nitrate pollution and emerging signs of salinity increase linked to early-stage seawater intrusion[49,51].

The island's water supply relies on a gravity-fed network of galleries and transfer channels that collect groundwater primarily from northern aquifer compartments. Three main conduits (LP-I, LP-II, and LP-III), plus the Aduares-Hermosilla pumping station, redistribute this water to the drier southern and central-coastal regions, including agricultural zones along the route. A series of irrigation reservoirs integrated into the system enhances storage capacity and operational redundancy. While this passive infrastructure significantly reduces energy demand and improves supply resilience, it has contributed to the disappearance of many natural springs[49].

Public water supply quality remains high, with all monitored parameters within regulatory limits owing to selective abstraction from high-quality aquifer compartments, although the 2021 eruption triggered short-term hydrochemical disturbances in monitoring wells near the *Tajogaite* fissure[37,57,58].

The 2021 Cumbre Vieja eruption[59–61], which lasted from 19 September to 25 December, was driven by a magma–gas decoupled system, enabling simultaneous tephra emissions and lava effusion from multiple vents. Gas emissions were dominated by water vapor, followed

by CO_2, SO_2, CO, and AsH_3, with a cumulative SO_2 output of approximately two million tonnes, leading to two documented episodes of acid rain. Magma-groundwater interactions triggered phreatomagmatic explosions, producing breccias and generating vertical water vapor columns entrained with ash. The eruption caused widespread environmental, infrastructural, and economic impacts[60,62–66]. Lava flows inundated approximately 1300 ha of land, destroying nearly 3000 buildings, 74 km of roads, and 3.7km^2 of cultivated area[67]. Although the eruption did not significantly affect the aquifer compartments used for abstraction, it underscored the system's reliance on uninterrupted infrastructure and sustained access to source areas.

Agriculture, especially banana production, and the tourism sector both rely heavily on the island's water-transfer network. Tourism infrastructure requires continuous, high-quality supply for hotels, pools, and recreational facilities, while irrigated agriculture depends on reliable distribution to meet crop demands[11,49]. This interdependence further increases the system's vulnerability to service disruptions.

Landslides and rockfalls represent a persistent hazard on La Palma, driven by the island's steep topography, deeply incised ravines, and the presence of unconsolidated volcanic materials[68,69]. These processes occur both during eruptive phases and in quiescent periods, often triggered by intense rainfall or seismic activity[68–71]. Water infrastructure is particularly exposed where pipelines, channels, water source infrastructure, and access roads cross unstable slopes or ravine walls. Such events can disrupt water transport, restrict operational access, and sever connections between supply and demand zones, particularly in areas with lower redundancy. Effective risk mitigation requires the integration of slope hazard assessments and terrain stability monitoring into both infrastructure planning and operational management.

La Palma's groundwater-dependent, water supply system represents a nature-based solution, as its volcanic aquifer configuration enables natural storage and gravity-driven conveyance. However, sustained pressures (including geochemical constraints, spatial imbalance in resource availability, salinization processes, agricultural contamination, volcanic hazards, and terrain instability) require coordinated management, protection of uncontaminated source zones, and long-term investment in infrastructure resilience to ensure supply security and regulatory water quality.

2.4. Cascading failure of critical infrastructure services

2.4.1. Factsheet for the model of cascading failure for critical infrastructure services

Size and complexity:

2454 nodes – including 37 different types of interdependent critical infrastructure services. Impact on crops takes into account about 51 450 fields.

Energy setup:

Diesel generators supply 90% of the energy. Renewable energy produces about 10% of the energy in La Palma – most of it - 7 % - come from wind generation and 3% come from hydro generation (prospective contribution). These percentages are reflected in the weights given to different types of input services for medium voltage power distribution nodes (where the input from wind generation, hydro, and diesel nodes have respective criticality weights of 0.07, 0.03, and 0.9).

Water setup:

12 types of critical nodes are relevant to the water domain (if including the wastewater treatment plant). The criticality of input services that go into irrigation reservoirs (main conveyance channels, normal irrigation channels) depends on the hydrological areas the nodes are located inside. In the case of La Palma the importance of the three main channels is very significant. There is also a clear separation between the final distribution networks for drinking water and distribution networks for irrigation (Figure 6).

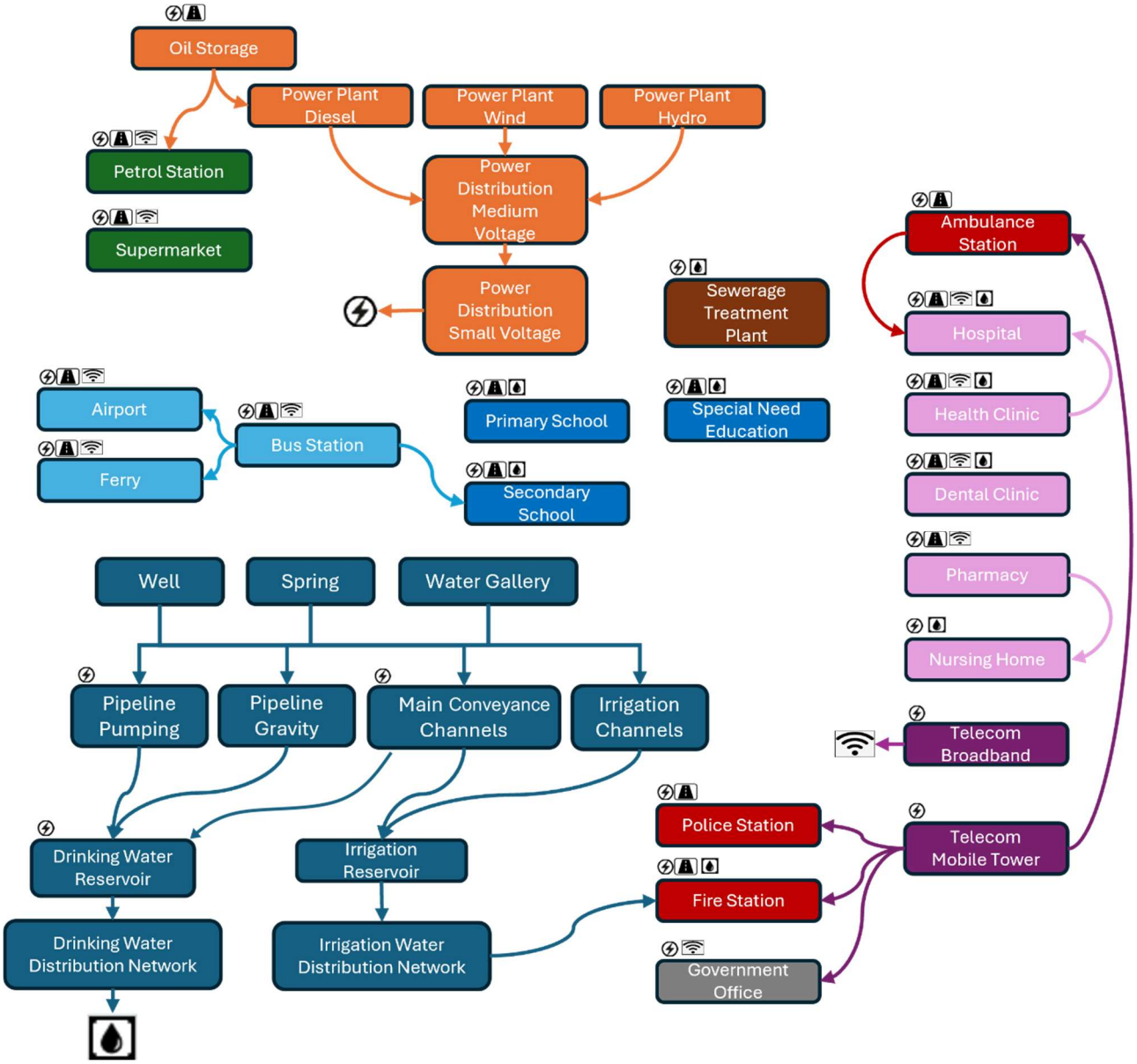

Figure 6 Simplified view of service dependencies between the 37 types of critical Infrastructure nodes in La Palma.

2.4.2. Experiment: coastal flood in the regions of Breña Alta, Breña Baja, and Santa Cruz de la Palma

This experiment shows the consequences of a coastal flood taking place in 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 7 compares the impacted services on the Island after the coastal flood with the impacted services, and after protecting these 19 critical oil tanks from flood damage.

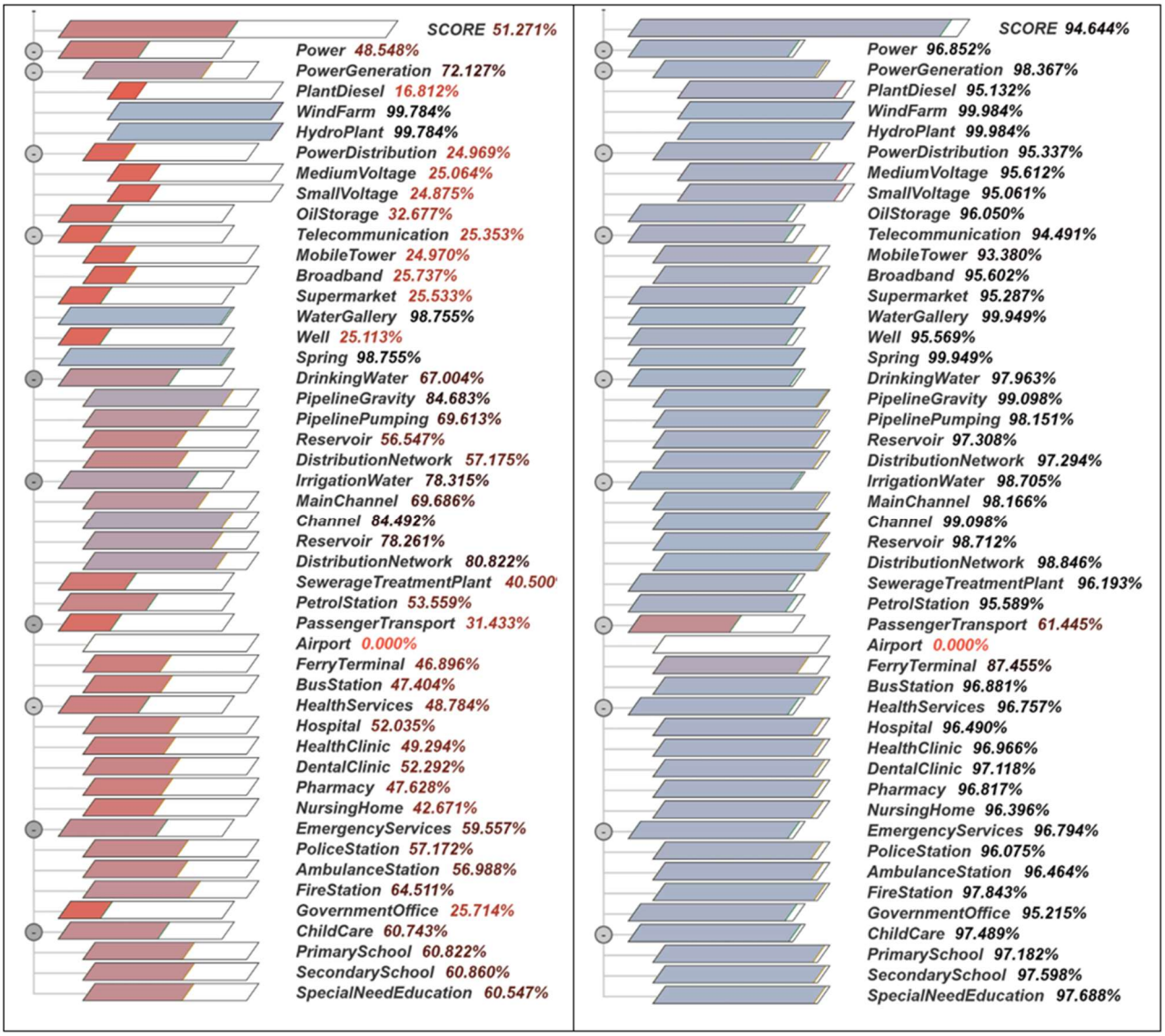

Figure 7 Simulated effects of a coastal flood (left) vs the same coastal flood where 19 critical oil tanks linked to the diesel power generator that supplies 90% of the electricity in the Island are shielded from flood damage (right).

2.4.3. Experiment: forest fires in the regions of El Paso, Breña Alta and Los Llanos de Aridane with GENESIS climate projection for 2100

This experiment shows the consequences of forest fires 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. Figure 8 shows the integrity scores for each critical infrastructure service as well as a map of impacted infrastructures on the Island where the impact goes well beyond the area directly damaged by the forest fires.

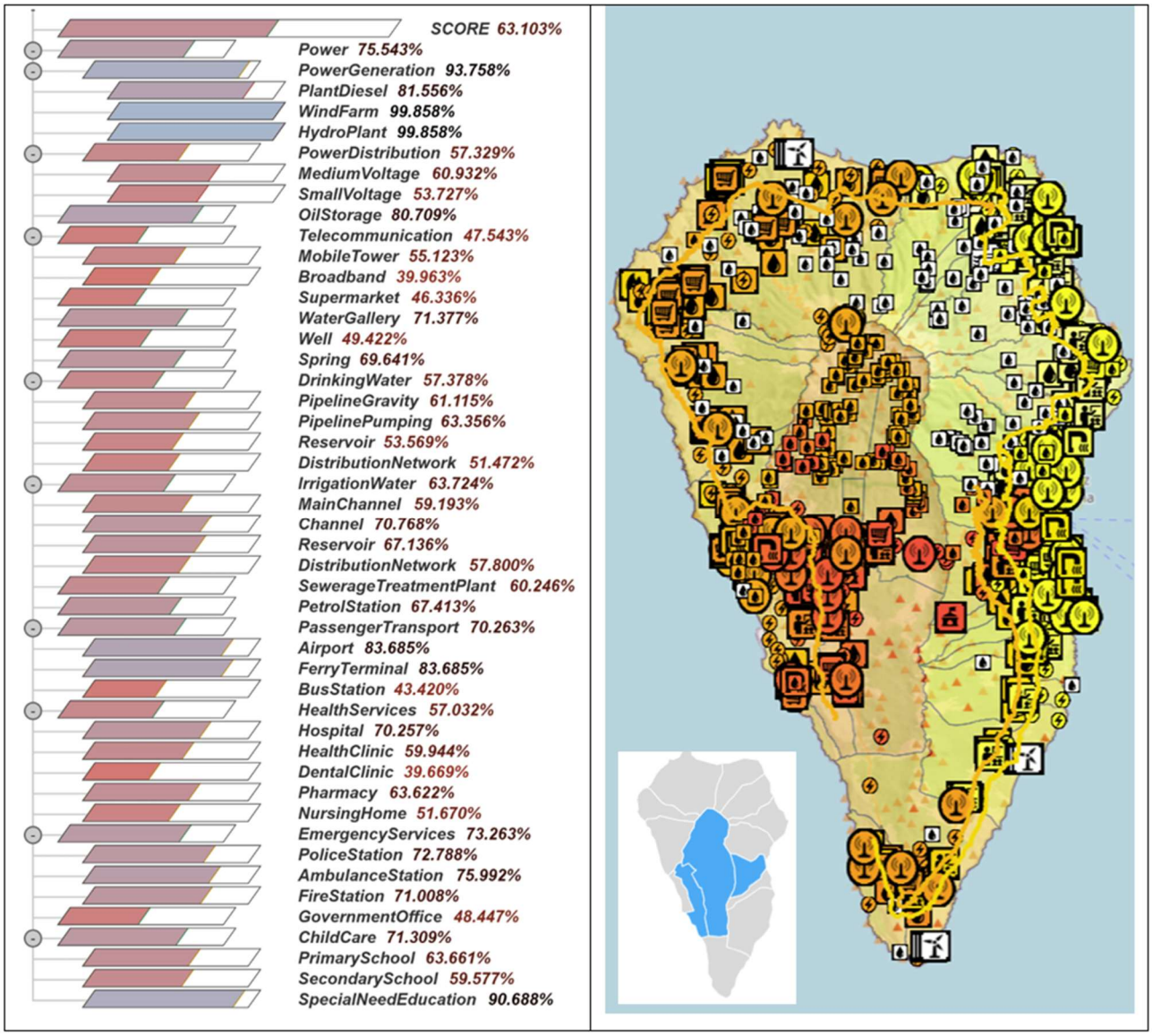

Figure 8 Simulated effects of localised forest fires taking place in the regions of El Paso, Breña Alta and Los Llanos de Aridane (in blue in the minimap), with increased disruption from wind alerts, and high temperature alerts from the 2100 climate projection. Critical services are impacted well beyond the directly affected areas.

2.4.4. Experiment: 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. Figure 11 shows the integrity scores for each critical infrastructure service.

Crop Type	Area (m^2)	Starting integrity	Integrity after cascading failure
Platanera	26,761,245	50.2%	21.2%
Aguacate	10,872,876	49.8%	18.4%
Viña	8,792,181	42.9%	16.1%
Barbecho	4,443,153	44.9%	15.7%
Huerta Limpia	2,398,780	47.4%	16.1%
Almendro	1,716,105	50.9%	17.5%
Cítricos	1,554,240	45.4%	15.3%
Tagasaste	1,549,673	48.5%	12.0%
Templado Otras Mezclas	1,390,610	49.0%	16.6%
Papa	1,023,718	47.0%	16.0%
Hortaliza Otras Mezclas	853,273	49.2%	17.7%
Subtropicales Otras Mezclas	811,345	52.6%	19.2%
Mango	562,924	54.0%	16.3%
Templado Pepita	341,677	55.5%	17.0%
Huerto Familiar	302,971	51.1%	16.8%

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	3,537 (4.2%)	2,803 (3.4%)
Hospitals	1,533 (1.8%)	4,807 (5.8%)
Health Clinics	3,856 (4.6%)	2,484 (3.0%)
Dental Practices	88 (0.1%)	6,252 (7.5%)
Bus Transport	6,340 (7.6%)	0 (0.0%)
Mobile Telecommunication	2,615 (3.1%)	3,725 (4.5%)
Clean Water	79 (0.1%)	6,261 (7.5%)
Power	3,209 (3.8%)	3,131 (3.8%)

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

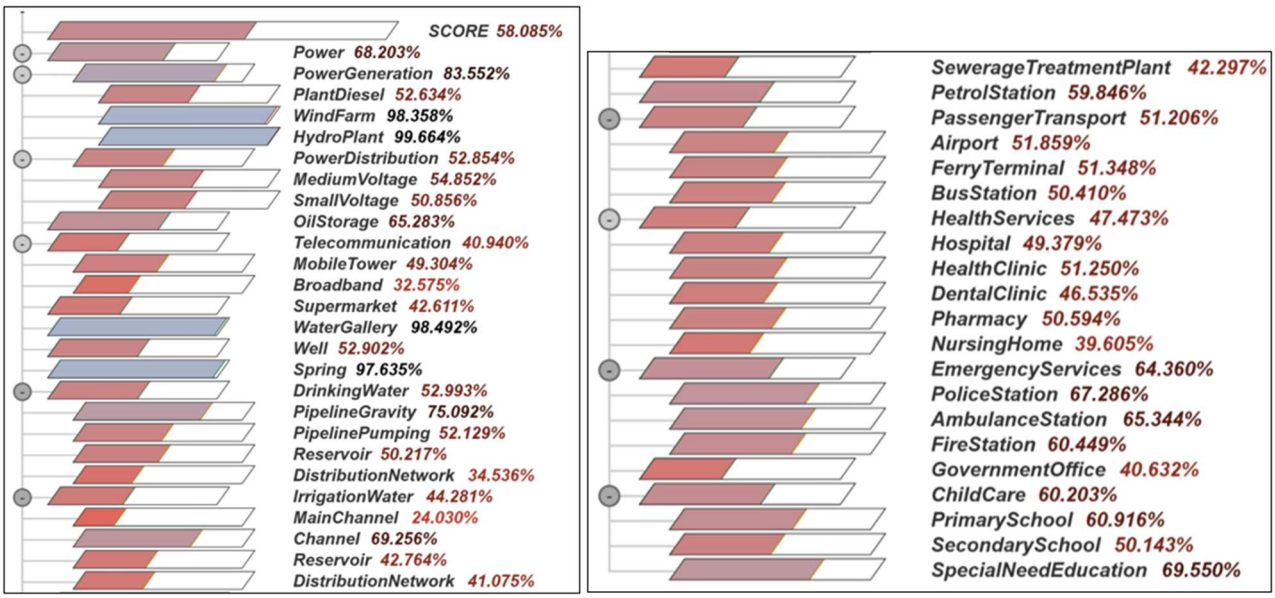

Figure 11 Simulated effects of an island-wide volcanic eruption on critical infrastructure services in La Palma.

2.5. Summary of vulnerabilities and key conclusions

La Palma's water supply system is structured around a decentralised, predominantly gravity-fed network of groundwater galleries and intermunicipal transfer conduits, adapted to the island's steep topography and compartmentalised volcanic aquifers. It comprises galleries, wells, springs, transfer pipelines and channels, disinfection and storage tanks, irrigation reservoirs, and separate sanitation and distribution infrastructure, allowing resource balancing across hydrogeologically diverse zones.

Despite generally favourable recharge and water quality, several conditions influence system vulnerability. Volcanic and agricultural pressures, along with overexploitation, have led to geochemical degradation in specific groundwater bodies, most notably salinity and nitrate increases in the Aridane–Tazacorte Valley, and volcanic contamination in southern compartments, which are unsuitable for abstraction. As a result, supply depends on unaffected aquifer compartments, with island-wide transfers maintaining continuity. This spatial heterogeneity reflects aquifer fragmentation, which, rather than a limitation, functions as a systemic strength by enabling hydrogeological redundancy.

Operational risks persist due to infrastructure located in steep, landslide-prone terrain and volcanically active zones. Key vulnerability factors include geochemical constraints, spatial imbalance in resource availability, salinization processes, agricultural contamination, volcanic hazards, and terrain instability. At the same time, the system benefits from multiple redundancy-enabling features: availability of high-quality water, aquifer compartmentalisation, favourable recharge conditions, proximity of demand centres to productive sources, reliance on gravity-fed conveyance with limited pumping requirements, minimal treatment needs limited to free chlorination (which can be manually applied in tanks), potable water storage sufficient for at least four days, and efficient irrigation reservoirs that provide additional operational redundancy.

This assessment integrated spatial data, technical literature, and infrastructure mapping to identify system-wide vulnerability patterns, which informed the cascading-effects model simulating failures across 2 454 infrastructure nodes and 37 interdependent services:

- Coastal flood scenario (Breña Alta, Breña Baja, Santa Cruz de La Palma): Damage to oil tanks supporting diesel generation, supplying around 90% of island electricity, triggered island-wide cascading impacts. Protecting 19 tanks significantly reduced service disruption.

- Forest fire scenario (GENESIS 2100 projections): Increased frequency of heat and wind alerts amplified infrastructure damage, with cascading effects extending beyond directly affected areas.
- Volcanic eruption scenario: Irrigation service losses exacerbated crop damage, indirectly affecting all 15 major crop types. Vulnerable populations, particularly young children and the elderly, experienced widespread service disruptions.

La Palma's system combines terrain-adapted infrastructure and hydrogeological redundancy but remains exposed to multi-hazard risks, systemic interdependencies, and sectoral pressures. Strengthening resilience requires improved inter-service coordination, hazard-informed contingency planning, and protection of critical infrastructure nodes.

3- GRAN CANARIA ISLAND

3.1. Introduction and environmental setting

3.1.1. Geographical and socioeconomic overview

Gran Canaria is the third-largest island in the Canary archipelago (Spain) (Figure 12), covering approximately 1560 km², with its highest area around Pico de las Nieves and Morro de la Agujereada reaching 1956 m. In 2024, the island's population was 869 984[72], accounting for nearly 40% of the archipelago's total population (2 228 862), making it the second most populous island. The capital, Las Palmas de Gran Canaria, has over 380 000 residents[72] and forms the core of a metropolitan area that includes several neighbouring municipalities.

Gran Canaria is one of Spain's major tourist destinations, recording more than 4,7 million visitor arrivals in 2024 from both international and domestic markets[73]. The economy is heavily reliant on tourism, which constitutes a significant portion of employment and economic output, especially concentrated along the coastal areas. Although agriculture has declined in economic significance, it remains present in rural zones, with irrigated crops such as bananas, tomatoes, and potatoes mainly cultivated in lowland and coastal plains[74].

The island's extensive tourist infrastructure along the coast shapes regional demographics, land use, and infrastructure development, while placing substantial demands on its water resources.

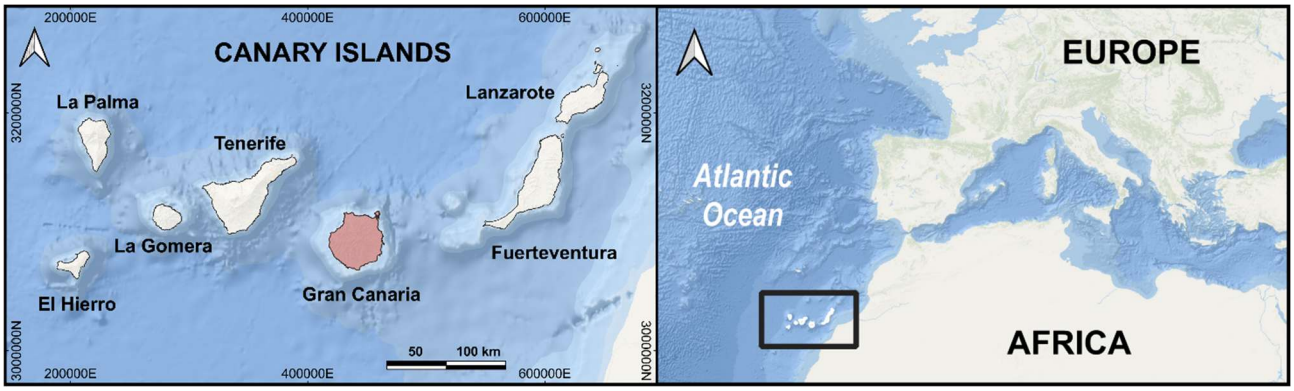

Figure 12 Gran Canaria's location within the Canary archipelago and wider regional context. CRS: EPSG:32628 WGS 84 / UTM 28N.

3.1.2. Climatic conditions

Gran Canaria's climate is shaped by its proximity to the Saharan dry environment, moderated by the northeast trade winds. These winds bring increased precipitation to the northern slopes, while the southern areas remain arid due to the highlands' barrier effect[21].

Average annual rainfall ranges from less than 100 mm in the southern coastal regions to around 1000 mm at intermediate elevations exposed to the trade winds[21]. An average annual rainfall of 600–650 mm is reported for specific study areas on the island, with groundwater recharge estimated at 250–270 mm per year[29].

Temperatures remain mild throughout the year in coastal zones but can be cold in the highlands, where occasional snowfall occurs[21]. The island frequently experiences Saharan dust intrusions (*calima*), which deposit substantial amounts of silicates, quartz, and carbonates onto soils, with notable effects on hydrogeochemistry[22]. These episodes are more frequent in summer; however, although less common in winter, they tend to be more intense, as reflected by a higher number of alerts during the season[22,75].

3.1.3. Geological evolution

Gran Canaria was formed by volcanic activity beginning in the Middle Miocene, around 14 million years ago, with multiple building stages and erosion shaping its current landscape[22]. The island features a heavily eroded volcanic structure with deep radial ravines (*barrancos*) and preserved original surfaces in areas unaffected by landslides. Volcanic activity peaked between 10 and 4 million years ago, with minor eruptions continuing until about 2000 years ago[22]. These geological processes created highly variable and layered strata that control groundwater flow and form perched aquifers in elevated areas, often separated from the main aquifer by tens to hundreds of meters[29]. Flat coastal zones formed from volcano-sedimentary deposits support dense settlements, irrigated agriculture, and urban, tourist, and industrial development[22].

3.1.4. Hydrogeological characteristics

Gran Canaria's hydrology is characterised by high evapotranspiration losses and limited surface runoff. Historical estimates indicate that with an average annual precipitation of 300 mm, approximately 65% of rainfall is lost to evapotranspiration, 16% becomes surface runoff, and 19% contributes to groundwater recharge[22,76]. Surface water use primarily depends on seasonal flows in ravines, where dams or indirect collection systems are installed when feasible[77]. Most soils on the island are permeable to highly permeable, facilitating infiltration. However, some coastal areas are affected by local marine intrusion risks[22]. Water supply has traditionally relied on groundwater extracted through wells, boreholes, and horizontal galleries. These systems integrate forestry engineering, historical practices, and semiarid land management strategies to optimise water availability for agriculture[77].

3.2. Water supply system and infrastructure

Gran Canaria's water supply system reflects centuries of adaptation to scarce and irregular rainfall. Since the conquest, the island has developed an extensive and diverse network of hydraulic infrastructure, including dams, reservoirs, ponds, wells, galleries, aqueducts, pipelines, transfer tunnels, desalination plants, and treatment facilities[78] (Figure 13). These works aim to secure water for urban supply, agriculture, and energy production, combining groundwater extraction, surface water storage, and, more recently, non-conventional resources to meet growing and diversified demands.

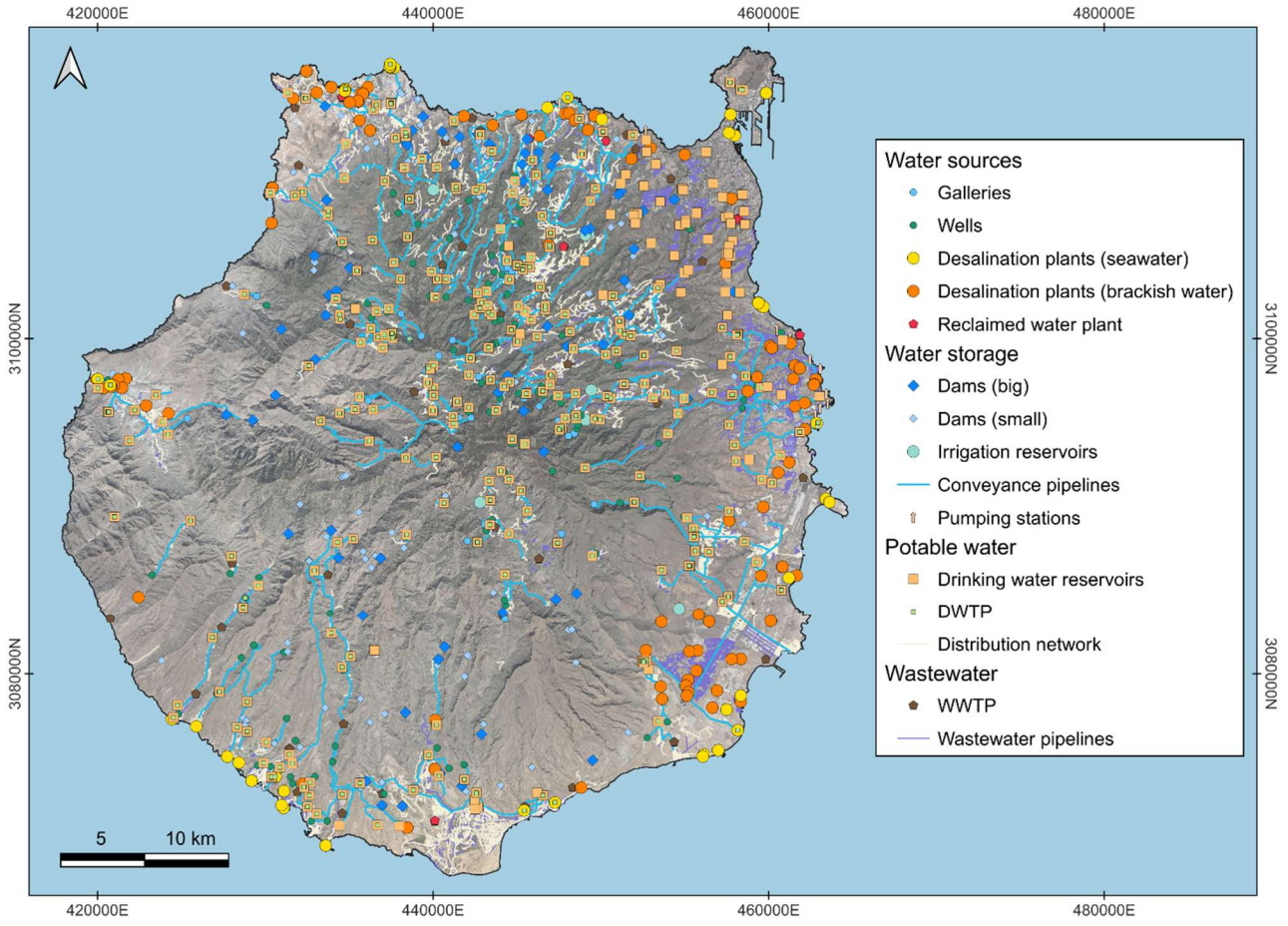

Figure 13 Gran Canaria water supply system and infrastructure. Data sources: CIAGC[74]; IDECanarias[54]. CRS: EPSG:32628 WGS 84 / UTM 28N.

Groundwater has historically been central to the island's supply system. Approximately 15 000 hectares of irrigated land depend almost entirely on groundwater[22,76]. Abstraction is primarily through wells and horizontal galleries, which tap aquifers elevated by geological dikes, aligning with the island's volcanic structure. However, intensive use has depleted reserves by an estimated 2 km³[22]. From the 1960s onward, rising demand due to agriculture, urban expansion, tourism, and industry has led to overexploitation, resulting in significant declines in piezometric levels, especially near the coast where seawater intrusion risk is highest[22,24].

By 1997, 1337 abstraction points were in use, declining to 805 by 2010 out of around 3640 registered points. In 2015, groundwater extraction was about 50 hm^3 annually, with only minor contributions from springs[22]. Over time, the share of renewable resources in total abstraction has grown, although by the late 1990s, more than half of assessed reserves (2125 hm^3) had been consumed[22]. Today, Gran Canaria represents an advanced stage of groundwater exploitation and is often referenced as a model for managing groundwater in small, mountainous islands[22,24].

Surface water resources are limited and mainly seasonal. The island has a surface reservoir capacity of 77 hm^3 (with 12% utilisation) and an additional 75 hm^3 stored in ponds (15% utilisation)[22]. Surface water use relies on ravine flows captured by dams, pipe intakes, or artificial reservoirs where dam construction is not feasible[77]. Although reservoir water supplies less than 10% of average annual demand, it remains important for agricultural areas such as La Aldea and shapes perceptions of water availability each year[78].

Desalination has become a key component of Gran Canaria's water strategy, supporting the Hydrological Plan's goals to increase urban water resources, improve network efficiency, reduce losses and unbilled consumption, and ensure a reliable supply[74,78]. Managed Aquifer Recharge (MAR) is also proposed to help restore aquifer levels and reduce reliance on desalinated water[24].

Maintaining the island's hydraulic heritage, including dams, galleries, and related infrastructure, is essential for continued service delivery and structural safety. However, these systems face increasing challenges such as aging structures, difficult terrain, low profitability from regulated volumes, and stricter safety and emergency requirements[78].

3.2.1. Desalination plants and their water supply role

Desalination infrastructure on Gran Canaria has expanded steadily over time, with facilities often grouped into "desalination complexes" that host multiple plants at a single site. These complexes typically comprise plants owned by different entities, using various systems and producing water for diverse purposes. The island's first desalination plant was installed in 1970 to supply Las Palmas de Gran Canaria, with an initial capacity of 18 000 m^3/day. Since then, the combined capacity of the desalination facilities serving Gran Canaria has increased to 229 184 m^3/day[78].

Currently, Gran Canaria has 17 registered desalination plants, organised into complexes located in strategic coastal and urban areas (Table 1). These facilities produce water for urban supply, agriculture, industry, and tourism. Although precise consumption figures are difficult to establish due to market complexity, estimates from 2006 indicate that

desalinated water use was distributed as follows: 48,6 hm³/year for urban supply (68%), 10 hm³/year for tourism (10%), 7,3 hm³/year for agriculture (10%), 5 hm³/year for industry (7%), with negligible volumes used for recreational purposes[74,78].

Table 1 Desalination plants in Gran Canaria by complex, municipality, and zone, with nominal capacity and primary use[78].

Complex	Municipality	Zone	Nominal production capacity (m³/day)	Use
Salinetas	Telde	E	15 000	Supply
Punta Camello	Arucas	N	11 300	Supply/irrigation
Piedra Santa	Las Palmas GC	NE	80 000	Supply/industrial
Various Las Palmas	Las Palmas GC	NE	40 000	Supply/medical
Bocabarranco	Gáldar	NW	25 000	Supply/irrigation
Roque Prieto	Guía	NW	5000	Supply/irrigation
Bco. La Aldea	La Aldea de S.N.	W	10 700	Supply/irrigation
Las Burras	S Bartolomé T	S	26 184	Supply
Juan Grande	S Bartolomé T	S	10 000	Irrigation
Bco. Tirajana	S Bartolomé T	SE	16 000	Industrial
Pozo Izquierdo	Santa Lucía	SE	33 000	Supply/irrigation
Gando	Agüimes	SE	2500	Supply
Vargas	Vargas	SE	5000	Supply/irrigation
Playa de Tauro	Mogán	SW	2000	Supply
Puerto Rico	Mogán	SW	4000	Supply
Playa de la Verga	Mogán	SW	500	Supply
TOTAL			**229 184**	

3.2.2. Dam infrastructure and surface water storage

Gran Canaria has 69 large dams, defined as hydraulic structures built to retain ravine flows with a height exceeding 15 meters or a capacity greater than 100 000 m³. This gives the island the highest density of large dams in the world, with one reservoir per 25 km². Together, the dams provide a regulation capacity of 25,5 hm³ managed by the Island Water Council, with the Soria Dam alone accounting for 15 hm³ of this volume (Table 2). The total storage capacity of large dams is 76,7 hm³, with 88,5% located in the southern municipalities of Artenara, Tejeda, Mogán, San Bartolomé de Tirajana, and Santa Lucía, and the remaining 11,5% in the north, where terrain permeability and rainfall patterns differ[78].

Table 2 Dams in Gran Canaria under the management of the Island Water Council[78].

Dam	Total height (m)	Maximum volume (m³)
Chira	32	5 640 000
Ayagaures	40	1 848 000
Gambuesa	42	1 348 000
Candelaria	25	396 000
Fataga	32	327 000
Vaquero	35	216 000
El Mulato	35	750 000
Soria	120	15 000 000
TOTAL		**25 525 000**

These dams encompass various construction types, including masonry, concrete, loose material, and mixed structures, reflecting diverse engineering adaptations to local conditions. The majority (48) are masonry dams, while others include riprap, concrete, and hybrid forms. Average dam height is 32 meters, with an average capacity of 1,3 million m³, although excluding Soria reduces this to 780 000 m³. Only 14 dams have basins larger than 10 km²[74,78]. The Soria Dam is the largest, with 32 hm³ capacity and 120 meters in height. It has never overflowed and has only filled to less than half of its capacity.

Overall, dams supply less than 10% of Gran Canaria's annual water needs in an average year, though they remain the primary reliable water source for agriculture in certain basins such

as La Aldea. Additionally, the Soria and Chira reservoirs (Figure 14) are key components of the planned reversible hydroelectric system, intended to act as a "battery" for the island's electrical grid, enhancing regulation, stability, and clean energy support[78].

Figure 14 Chira Dam (left), and Siberio Dam with Caidero de La Niña (right). Source: CIAGC[78].

Dam density varies geographically: northern dams regulate runoff for agriculture despite more permeable soils, while southern dams exploit low-permeability terrains to achieve larger storage despite lower rainfall. Dams play a crucial role in flood risk mitigation and preventing runoff losses to the sea. However, their maintenance and modernisation face growing challenges due to stricter safety standards and emergency planning requirements, adding technical and financial pressures[78].

Despite this, over the past 15 years, the dams of Gran Canaria have experienced a significant decline in stored water availability due to reduced rainfall. As of September 2025, the volume of water stored in the public reservoirs managed by the Island Water Council of Gran Canaria was only 4.21%, with the largest volume concentrated in just two reservoirs (El Mulato and La Gambuesa)[79]. The adaptation strategy implemented to compensate for this shortage of resources has been the mobilization of reclaimed water for agricultural irrigation in the irrigation zones traditionally supplied by the reservoirs.

3.2.3. Reclaimed water reuse systems

In Gran Canaria, according to the Guide on Vulnerability Analysis in the Industrial Water Cycle[80], numerous interconnected reclaimed water reuse systems have been identified, with different sources of reclaimed water, as well as several small, isolated systems. The main source of reclaimed water on the island is the Barranco Seco WWTP and Water

Reclamation Plant, with an actual production capacity of 700–800 m³/hour. From this facility, reclaimed water is distributed eastward and southward, as well as toward the central area (Tafira) and the north of the island. Along the entire reclaimed water transport and storage network, additional flows from other WWTPs, such as that of the Southeast of Gran Canaria, are incorporated. In specific territorial areas, there are also other, more or less isolated, local reuse systems, such as those in Guía-Gáldar and Agaete in the northwest of the island. The reclaimed water irrigation infrastructure provides a high level of climate resilience in the face of drought[81].

3.3. Vulnerabilities and system weaknesses

Gran Canaria's water infrastructure is exposed to multiple vulnerabilities stemming from its natural environment, geological characteristics, technical constraints, and socio-economic context.

3.3.1. Climatic and environmental vulnerabilities

The island's semi-arid climate and irregular rainfall result in water scarcity, leading to an unsustainable water cycle without the integration of reclaimed water[11,24]. Although climatic conditions do not directly reduce groundwater reserves, they intensify the imbalance between limited recharge and high demand[74].

3.3.2. Hydrogeological and water resource vulnerabilities

Gran Canaria's aquifers are under significant stress from historical overexploitation. By the late 1990s, over 50% of groundwater reserves had been depleted[22]. Intensive abstraction causes water table declines, increased salinity and fluoride levels in upland waters, and seawater intrusion in coastal areas[77]. Marine intrusion is particularly severe in the north (Guía–Gáldar), east (Telde), and southeast (Vecindario–Juan Grande)[22]. Groundwater depletion has reached levels where natural recovery, even if abstraction stopped, would take decades to a century. These conditions heighten vulnerability to further degradation and salinization.

3.3.3. Technical and infrastructure vulnerabilities

The island's dams face challenges related to aging structures and the need for continuous maintenance. New technical safety standards are being implemented to ensure their integrity throughout operational life[78]. The infrastructure is vulnerable due to its dispersion across rugged terrain, low profitability linked to small regulated volumes, difficult access, inadequate maintenance, and high population densities downstream. However, without

these dams, significant water volumes would be lost to the sea, and flood risks within ravines would increase.

A complementary analysis of the vulnerability of infrastructures within the industrial water cycle, associated with climate change in the northwest of Gáldar, was carried out by the Canary Islands Institute of Technology (ITC) in 2023, including additional information on the impacts on desalination, distribution, sanitation, treatment and reuse[80].

3.3.4. Socio-economic and governance vulnerabilities

Decades of intensive groundwater extraction have shaped both the island's environment and its socio-economic structures. An established groundwater trading system has created complex governance relationships and raised ethical concerns[22]. Balancing historical rights, economic needs, and sustainability remains difficult. Gran Canaria continues to fall short of Water Framework Directive objectives for groundwater, including pollution prevention, balancing abstraction with recharge, and reversing negative trends from human activities[24]. Without substantial policy and management reforms, the island will continue to face major barriers to sustainable water resource management.

3.4. Cascading failure of critical infrastructure services

3.4.1. Factsheet for the model of cascading failure for critical infrastructure services

Size and complexity:

6115 nodes, including 36 different types of interdependent critical infrastructure services (Figure 15). Impact on crops considers about 111 750 fields.

Energy setup:

Diesel generators supply 74% of the energy. Renewable energy produces about 26% of the energy in Gran Canaria – the majority of it – 17.5% - come from Wind generation and 8.5% come from Solar generation[82]. These percentages are reflected in the weights given to different types of input services for medium voltage power distribution nodes (where the input from wind generation, solar, and diesel nodes have respective criticality weights of 0.175, 0.085, and 0.74).

Water setup:

11 types of critical nodes are relevant to the water domain (if including the sewerage treatment plant). The scale of Gran Canaria, in terms of population, infrastructure and orography differs from La Palma and El Hierro. That's why for Gran Canaria, there was less up-to-date data available regarding water services, so a slightly coarser model was built

than for La Palma and El Hierro. For example, for irrigation water distribution, we directly considered the output service of irrigation reservoirs for crops integrity. Because, although the main infrastructures related to regenerated water were identified, they have not yet been integrated in detail into the cascading study, but could be incorporated in the future once more detailed information becomes available. There is also a clear separation between supply networks for drinking water and supply networks for irrigation.

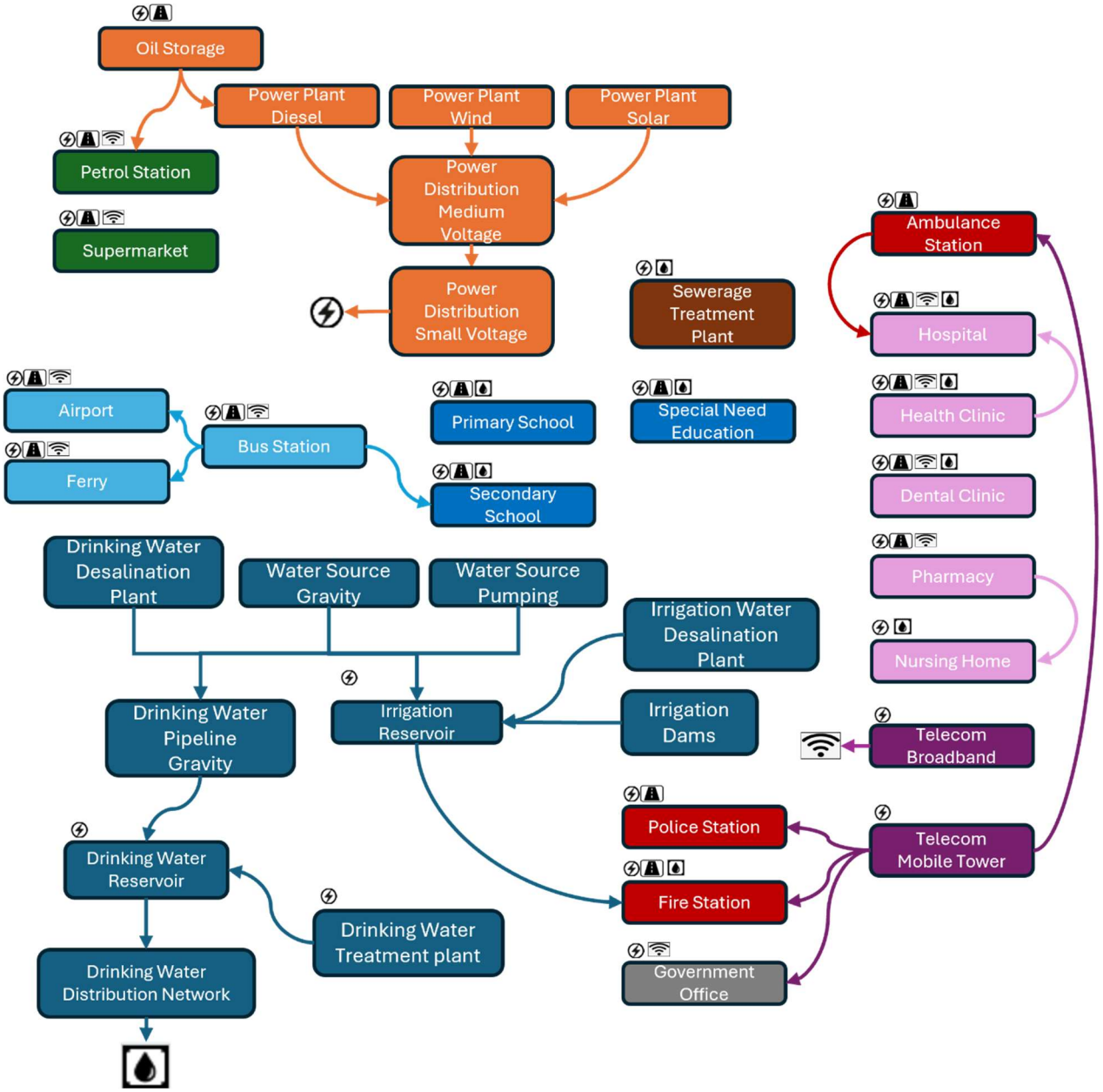

Figure 15 Simplified view of service dependencies between the 36 types of critical infrastructure nodes in Gran Canaria.

3.4.2. Experiment: coastal flood in Las Palmas de Gran Canaria with GENESIS climate projection for 2100

This experiment shows the consequences of a very localised coastal flood in the main urban area. Figure 16 shows the integrity scores for each critical infrastructure service as well as a map of impacted infrastructures on the Island where the impact goes well beyond the area directly damaged by the coastal flood.

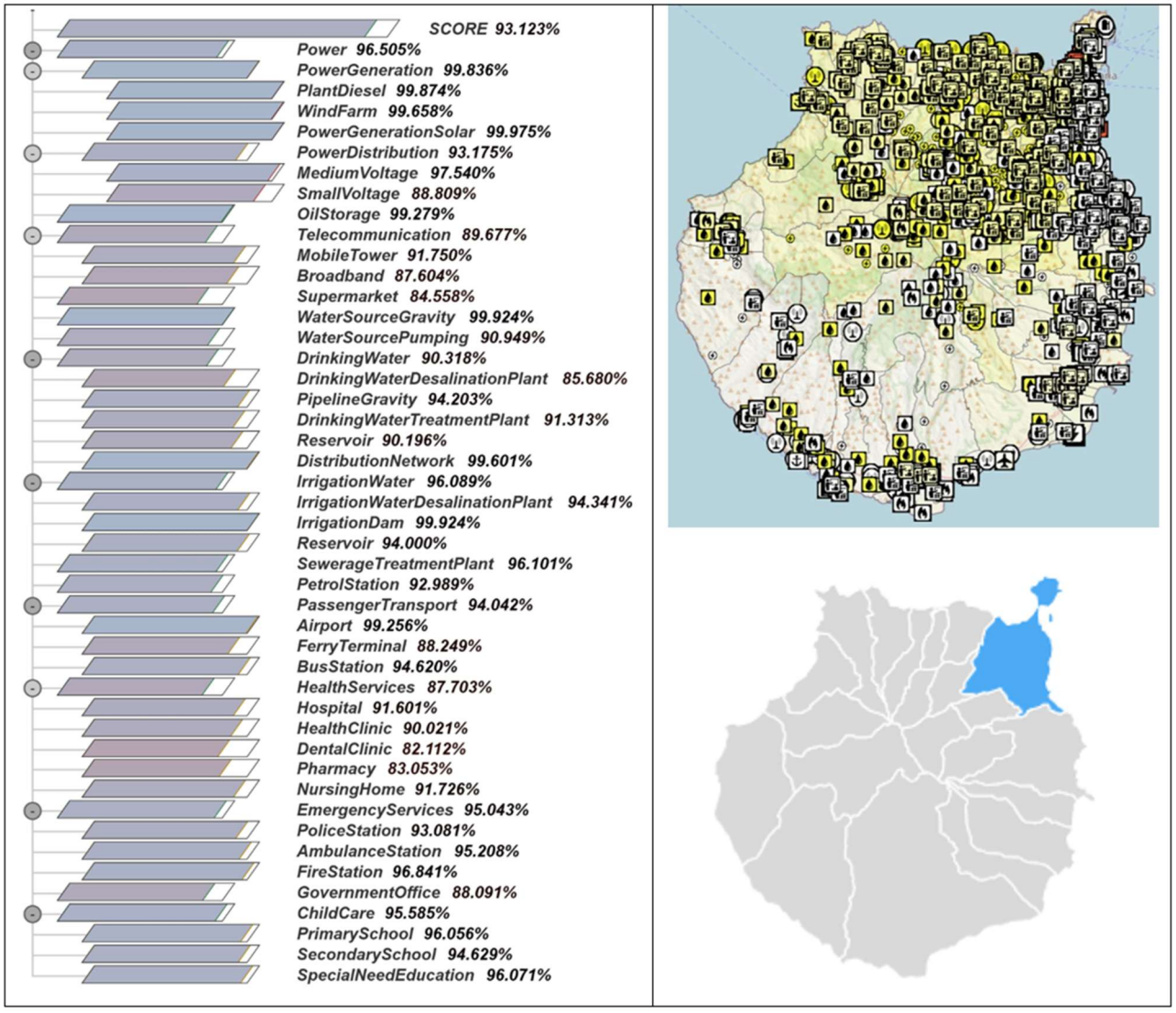

Figure 16 Simulated effects of localised coastal flood taking place in Las Palmas de Gran Canaria (in blue in the minimap), with increased disruption from wind alerts, coastal alerts, and storm alerts from the 2100 GENESIS climate projection. Critical services are impacted well beyond the directly affected areas.

3.4.3. Experiment: island-wide forest fires in Gran Canaria when comparing effects of climate projection for 2050 and for 2100

This experiment shows the consequences of island-wide forest fires and how different climate projections (2050 vs. 2100) can change the impact on critical infrastructure services significantly as damages due to fires are amplified by the number of high temperature alerts and wind alerts that increase from 2050 to 2100. Figure 17 shows a

significant difference on how critical infrastructure services are impacted for the same island-wide forest fires event if taking place in the climate projected for 2050 or in the 2100 projection.

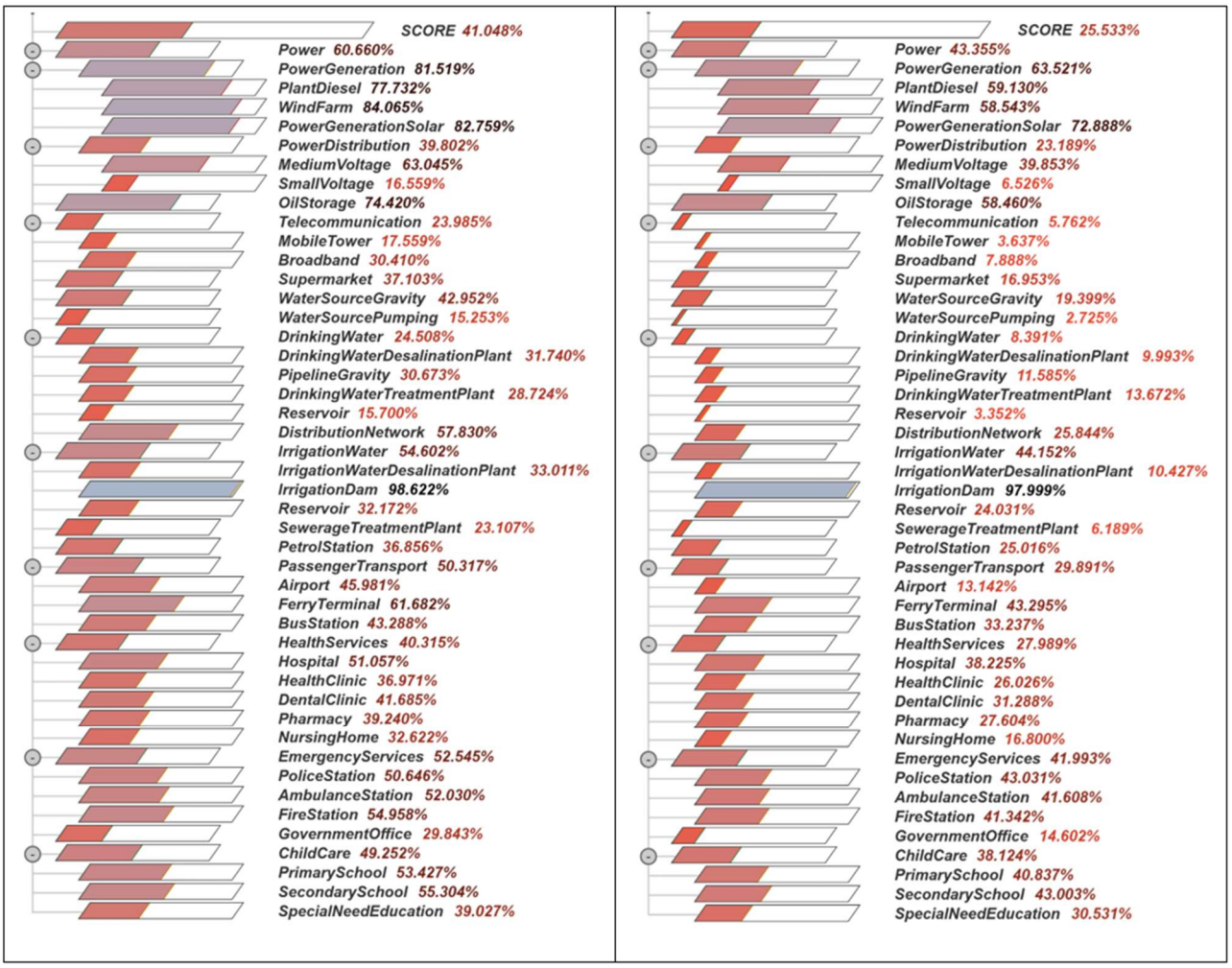

Figure 17 Simulated effects of the same island-wide forest-fires in a 2050 climate projection (left) vs a 2100 climate projection (right).

3.5. Summary of vulnerabilities and key conclusions

Gran Canaria's water system reflects high demand from a densely populated territory with intensive tourism and limited natural recharge. It is sustained through a combination of groundwater abstraction, seawater desalination, and surface storage. Groundwater remains critical, particularly for agriculture, but has been extensively overexploited, with more than 50% of reserves depleted and seawater intrusion in coastal zones. Recharge is insufficient to support recovery, and continued abstraction has led to progressive water quality degradation.

The island hosts the highest density of large dams globally. While contributing less than 10% of total supply, they are essential for irrigation in specific basins and play a key role in mitigating surface runoff risks. However, aging infrastructure, topographic constraints,

and increasing regulatory demands pose significant operational challenges. Desalination has become a major source of urban and tourism supply, yet remains vulnerable due to high energy dependency and coastal exposure.

System governance is shaped by historical groundwater rights and institutional fragmentation. Despite improvements in infrastructure integration and expansion of non-conventional resources, the island remains exposed to aquifer degradation, climatic variability, and energy-related disruptions.

Scenario modelling with the GENESIS cascading-failure engine demonstrated that even localised events, such as a coastal flood in Las Palmas de Gran Canaria, can trigger widespread infrastructure impacts due to high interdependence. Island-wide wildfire scenarios under 2050 and 2100 GENESIS climate projections revealed a marked increase in disruption under future conditions, primarily due to the compounding effects of high-temperature and wind alerts. These results underscore the importance of integrated planning, climate-informed risk analysis, and targeted investments to improve system resilience.

4- EL HIERRO ISLAND

4.1. Introduction and environmental setting

4.1.1. Geographical and socio-economic overview

El Hierro is the youngest island in the Canary Archipelago (Spain), formed approximately 1,12 million years ago[83]. It is also the westernmost and smallest island, covering an area of 268,71 km² (Figure 18). The island features rugged, mountainous volcanic terrain, reaching 1501 m at Pico de Malpaso, with an average elevation of 210 m above sea level[30,84]. Despite its small size and remote location, El Hierro has a population of 11 786 residents (2024)[72], distributed across the municipalities of Valverde, Frontera, and El Pinar.

Historically, the island was marked by isolation, limited transport connections, and water scarcity, with an economy based on pastoralism and rainfed subsistence agriculture until the mid-20th century. Today, it remains predominantly rural, although tourism and renewable energy have become increasingly important for local development[85].

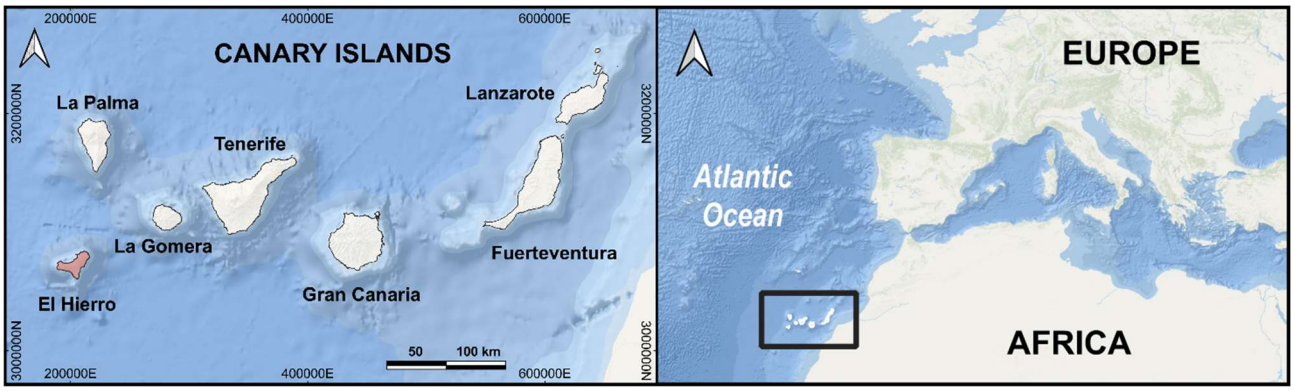

Figure 18 El Hierro's location within the Canary archipelago and wider regional context. CRS: EPSG:32628 WGS 84 / UTM 28N.

4.1.2. Climate and precipitation

El Hierro has a subtropical oceanic climate with mild, stable temperatures between 22,3°C and 26,4°C and highly variable rainfall, most of which occurs between October and April[84]. Average annual precipitation is around 400 mm, but it ranges from less than 150 mm in coastal areas to over 700 mm on the Nisdafe plateau and elevated zones near El Golfo[86].

4.1.3. Geological structure and evolution

El Hierro is the emergent part of a volcanic edifice built upon oceanic crust at depths of 3500–4000 m, with a base diameter of about 90 km[22,83]. Its morphology is shaped by a three-armed rift system and successive massive lateral collapses between rift arms, giving

the island its triangular, pyramid-like form with arcuate flanks and deep coastal embayments[22,30,83]. The geological history comprises three main volcanic construction–destruction cycles: Tiñor edifice (1,12–0,88 Ma), El Golfo–Las Playas edifice (545–175 ka), and Rift volcanism (158 ka to present)[83]. Each phase involved unstable growth, collapse, and the formation of younger edifices nested within basins left by earlier structures[30]. The island is composed mainly of basic lavas, including picrites, tephrites, nephelinites, and trachytes[22].

Major gravitational collapses, such as El Golfo, extend from Pico de Malpaso to depths of 3000–3200 m offshore, covering an area of 1500 km² and reaching over 65 km from the coast[83]. El Hierro remains volcanically active, as shown by the 2011–2012 submarine eruption near La Restinga[87].

4.1.4. Hydrogeological characteristics

El Hierro receives an estimated 9.5×10^7 m³ of annual precipitation, of which only about 27 % recharges aquifers; the remainder is lost to runoff and evaporation[88]. The island's hydrogeology is dominated by unconfined aquifers within the volcanic formations of the El Golfo edifice and related volcanism, which have relatively high hydraulic conductivity compared to the older, more compacted Tiñor materials[22,28]. Volcanic dykes act as both barriers and conduits, resulting in complex groundwater flow patterns.

The absence of low-permeability layers within the island's volcanic sequence prevents the formation of significant springs or natural surface water reservoirs, contributing to El Hierro's water scarcity[22]. Groundwater quality is affected by seawater intrusion, endogenous CO_2 dissolution, nitrate contamination likely from fertiliser use, and water–rock interactions driven by CO_2 input[28,89]. Dyke barriers protect areas such as the Gulf of El Hierro from saline intrusion and nitrate contamination, while zones with high CO_2 emissions in the northeast and west lead to acidification and elevated bicarbonate levels[28,84]. These dynamics highlight the importance of targeted groundwater monitoring on volcanic islands.

4.2. Water supply system and infrastructure

4.2.1. Overview and historical context

El Hierro's water supply system reflects its challenging hydrogeological conditions and longstanding struggle to secure reliable water resources. Historically, rural communities depended on rainwater harvesting, storing precipitation in rooftop cisterns, natural rock pools, and constructed tanks. Fog water collected by vegetation, such as the famous

Garoé tree, provided a minor supplementary source in the highlands[22,90]. Due to the scarcity and low flow of natural springs, inhabitants developed diverse collection methods that remained essential for domestic use until recent decades.

Initial groundwater abstraction focused on shallow coastal wells, which yielded limited and often brackish water. The success of deeper inland wells, such as the Agua Nueva well in El Golfo valley, demonstrated that groundwater of adequate quality and quantity could be accessed. This spurred further development in the 1960s and 1970s, including additional wells and hydraulic works like the Frontera–El Verodal canal[90].

Today, El Hierro's water supply system combines the legacy of historical practices with modern infrastructure, relying primarily on groundwater abstraction, desalination plants, extensive transport networks, and storage facilities, as illustrated in Figure 19[86]. Each of these water supply system components is described in detail in the following sections.

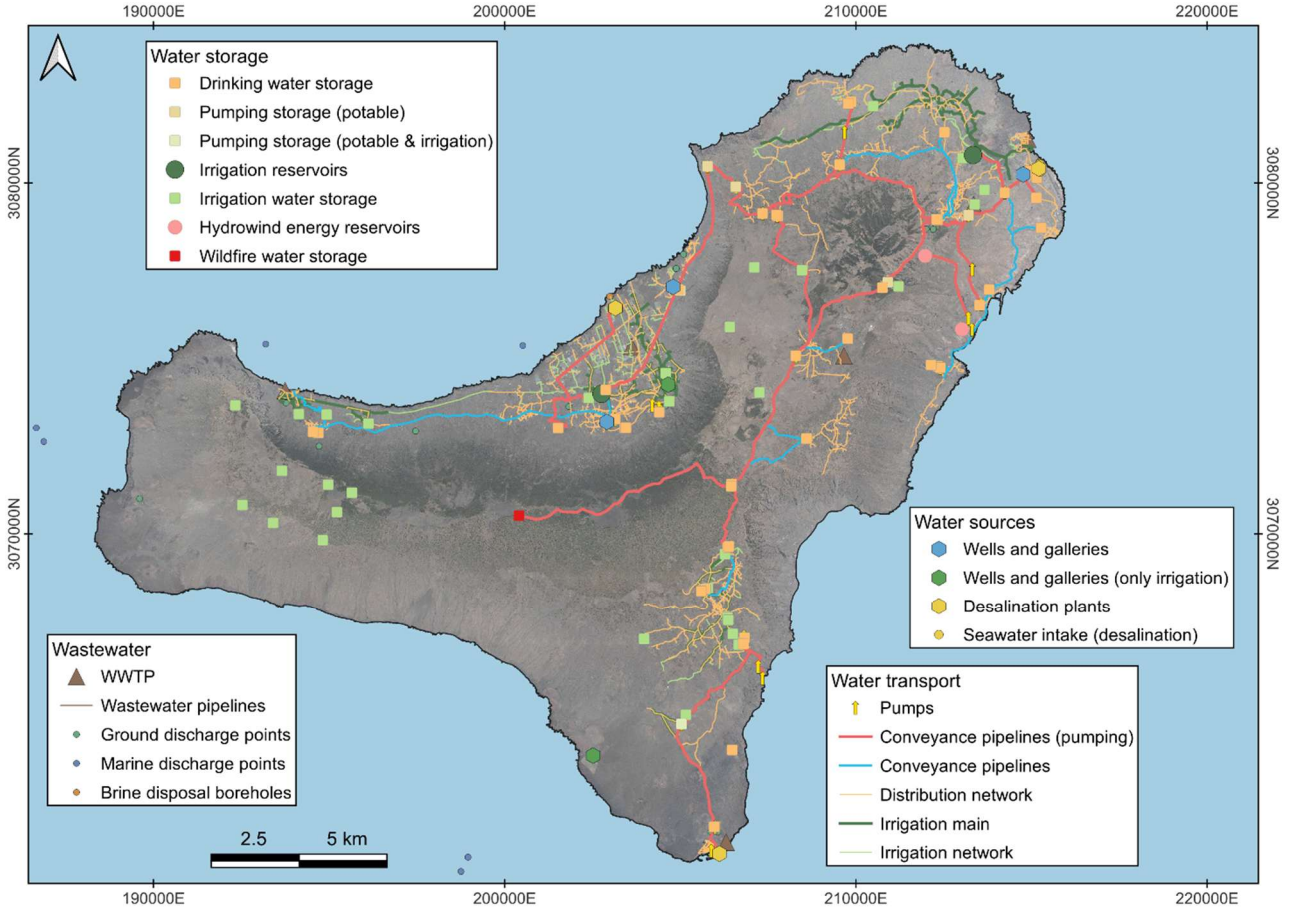

Figure 19 El Hierro water supply system and infrastructure. Data source: CIAEH[90]; IDECanarias[54]. CRS: EPSG:32628 WGS 84 / UTM 28N.

4.2.2. Groundwater abstraction and well-gallery systems

El Hierro's groundwater infrastructure includes conventional galleries, simple wells, wells with bottom galleries, and sloping-entry galleries[86]. According to the 1999 Hydrological Plan, the island had 49 groundwater abstraction structures, though only five were

operational at the time, collectively extracting 2,2 hm^3 per year from an estimated recharge of 27 hm^3 per year[22].

The most productive source is the Los Padrones well-gallery, which supplies around 1,1 hm^3 per year. It consists of a 52 m deep well connected to a 1011 m gallery extending towards the El Golfo escarpment, intersecting both rift volcanism materials and older El Golfo edifice rocks cut by numerous NE–SW dykes[84,86,90]. Other important public sources include the Tamaduste well-gallery (105 m deep with a 600 m gallery). Most important private sources are La Frontera well (700 000 m^3 per year; 235 m deep), the Tigaday well-gallery (220 000 m^3 per year; 275 m deep with 160 m and 113 m galleries), and the Tacorón sloping-entry gallery (100 000 m^3 per year; 1510 m long)[90].

Historic coastal wells consistently yielded water of inadequate quality for urban and agricultural use. Natural springs provide minimal flows, mainly used for livestock, while borehole explorations in the 1970s revealed saline stratification, characteristic of a thick, transmissive aquifer with low recharge[22,88].

4.2.3. Desalination infrastructure

Due to the island's vulnerability to groundwater over-extraction and salinization, seawater desalination is critical for water security. El Hierro operates several reverse osmosis desalination plants:

- Los Cangrejos (Valverde): 1800 m^3/day (2019) + 1200 m^3/day (2004)
- La Restinga (El Pinar): 1000 m^3/day (2013) + 1200 m^3/day (2004)
- El Golfo (La Frontera): 1300 m^3/day (2012)

Collectively, these facilities produce around 6500 m^3/day (≈2,34 hm^3/year), with expansion projects underway to increase capacity further[86,90].

4.2.4. Water transport and distribution

El Hierro's water transport system forms an island-wide ring network that enables transfers between municipalities (Figure 19). Water is conveyed from abstraction points and desalination plants to regulatory and distribution reservoirs via pressurised pipelines and gravity-fed conduits. The network is supported by multiple pumping stations capable of elevating water from sea level to over 1000 m, with high-pressure stations operating at up to 50 kg/cm^2[86,90].

4.2.5. Water storage

El Hierro's storage infrastructure includes distribution tanks, regulation tanks, ponds, and dams integrated into the transport network to balance supply and support firefighting, irrigation, and industrial needs. Municipal storage facilities comprise:

- Valverde: 33 tanks (26 452 m³)
- La Frontera: 8 tanks (7 005 m³)
- El Pinar: 10 tanks (6 429 m³)

For irrigation, industrial, and firefighting purposes:

- Valverde: 3 irrigation ponds and 1 dam with a total capacity of 587 000 m³
- La Frontera: 1 irrigation pond, 7 storage tanks, plus various private ponds and reservoirs (335 500 m³)
- El Pinar: 3 irrigation tanks and 2 firefighting tanks (15 800 m³)

These reservoirs and tanks are distributed across various elevation levels, with storage facilities located at altitudes up to 1365 m above sea level[86,90].

4.2.6. Sanitation and wastewater management

El Hierro's wastewater system serves selected towns through combined sewers and several treatment plants using extended aeration activated sludge processes. Major plants include:

- Valverde: 600 m³/day, treating 20 735 m³ per year
- La Restinga: 300 m³/day
- Frontera: 300 m³/day, with treated water reused for irrigation

Other smaller plants are located in El Majano, Tamaduste, and Pozo de La Salud. Treated effluent is typically discharged into soakaway pits, while scattered settlements depend on absorption wells[86,90].

4.3. Vulnerabilities and system weaknesses

El Hierro's water supply infrastructure is exposed to multiple vulnerabilities stemming from its geology, hydrogeology, and socio-technical context. The island's structure, dominated by rift zones, dense dyke networks, and major landslide scars, creates complex hydrogeological conditions that limit aquifer capacity and stability. Its steep relief and unstable volcanic formations present landslide risks, particularly in areas affected by past

massive gravitational collapses such as El Golfo and Las Playas. These geological instabilities pose hazards for water supply systems situated in or near vulnerable zones[22].

The island's natural hydrogeological characteristics compound these vulnerabilities. Although El Hierro has a highly permeable surface and aquifers with high transmissivity, recharge capacity is limited, making sustainable groundwater management inherently challenging. Groundwater abstraction frequently encounters rapid salinization, especially in coastal wells where marine intrusion occurs via ascending saline cones. Continuous pumping intensifies this process, shifting groundwater from bicarbonate-sodium to chloride-sodium type as salinity rises[22]. The Los Padrones well-gallery is an exception due to active water level management preventing seawater intrusion, but much of the coastal aquifer has been severely affected[86].

Natural salinity in the island's western areas further degrades water quality, influenced by climatic factors and geogenic CO_2 inputs that alter groundwater chemistry[84]. Isotopic studies[89] show that recharge predominantly occurs at elevations between 800 and 1 400 m, with aquifers exhibiting varied renewal rates. Regional systems display slow renewal with strong water–rock interaction, while local systems, such as springs, have more rapid turnover. This variability complicates the management of both water quantity and quality, particularly during droughts or under rising demand.

Technical and systemic vulnerabilities also threaten El Hierro's water security. While desalination is critical to supplement local resources, it faces technical, operational, and economic limitations that prevent it from fully resolving scarcity issues[86]. High desalination costs, coupled with the energy required to pump water to high elevations across rugged terrain, place additional strain on the system. Efforts to support agriculture with coastal groundwater abstraction have largely failed, as these wells quickly became too saline for irrigation. The island's reliance on a dispersed and complex infrastructure network, including pumping stations, pipelines, and storage facilities located in geologically and topographically challenging areas, further heightens risks from natural hazards and aging systems.

Taken together, El Hierro's water infrastructure is vulnerable to geological instability, limited and variable aquifer recharge, marine intrusion risks, desalination constraints, and the operational challenges of managing a complex distribution system under these conditions. These factors highlight the need for integrated management strategies that address both natural limitations and socio-technical realities.

4.4. Cascading failure of critical infrastructure services

4.4.1. Factsheet for the model of cascading failure for critical infrastructure services

Size and complexity:

823 nodes – including 39 different types of interdependent critical infrastructure services (Figure 20). Impact on crops takes into account about 18 000 fields.

Energy setup:

Renewable energy produces about 46% of the energy in El Hierro – the majority of it - 41% - come from wind farms. Hydro pumps displace water to a reservoir that produce hydro power generation (about 5% of the energy production of the Island). Finally, diesel generators supply the remaining 54% of the energy. This percentage are reflected in the weight given to different type of input services for power distribution nodes (where the input from wind generation, hydro, and diesel nodes have respective criticality weights of 0.41, 0.05, and 0.54).

Water setup:

11 types of critical nodes are relevant to the water domain (if including the sewerage treatment plant). The criticality of the desalination plants and wells input services for gravity driven water pipelines are respectively 63% and 37% (due to identification of given critical nodes in the concerned areas). Similarly, the criticality of the desalination plants, wells, and pumps input services for pumping driven water pipelines are respectively 31.5%, 18.5%, and 50%. Finally, the criticality of the input services irrigation wells, irrigation gallery, gravity driven pipelines, and pumping driven pipelines for irrigation reservoirs are estimated at respectively 4%, 29%, 11.17%, and 55.83%. It is notable that El Hierro model has no clear separation between transport networks for drinking water and those for irrigation, as both rely on the same gravity -or pumping-driven conveyance pipelines. Distribution networks, however, remain separated after drinking water disinfection.

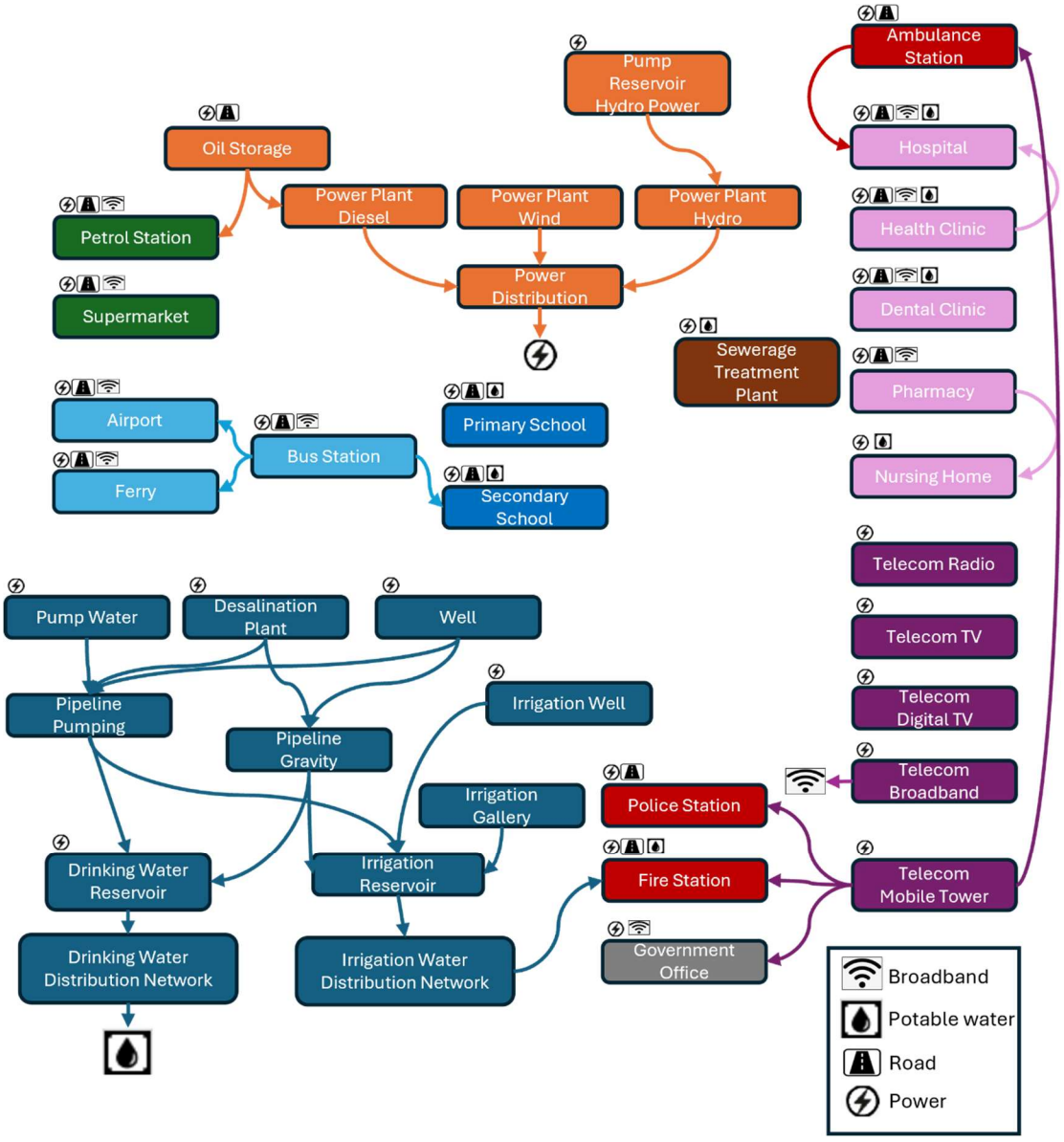

Figure 20 Simplified view of service dependencies between the 39 types of critical infrastructure nodes in El Hierro.

4.4.2. Experiment: island-wide earthquake in El Hierro

This experiment shows the consequences of an island-wide earthquake for El Hierro. Critical infrastructure services are impacted as shown in the results displayed by the visualisation part of the simulation engine. Figure 21 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). Figure 22 shows an estimation of the number of parents impacted by the loss of primary schools and secondary schools' services. Figure 23 shows an estimation of the number of people facing a critical service loss where these services are more than 50% impacted. Figure 24 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 25 shows how crops are affected the earthquake.

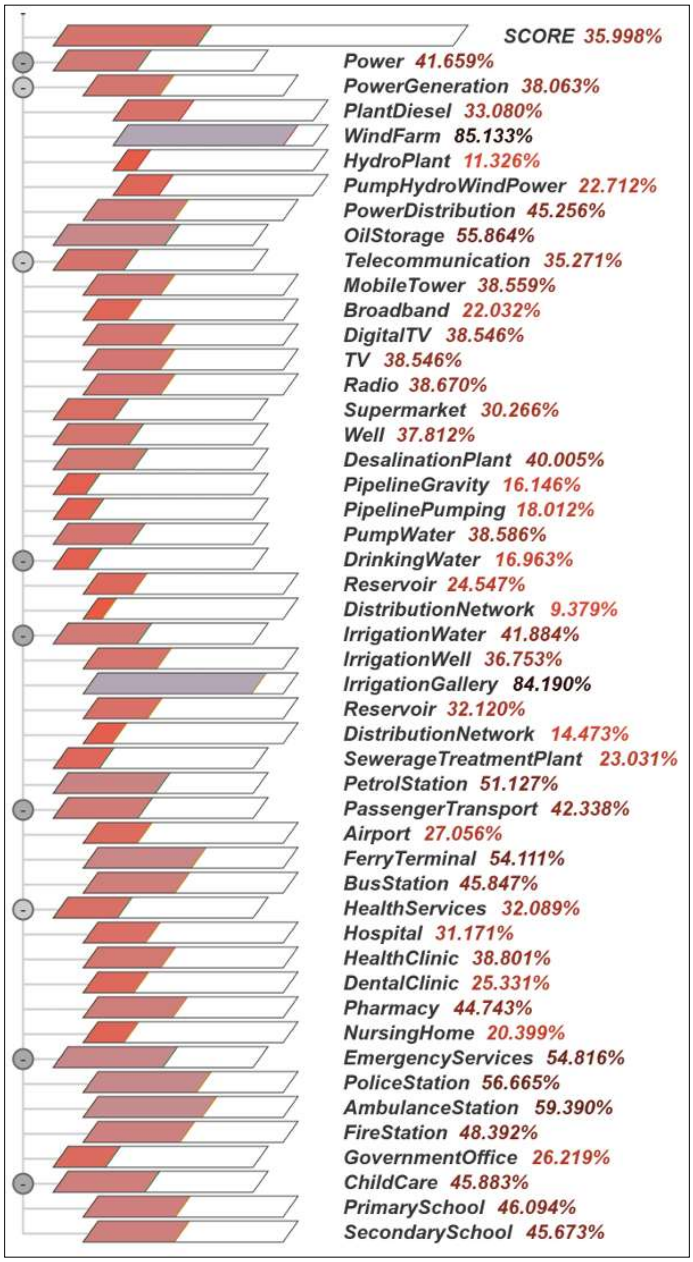

Figure 21 Simulated effects of an island-wide earthquake on critical infrastructure services in El Hierro.

Service	Parents Facing 10-50% Service Loss	Parents Facing (+50%) Service Loss
Primary School	96.503 (0.9%)	130.592 (1.2%)
Secondary School	0 (0.0%)	227.094 (2.0%)
Special Education	0 (0.0%)	0 (0.0%)

Service	Parents Facing 10-50% Service Loss	Parents Facing (+50%) Service Loss
Primary School	273.389 (2.4%)	1,179.67 (10.4%)
Secondary School	0 (0.0%)	1,453.059 (12.9%)
Special Education	0 (0.0%)	0 (0.0%)

Figure 22 Simulated effects of an island-wide earthquake on number of lone parents (top) and parents in pluri-parental families (bottom) facing primary and secondary school service loss.

Service	People Facing (+50%) Service Loss
Pharmacies	11,298 (100.0%)
Hospitals	11,298 (100.0%)
Health Clinics	11,298 (100.0%)
Dental Practices	11,298 (100.0%)
Bus Transport	11,298 (100.0%)
Mobile Telecommunication	11,298 (100.0%)
Clean Water	11,298 (100.0%)
Power	11,298 (100.0%)
Total Population	11,298

Figure 23 Simulated effects of an island-wide earthquake on number of people facing critical infrastructure loss of service above 50%.

Industry	Workforce (Current / Initial)	Availability (%)
O Administración Pública y defensa; Seguridad social obligatoria	698 / 769	90.81%
I Hostelería	529 / 588	90.03%
P Educación	438 / 478	91.67%
Q Actividades sanitarias y de servicios sociales	353 / 387	91.22%
G Comercio al por mayor y al por menor; reparación de vehículos de motor y motocicletas	323 / 361	89.60%
H Transporte y almacenamiento	230 / 250	91.92%
F Construcción	185 / 206	90.01%
A Agricultura; ganadería; silvicultura y pesca	156 / 177	88.11%
S Otros servicios	133 / 144	92.03%
M Actividades profesionales; científicas y técnicas	77 / 84	91.71%
T Actividades de los hogares como empleadores de personal doméstico y como productores de bienes y servicios para uso propio	77 / 84	91.46%
C Industria manufacturera	75 / 84	89.38%
K Actividades financieras y de seguros	74 / 83	88.67%
N Actividades administrativas y servicios auxiliares	57 / 63	90.41%
J Información y comunicaciones	38 / 44	87.10%
E Suministro de agua; actividades de saneamiento; gestión de residuos y descontaminación	34 / 37	92.95%
D Suministro de energía eléctrica; gas; vapor y aire acondicionado	20 / 21	92.93%
U Actividades de organizaciones y organismos extraterritoriales	5 / 5	92.96%
B Industrias extractivas	0 / 0	0.00%
L Actividades inmobiliarias	0 / 0	0.00%
R Actividades artísticas; recreativas y de entretenimiento	0 / 0	0.00%
Total	7,005	

Figure 24 Simulated effects of an island-wide earthquake on workforce availability in El Hierro.

Crop Type	Area (m^2)	Starting integrity	Integrity after cascading failure
Viña	2,550,964	37.8%	5.4%
Higuera	1,270,094	61.9%	9.8%
Piña	1,258,558	33.8%	4.4%
Templado Otras Mezclas	734,240	33.1%	5.1%
Cereal Otros	605,127	33.3%	5.3%
Platanera	597,889	49.6%	6.8%
Barbecho	590,269	33.2%	4.7%
Huerta Limpia	547,728	33.1%	5.0%
Aguacate	311,126	35.7%	5.0%
Subtropicales Otras Mezclas	260,138	33.8%	4.6%
Hortaliza Otras Mezclas	243,427	33.4%	5.0%
Tunera	241,278	35.0%	5.4%
Almendro	234,331	33.2%	5.3%
Mango	226,610	38.1%	5.1%
Papa	181,191	34.7%	5.3%

Figure 25 Simulated effects of an island-wide earthquake on crops. Indirect damages due to loss of irrigation are very significant.

4.4.3. Experiment: landslides in the region of Frontera in El Hierro with GENESIS climate projection for 2100

This experiment shows the consequences of landslides takin place in the region of Frontera, with increased disruption from precipitation alerts (+1% damage to an already impacted node per alert) estimated for 2100 over the area. Figure 26 shows the integrity scores for each critical infrastructure service.

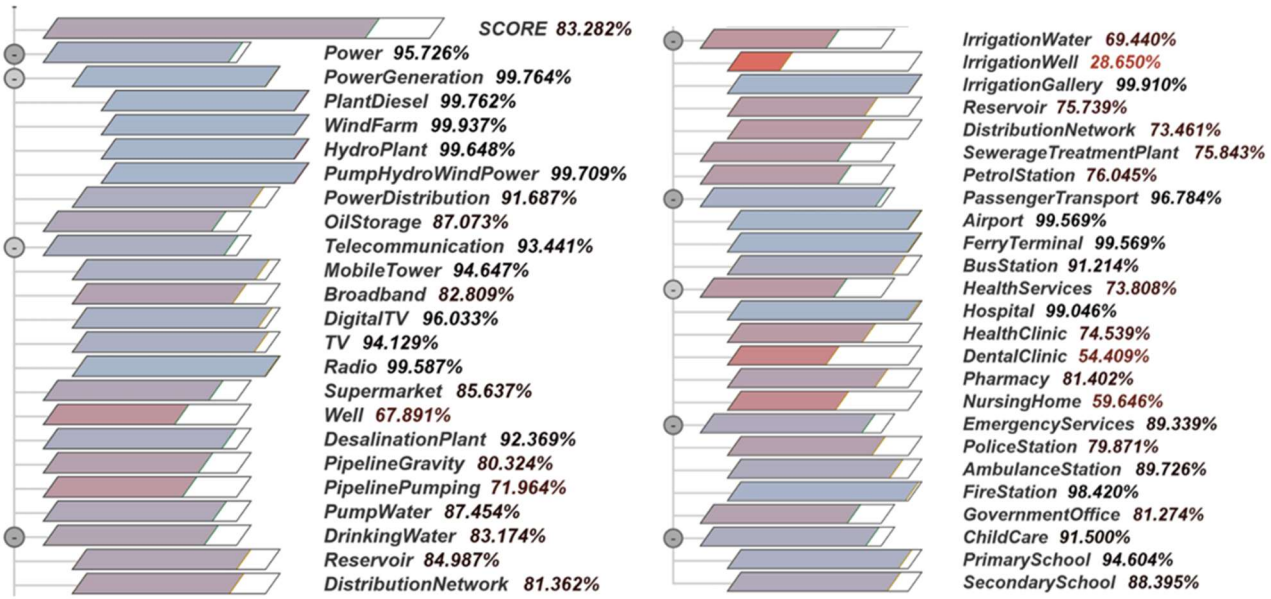

Figure 26 Simulated effects of landslides taking place in the Frontera region, where the number of estimated precipitation alerts from the 2100 climate projection impact critical infrastructure services in El Hierro.

4.5. Summary of vulnerabilities and key conclusions

El Hierro's water supply system reflects the constraints of a geologically complex volcanic island with limited recharge capacity, unstable terrain, and dispersed demand centres. The system combines groundwater abstraction and desalination, supported by a ringed distribution network, elevation pumping infrastructure, and strategically located storage reservoirs. While historical reliance on low-yield springs and shallow wells has declined, sustained abstraction from deeper sources and the increasing role of reverse osmosis have introduced new operational dependencies.

Key vulnerabilities arise from limited and uneven recharge, seawater intrusion, and geochemical degradation linked to sustained abstraction, particularly in coastal wells. Groundwater salinization, natural background salinity, and geogenic CO_2 inputs further reduce resource quality. Productive sources such as the Los Padrones well-gallery require active level control to prevent contamination. In parallel, geological instability, associated with rift structures and landslide-prone slopes, threatens the physical integrity of pipelines, wells, and pumping stations, especially in zones such as El Golfo and Las Playas.

System fragility is further shaped by technical and energy-related dependencies. Desalination plays a critical role in supplementing supply, but its operational complexity and higher energy requirements, relative to groundwater abstraction, increase reliance on stable energy inputs. While backup generation capacity exists at pumping stations, continuity may be constrained by access or logistical conditions during hazard events. Potable and irrigation networks are technically distinct, but shared routing corridors and partial overlap in storage infrastructure may limit functional separation. This configuration reduces redundancy under disruptive conditions. Lastly, most coastal wells have become unsuitable for irrigation due to seawater intrusion.

While El Hierro benefits from relatively low demand and moderate population pressure, overall redundancy remains limited. Resilience depends on a small number of high-quality sources, continuous monitoring, and integrated management of aquifers, infrastructure, and energy systems.

The cascading-effects assessment simulated disruptions across 823 infrastructure nodes and 39 interdependent service types, including impacts on approximately 18 000 agricultural fields:

- Island-wide earthquake scenario: System-wide damage significantly reduced infrastructure service integrity across all categories. Educational facility closures (primary and secondary schools) caused widespread secondary impacts, affecting

parental availability in the workforce. Over 50% loss of essential services was recorded for a large segment of the population, and crop production was substantially impaired due to irrigation system disruption.

- Landslide scenario (Frontera, GENESIS 2100 climate projections): Localised failures were intensified by precipitation-triggered alerts, with cumulative degradation of node integrity. Disruptions to transport and energy cascaded into multiple sectors, highlighting the vulnerability of services concentrated in geologically unstable zones under future climate conditions.

Taken together, El Hierro's system is vulnerable to aquifer degradation, desalination and energy constraints, and natural hazards affecting infrastructure continuity. Ensuring the protection of productive sources, maintaining the operability of infrastructure in hazard-prone areas, and coordinating water and energy services are essential to sustain system functionality under both long-term resource constraints and short-term hazard-related disruptions.

5- MADEIRA ISLAND

5.1. Introduction and environmental setting

The Autonomous Region of Madeira (RAM) is an archipelago in the North Atlantic Ocean, belonging to Portugal, located between latitudes 30°01′N and 33°08′N and longitudes 15°51′W and 17°16′W. It consists of Madeira (741,7 km²), Porto Santo (42,6 km²), the Desertas (14,1 km²), and the Selvagens (2,7 km²) (Figure 27). Madeira Island is the largest and serves as the administrative centre, with a population of approximately 257 000 residents across ten municipalities[91,92].

The island's rugged volcanic terrain, steep orography, sharp climatic gradients, dense hydrographic network, and high annual rainfall create a complex environmental setting that shapes land use, water availability, and vulnerability to natural hazards[93–95]. These conditions have driven long-standing adaptation measures, including the *levada* irrigation system (traditional irrigation channels or aqueducts), hydroelectric infrastructure, and intermunicipal water governance, demonstrating both resilience and innovation. However, ongoing climate change and demographic pressures continue to necessitate investment in sustainable water management and hazard mitigation.

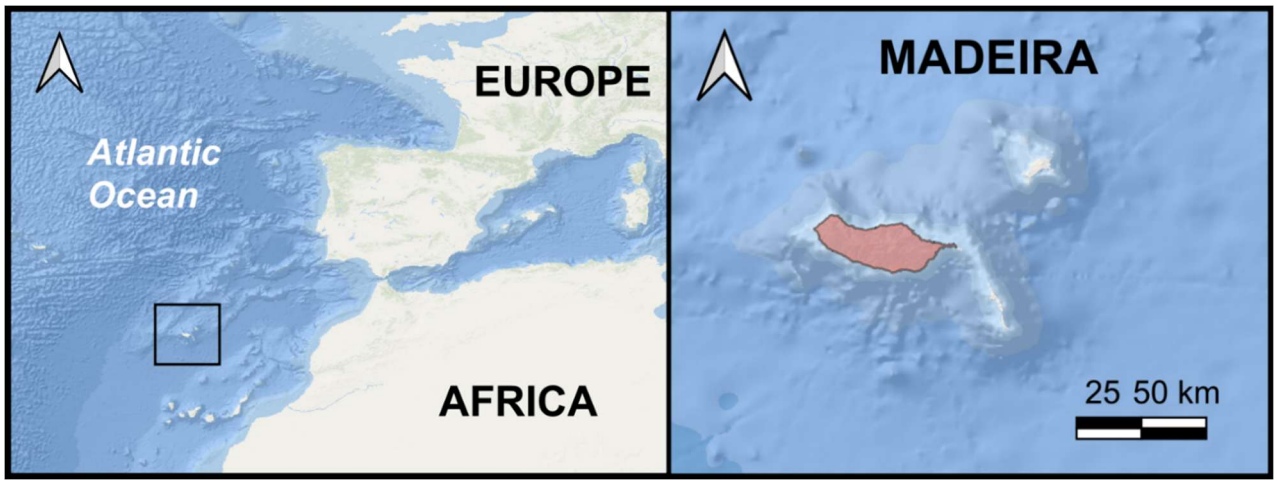

Figure 27 Madeira's location within the archipelago and wider regional context.

5.1.1. Geographical and orographic setting

Madeira's topography is characterized by a central mountain ridge, oriented northwest–southeast, with peaks including Pico Ruivo (1861 m), Pico das Torres (1852 m), and Pico do Areeiro (1818 m). Over 64% of the island lies above 500 m elevation, while only 4,9 % is below 100 m. Steep slopes define the terrain: 35% of the surface has slopes exceeding 30%, and 8,3% exceeds 50%[93]. The terrain is deeply dissected by valleys and short, torrential streams

that flow towards the coast. The western part of the island is more mountainous, while the east is drier with less vegetation cover[96,97]. This rugged orography strongly shapes climatic conditions, hydrology, settlement distribution, and infrastructure development.

5.1.2. Climate and meteorology

Located in a subtropical zone with a mild maritime climate, Madeira experiences pronounced microclimatic contrasts shaped by its orography and the Azores High. Coastal areas are warmer and drier, while highland zones are cooler and wetter. Annual temperatures range from 8°C in the mountains to 19°C along the coast, with summer averages reaching 23°C in lowlands and 16°C at higher elevations[93]. Between 2000 and 2021, average temperatures increased across the archipelago, reaching 20,2 °C in Funchal and peaking at 20,7 °C in Lugar de Baixo (Observatório Clima Madeira[93]).

Precipitation varies significantly with elevation and slope orientation: Funchal records an average of 641 mm/year, while mountain stations such as *Bica da Cana* receive over 2966 mm/year[93,94,97], reflecting a strong north–south asymmetry driven by orographic rainfall. The Laurisilva forest, a UNESCO World Heritage site, plays a vital role in water retention through fog capture and horizontal precipitation. However, recent data show declining rainfall in high-altitude areas[93,95].

5.1.3. Geology and hydrogeology

Madeira was formed by Miocene–Holocene shield volcanism linked to a mantle hotspot, resulting in a fractured landscape of lava flows, pyroclastic deposits, and dike structures with high water-retention capacity[32]. Its hydrogeological setting includes perched aquifers in less permeable layers and basal aquifers within fractured volcanic units. Groundwater quality varies by depth and lithology: upper perched aquifers are less mineralised, while deeper units show higher conductivity and pH[32,94]. Transmissivity ranges from $2{,}31\times10^{-4}$ to $2{,}89\times10^{-1}$ m²/s, with older formations showing increased mineralisation[32]. Springs are most abundant between 600 and 1500 m elevation, particularly on the northern slopes. Despite groundwater's crucial role in public supply and irrigation, monitoring remains limited, and access to springs and galleries is often constrained by challenging topography.

5.1.4. Hydrography and water resources

The island's hydrographic network includes 126 watersheds and 234 mapped streams (*ribeiras*), shaped by steep gradients and short catchments that result in rapid concentration times and high flash flood risk[93,95]. Southern *ribeiras* generally have

ephemeral flows and rocky beds with limited sediment retention, while northern streams are often perennial due to sustained groundwater discharge[94]. Waterfalls along valley slopes, fed by rainfall, infiltration, and surface runoff, are notable natural features[97].

The Socorridos hydroelectric project exemplifies adaptation to these hydrological conditions, using a reversible system with a network of tunnels and reservoirs to transfer water from the wetter north to the drier south, supporting both irrigation and electricity generation[98].

5.1.5. Land use and population distribution

Land cover[93] is predominantly forests and natural vegetation (78%), while urban areas, concentrated along the southern coast around Funchal, occupy just 6%. Agricultural land covers 8%, with infrastructure and transport zones accounting for the remaining 2%.

The region's population declined to 250 744 in 2021, representing a 6,4% decrease over the decade, making it the sharpest drop since 1970. This demographic decline has coincided with urban expansion into water-stressed areas, increasing localised pressure on supply infrastructure despite the overall population decrease[93,99].

5.1.6. Cultural and environmental heritage: the *levada* network

Madeira's *levada* network (traditional irrigation channels or aqueducts), spanning 800 km, was developed from the 15th century onwards to divert water from the humid northern slopes to farmland in the south, representing a unique cultural and technical adaptation to the island's topography and climate[100]. Today, these channels also function as popular hiking trails, used by over 60% of tourists[97,101]. Originally managed by local communities, the *levadas* were later privatised, leading to governance challenges and prompting institutional reforms that expanded supply networks and facilitated hydroelectric development[97].

5.2. Water supply system and infrastructure

5.2.1. Introduction and system description

Madeira's water supply system (WSS) is a territorially adapted infrastructure combining surface and groundwater sources to meet water demands across its steep and uneven terrain. It captures surface water via *levadas*, streams, and springs; abstracts groundwater through wells, boreholes, and horizontal galleries; and integrates infrastructure for pumping, transport, treatment, storage, and distribution. The system includes over 200 *levadas*, 30 water treatment plants, numerous reservoirs, and thousands of kilometres of

pipelines, supplying water for domestic use, irrigation, and energy production (Figure 28)[94,97,101,102].

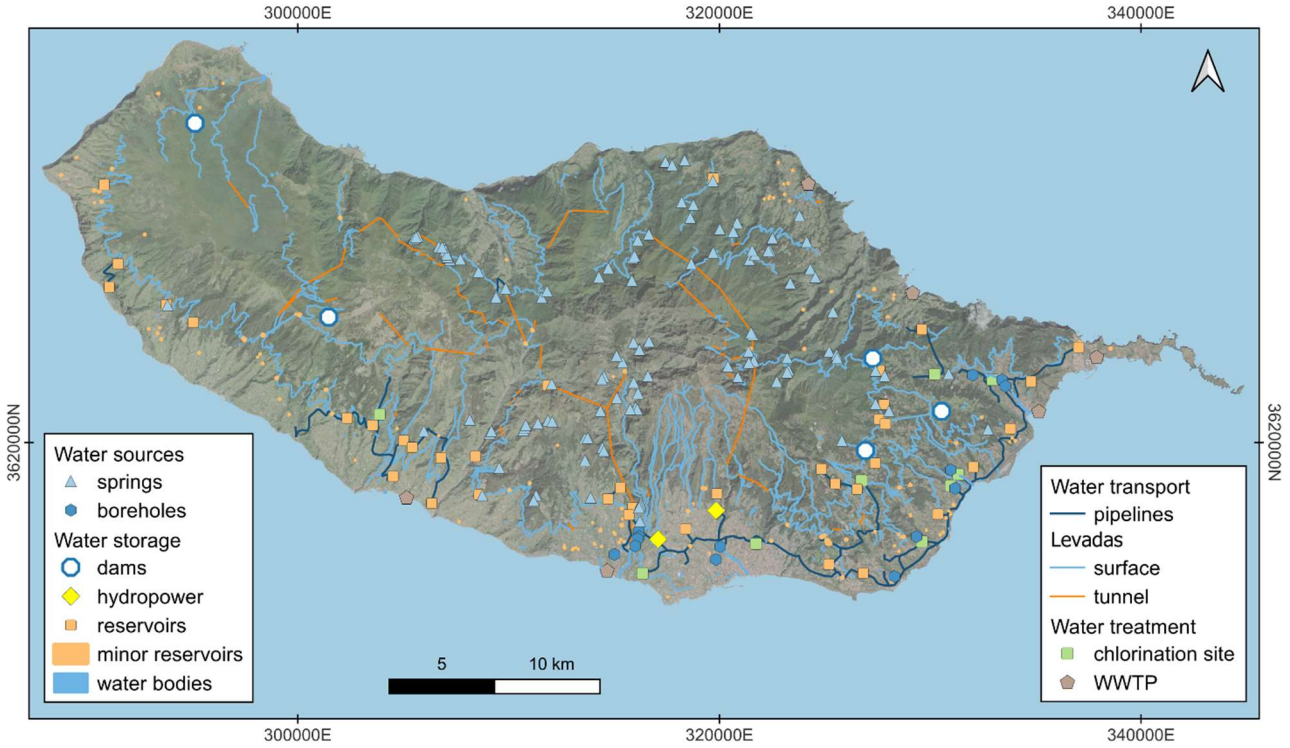

Figure 28 Madeira water supply system and infrastructure. Data: IP-RAM SR de PC[92]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Functionally, the WSS is divided into upstream and downstream networks[102]. The upstream segment covers water intake from surface and groundwater sources depending on regional needs; pumping systems to lift raw or treated water across elevation differences towards treatment or storage facilities; transport pipelines operating under pressure or as free-flow channels to convey water to treatment plants or distribution points; water treatment plants (*ETAs*) using decantation, filtration, disinfection, and fluoridation to achieve potable standards[101]; and storage in surface and elevated reservoirs that buffer daily and seasonal demand, stabilise network pressure, and provide reserves for firefighting or service disruptions.

The downstream network distributes treated water to consumers. It consists of exterior distribution systems (pipes, joints, valves, hydrants, and flow meters) carrying water from reservoirs to end users, along with household connections ensuring adequate pressure and flow at the point of consumption.

System configurations are adapted[101] to the terrain: gravity-fed systems operate where elevation differences allow, pumped systems supply areas above water sources, and mixed systems combine both approaches by pumping water to elevated reservoirs for subsequent gravity-fed distribution. In regions with limited surface water, groundwater abstraction supplements supply via vertical and horizontal capture structures. The WSS

also integrates hydroelectric infrastructure, with several plants harnessing the gravitational potential of high-altitude water flows transported by *levadas*[94]. Groundwater-fed hydroelectric stations supply approximately 20% of Madeira's total electricity demand[32].

5.2.2. Water sources

Groundwater in Madeira is extracted from springs, wells, boreholes, and horizontal galleries. Springs originate from perched aquifers located between 600 and 1500 m elevation and discharge into the extensive *levada* network for transport[32]. Horizontal galleries are situated in higher parts of the island and excavated almost horizontally to enable gravity-driven flow. They typically range from 500 m to 3 km in length and are constructed just below the water table to intercept the regional piezometric level or permeable geological structures such as fractured zones and faults[32]. A notable example is the 1107 m-long gallery on the right bank of *Ribeira de Machico*, at 350 m elevation, which is among the island's most important water sources and a frequent destination for educational and tourist visits[97].

Wells and boreholes are mainly located in coastal valleys and lower riverbeds. Shallow wells (up to 10–12 m) are used where feasible, while deeper boreholes are required in areas with insufficient surface or *levada* water[101]. Of the 30 original wells, 24 remain operational, with specific capacities ranging from 0,2 to 667 L/s/m[32]. However, over-extraction from coastal boreholes risks saltwater intrusion[97]. Tubular extractions were introduced in the 1980s in lower watersheds such as *Machico* and *Socorridos* to improve irrigation on the southern slopes[97]. Site selection for boreholes and galleries prioritises areas with higher transmissivity and favourable geological conditions, though costs and technical complexity increase with greater depth and challenging terrain[101].

5.2.3. Transport and treatment

The *levadas* of Madeira[100] form a historically significant and technically adapted water transport system, designed to address the island's steep terrain and uneven water availability. Extending over 800 km, these gravity-fed open channels were first constructed in the 15th century to irrigate sugarcane fields and power mills, later evolving into a multifunctional backbone for irrigation, domestic supply, and hydroelectric production. *Levadas* convey water from humid high-altitude areas, often above 1000 m, to the drier southern slopes. Primary *levadas* collect spring discharges, surface runoff, or diverted streams and direct them to reservoirs or hydropower plants, while lower-elevation distribution *levadas* deliver water for irrigation or domestic use. Technically, they are

narrow channels with a minimal, consistent slope that ensures laminar surface flow over long distances without pumping. In mountainous areas, levadas are carved into rock, built along stone walls, or bridged across ravines, often incorporating tunnels, siphons, and gates to manage flow and terrain constraints.

Branches known as *rega lines* supply terraced fields intermittently and are managed by local irrigation associations. The integration of levadas with hydropower infrastructure enables water to generate electricity before continuing downstream for agricultural use. This low-energy, decentralised system combines technical efficiency with local governance, making levadas a key component of Madeira's water infrastructure and cultural heritage.

Water treatment is primarily conducted at Water Treatment Plants (*ETAs*), where chlorination and disinfection ensure potable quality. Supplementary chlorination points are also installed downstream, particularly after reservoirs or in remote areas, to maintain residual chlorine levels along extended pipeline networks. For example, in Ribeira Brava, water quality is managed by one ETA supported by five additional chlorination stations[103].

5.2.4. Reservoirs

Reservoirs in Madeira serve to store potable water, irrigation water, and provide reserves for firefighting. They are strategically positioned to maintain minimum operating pressure within the WSS. In areas with complex terrain, intermediate reservoirs regulate pressure, while in large distribution zones, multiple reservoirs ensure uniform water delivery. With population growth, additional lower-elevation reservoirs may be required to manage pressure variations[104].

Most reservoirs have capacities between 200 and 6000 m^3, with the *Lagoa do Bardo* dam reservoir holding up to 35 000 m^3[94]. Based on capacity, they are classified as small (<500 m^3), medium (500–5000 m^3), or large (>5000 m^3)[104]. Structurally, reservoirs may be buried, semi-buried, ground-supported, or elevated, depending on terrain characteristics and pressure requirements[104].

5.2.5. Distribution networks

Madeira's water distribution networks include branched, meshed, and mixed configurations, chosen based on topography, urban layout, and operational requirements[103,105]. Branched systems are simpler and more cost-effective but are susceptible to service interruptions if a pipe fails. Meshed networks enable bidirectional flow, providing greater reliability and flexibility, though they require more complex

infrastructure and management. Mixed systems integrate elements of both, balancing cost, redundancy, and hydraulic performance.

5.2.6. Wastewater

Wastewater in Madeira is treated at wastewater treatment plants (WWTPs) using a three-stage process to remove solids, reduce biodegradable organic matter, eliminate pathogenic organisms, improve water quality, and minimise environmental impacts[103]. The main sources of pollution are discharges from urban, livestock, and industrial activities, with urban wastewater being the largest contributor. Additional contamination arises from leachate produced by poorly managed solid waste landfills and from soil deposits in flood-prone areas. Industrial pollution poses further risks due to the limited number of pre-treatment systems and inadequate control measures, increasing the likelihood of hazardous substances entering sewer networks, natural water bodies, and surrounding soils. Treated effluent from WWTPs is ultimately discharged into the Atlantic Ocean.

5.3. Vulnerabilities and system weaknesses

Madeira's WSS faces persistent structural, operational, and environmental vulnerabilities. Despite universal household access to potable water, the island's steep orography complicates infrastructure layout, access, and pressure regulation[94,97]. Floods frequently damage *levadas* and distribution networks, while financial constraints affect timely maintenance. Irrigation remains limited in areas above *levada* levels, relying solely on rainfall. Overall water losses are severe, with 62% of supply lost, split between non-invoiced consumption (30%) and leakage (32%)[94]. To reduce these losses, operators are implementing technologies for leak detection, pressure management, remote monitoring, and digital network modelling[101].

Municipal data reveal severe inefficiencies (Table 3)[102,103]. On average, only 33% of water supplied is billed, equating to a 71% loss rate from physical leakages or administrative shortcomings. Machico shows the most critical inefficiency, billing only 18% of its water and losing 82%, while Câmara de Lobos and Ribeira Brava report losses exceeding 50%. High per capita consumption, ranging from 122 to 189 L/day, further strains the system. In 2013, water use was divided among agriculture (51 hm^3/year; 49% of total use, 43% efficiency), public supply (44,6 hm^3/year; 43%, 38% efficiency), and industry (7,8 hm^3/year; 8%, 55% efficiency), underscoring substantial losses across sectors[103].

Table 3 Municipal water supply performance in Madeira, including sources, billed volumes, system inefficiency, and consumption indicators, adapted from[102].

Municipality	Water supplied (hm^3/year)	From springs (hm^3/year)	Water billed (hm^3/year)	Inefficiency (%)	Avg. monthly consumption (hm^3)	Per capita consumption (L/day)
Câmara de Lobos	4,65	0,25	1,55	68%	0,13	121,9
Ribeira Brava	1,48	0,24	0,72	58%	0,06	152,8
Machico	6,62	0,16	1,21	82%	0,10	156,9
Santana	0,41	1,22	0,50	69%	0,04	189,1
Tot. /Avg.	13,9	1,87	4,58	71%	0,38	154,1

Additional systemic weaknesses include limited infrastructure redundancy and an almost complete absence of large-scale storage systems, as construction costs in Madeira's rugged terrain are prohibitive[94]. The dispersed population requires multiple small-scale treatment units, increasing operational complexity. Hydrometric monitoring is insufficient, limiting diagnostics and flow assessment in *levadas*, while flood vulnerability is intensified by irregular channel maintenance and limited site-specific hazard understanding.

Water quality degradation, while still moderate, is an increasing concern. In agricultural areas, unregulated fertiliser and pesticide use causes diffuse groundwater pollution. Some public supply systems relying on springs operate without adequate treatment, and a small portion of the population remains served by inadequate or poorly regulated systems. Inland water monitoring has detected pollution from untreated domestic and industrial wastewater[94].

The irrigation system also faces persistent challenges. Rainfall is more abundant in the north, while irrigation demand is greater in the south, creating an imbalance worsened by limited storage and long transport distances. Inefficiencies are compounded by outdated irrigation methods and undersized distribution networks. During droughts, competition for water intensifies, with urban supply generally prioritised over agriculture[94].

Madeira's steep slopes, impermeable volcanic geology, and intense rainfall, amplify the runoff, erosion, and landslide risks, threatening infrastructure integrity[101]. Climate change adds further uncertainty, increasing drought risk and demand variability, particularly during peak tourism seasons, which place additional stress on supply capacity and

resilience. Energy-intensive pumped systems elevate operational costs and reliance on mechanical infrastructure, while groundwater extraction in geologically complex areas remains costly and risks sustainability if poorly managed. Additionally, *levadas*, despite their historical value, have limited adaptability due to their fixed routing and gravity-based design.

To address these challenges, priority actions have been proposed[103]. Recommendations include promoting efficient irrigation technologies such as drip systems; expanding sanitation infrastructure with attention to topography and settlement patterns; reducing chemical fertiliser and pesticide use through training and organic practices; raising public awareness on rational water use; and planning for drought resilience by increasing storage capacity.

5.4. Natural hazards and exposure

Madeira is exposed to a range of natural hazards that significantly affect its population and critical infrastructure, including the water supply system. The island's steep terrain, intense rainfall patterns, and geomorphological characteristics contribute to frequent flash floods, landslides, and slope instability, particularly during heavy precipitation events[94]. Urban development in flood-prone areas amplifies flood impacts, while vegetation loss and soil degradation from wildfires reduce infiltration capacity and increase erosion risk in upland zones. Coastal areas, especially in the northwest, are vulnerable to marine erosion, cliff retreat, and recurrent coastal flooding during storm events coinciding with high tides or intense rainfall[94].

These hazards are further intensified by climate change[94], which is projected to alter rainfall patterns, increase the frequency of extreme hydrological events such as floods and droughts, and reduce soil moisture and water quality. Sea level rise adds additional stress to low-lying coastal settlements and protective infrastructure. In response, both the Regional Water Plan (PRAM)[94] and local scientific studies[96,103,106–108] propose a range of structural and site-specific measures to mitigate hazard impacts. Proposed solutions include slope stabilisation, flood and erosion control, resilient infrastructure planning, reducing impermeable surfaces, restoring natural hydrological buffers through vegetation cover, and planting species that enhance rainfall retention and reduce surface erosion in upland areas. The analysis in the following sections is based on data from the Risk Assessment of the Autonomous Region of Madeira IP-RAM (2023)[93].

5.4.1. Flood risk

Flash floods are Madeira's most frequent and destructive hazard, driven by intense, short-duration rainfall over steep, short river basins with minimal early warning time. These *aluviões* generate high-velocity flows carrying large debris loads, with channels descending over 1200 m in under 20 km before converging in densely populated coastal areas (Figure 29). Urbanisation, soil sealing, and reduced infiltration lead to greater runoff, increasing sediment accumulation and channel blockages that lead to overbank flooding.

Historical floods, such as the catastrophic 1803 event (up to 1000 deaths) and the February 2010 flood (47 deaths, severe damage to infrastructure and ports), demonstrate high exposure and vulnerability. The Flood Risk Management Plan[95] identifies 27 zones with significant risk, prioritising land-use regulation, river corridor rehabilitation, drainage upgrades, and protection of critical facilities including water transfer stations. IP-RAM (2023) classifies the overall flood risk as high, with medium–high probability (5–20-year return periods) and high severity. Climate change is projected to increase extreme rainfall events, while wildfires reduce vegetation cover, amplifying erosion and debris flow hazards.

Flood risk from dam failure is recognized as a high-consequence scenario, despite its low probability (Figure 29). Reservoirs and dams critical due to their stored water volumes and downstream exposure include:

- *Lagoa das Águas Mansas* (Camacha): Capacity of 214 500 m³; supplies the public water network and irrigation systems in Santa Cruz.
- *Lagoa do Bardo* (Santa, Porto Moniz): Earthen dam with a maximum depth of 5,5 m and an approximate capacity of 35 000 m³; supports irrigation associated with the *Levada dos Brasileiros*.
- *Barragem da Portela* (Santo António da Serra, Machico): Capacity of 87 800 m³; enhances irrigation in Machico and supports the Funchal–Machico irrigation system.
- *Lagoa do Palheiro Ferreiro* (São Gonçalo): Approximate capacity of 120 000 m³; supplies irrigation water, garden maintenance, and a golf course.
- *Lagoa do Santo da Serra*: Capacity of 640 000 m³; supports an irrigation zone extending from Santa Cruz to Machico.
- *Barragem do Paúl da Serra*: Capacity of 1 000 000 m³; increases regional water storage and hydroelectric production capacity.

Hydraulic simulations for Portela indicate that overtopping could send a flood wave down Ribeira de Machico's 11 km channel in 18 minutes, primarily affecting roads and residential

areas. The probability of failure is considered medium–low, and the severity low, leading to a low overall risk classification.

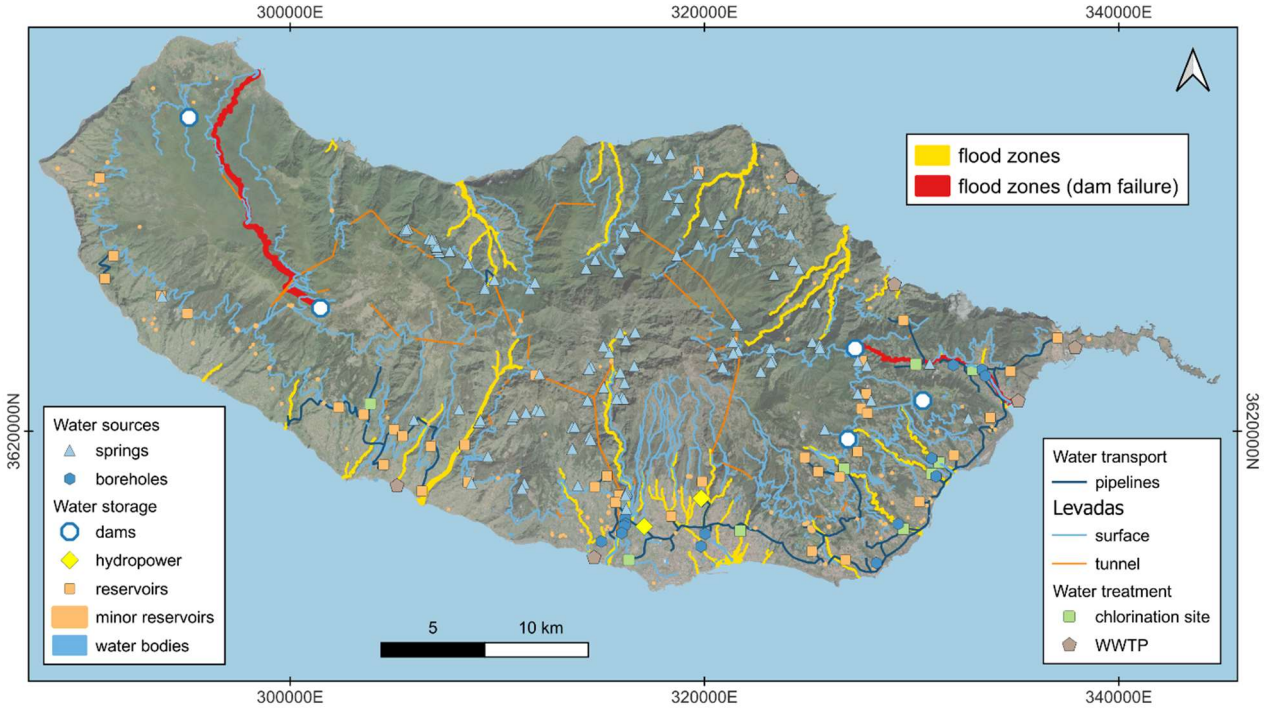

Figure 29 Flood-prone areas on Madeira: flood zones (yellow) and zones at risk from dam failure scenarios (red). Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Recent hydrological and hydraulic studies have further contributed to understanding and mitigating Madeira's flood vulnerability[42,45–47], revealing drainage undercapacity in urban watersheds of Ribeira Brava, São João, Tabua, Santa Luzia, and João Gomes. Factors include sedimentation, invasive vegetation, channel slope limitations, and outdated infrastructure unable to convey 100-year peak flows. Recommended measures are channel widening or deepening, roughness reduction, and replacing rigid surfaces with materials that reduce turbulence and enhance flow capacity.

Collectively, these findings support a comprehensive flood mitigation strategy combining localized engineering interventions with long-term planning. Priority measures include simplified detention basins, systematic sediment and vegetation management, channel roughness adjustments, and continuous integration of hydrological risk into urban development policy. Such a strategy is essential to enhance the resilience of Madeira's steep, densely settled catchments and to protect critical water infrastructure, including intake structures, transfer stations, and treatment facilities located in flood-prone valleys.

Flood events can damage conveyance pipelines through erosion, scour, or debris impact; cause sediment inflow and contamination at surface water intakes; obstruct access roads to reservoirs, pumping stations, and treatment plants; disrupt site-specific electricity supply systems; and overwhelm treatment processes with sudden increases in turbidity

and pollutant loads. Ensuring infrastructure redundancy, protective design measures (e.g. elevation, barriers), operational continuity planning, and reliable access routes is therefore a fundamental component of effective flood risk management.

5.4.2. Drought risk

Droughts are prolonged periods of insufficient precipitation, posing significant risks to Madeira's water supply systems. The eastern lowlands (Figure 30), particularly Santana, Santa Cruz, Machico, and Funchal, are most affected, with records indicating severe drought recurrence every 3–5 years. Since 2000, annual precipitation has declined by up to 50% in some areas, with highland stations such as *Chão do Areeiro* and *Bica da Cana* recording reductions of 30% and 23%, respectively. This pattern, where heatwaves tend to intensify in high-altitude areas, is also observed in the Canary Islands[109].

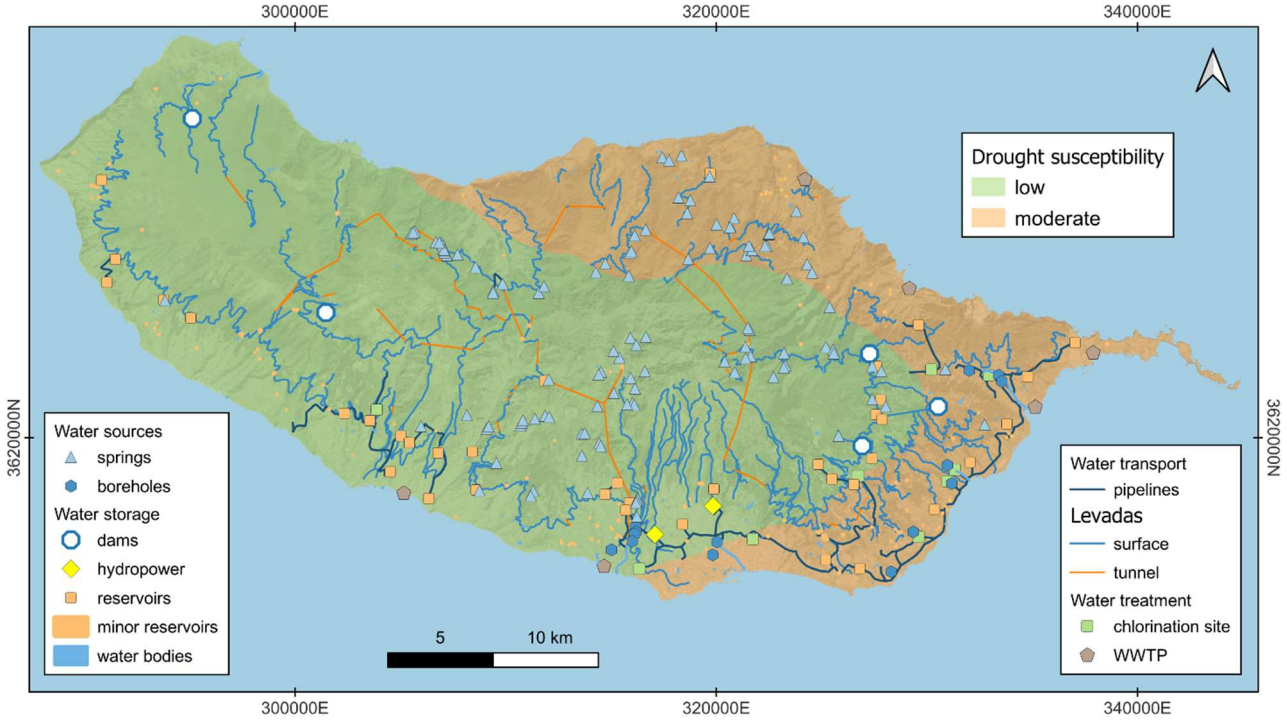

Figure 30 Drought susceptibility on Madeira. Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Drought impacts critical water infrastructure by reducing reservoir storage volumes and groundwater recharge, leading to supply restrictions, lower intake availability, and increased competition between urban, agricultural, and ecological demands. Extended droughts can also limit hydroelectric production and impact firefighting capacity dependent on stored water. Poor land and irrigation management worsen these risks by decreasing soil moisture retention and increasing water losses.

Risk assessments classify drought as a moderate hazard with medium–high probability and low severity, though future vulnerability is expected to intensify in southern and eastern Madeira. Adaptive measures include improving intake system efficiency, rehabilitating and

restoring the water distribution networks, increasing water storage capacity, and reducing agricultural demand through efficient, automated irrigation technologies.

Although droughts cannot be prevented, their impacts can be mitigated through strategic water transfers and enhanced storage systems. Moreover, poor land management and unsustainable agricultural practices have degraded soil and water resources, increasing population vulnerability to drought.

5.4.3. Slope movements and landslide risk

Landslides, rockfalls, and debris flows are frequent hazards in Madeira, driven by its steep topography, intense rainfall, and geological formations prone to weathering and slope instability. These events involve the downslope movement of rock, soil, and vegetation, triggered by prolonged or intense rainfall, seismic activity, or human activities that alter slope stability.

High-susceptibility zones are concentrated in the central mountainous areas and along unstable coastal cliffs, while moderate susceptibility applies for most terrain except lower urban zones (Figure 31). Risk assessments classify slope movements as a high-risk hazard with high probability and moderate severity.

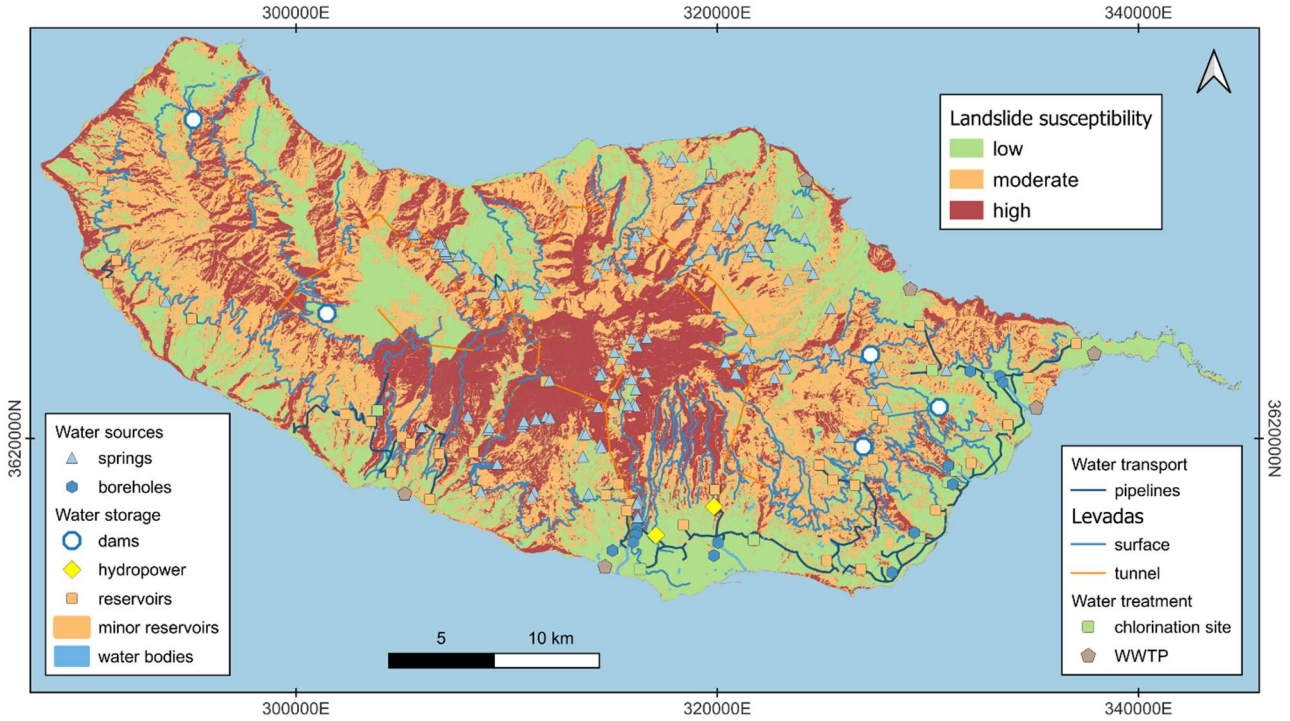

Figure 31 Landslide susceptibility on Madeira. Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Slope failures impact critical water infrastructure by damaging intake structures located on unstable slopes, rupturing conveyance pipelines crossing landslide-prone areas, and undermining reservoir embankments through ground displacement or lateral loading. Rockfalls and debris flows can obstruct access roads to treatment plants, pumping

stations, and reservoirs, delaying repairs and restricting operational continuity. Landslides may expose or displace buried pipelines, increasing rupture risk, and mobilise sediments and contaminants that degrade surface water quality at intakes. In severe cases, slope movements can obstruct hydroelectric channels or damage penstocks, compromising electricity generation and water transfer systems.

Future landslide risk is expected to increase due to climate change, with higher rainfall intensity and greater wildfire incidence reducing vegetation cover, decreasing slope cohesion, and raising exposure of water supply infrastructure to damage and operational disruption.

5.4.4. Seismic and volcanic risk

Seismic risk

Madeira is exposed to low-to-moderate seismic hazard due to its proximity to the Azores–Gibraltar Fault Zone (Figure 32). Although not located on a plate boundary, earthquakes from this region can affect the island. Historical records show four major earthquakes (magnitude 8.1–8.7) within 1000 km between 63 BCE and 1975. More recently, a magnitude 5.2 event in March 2020 and a magnitude 5.0 in February 2022 reached intensity V on the Mercalli scale and were widely felt but caused no injuries or structural damage[93].

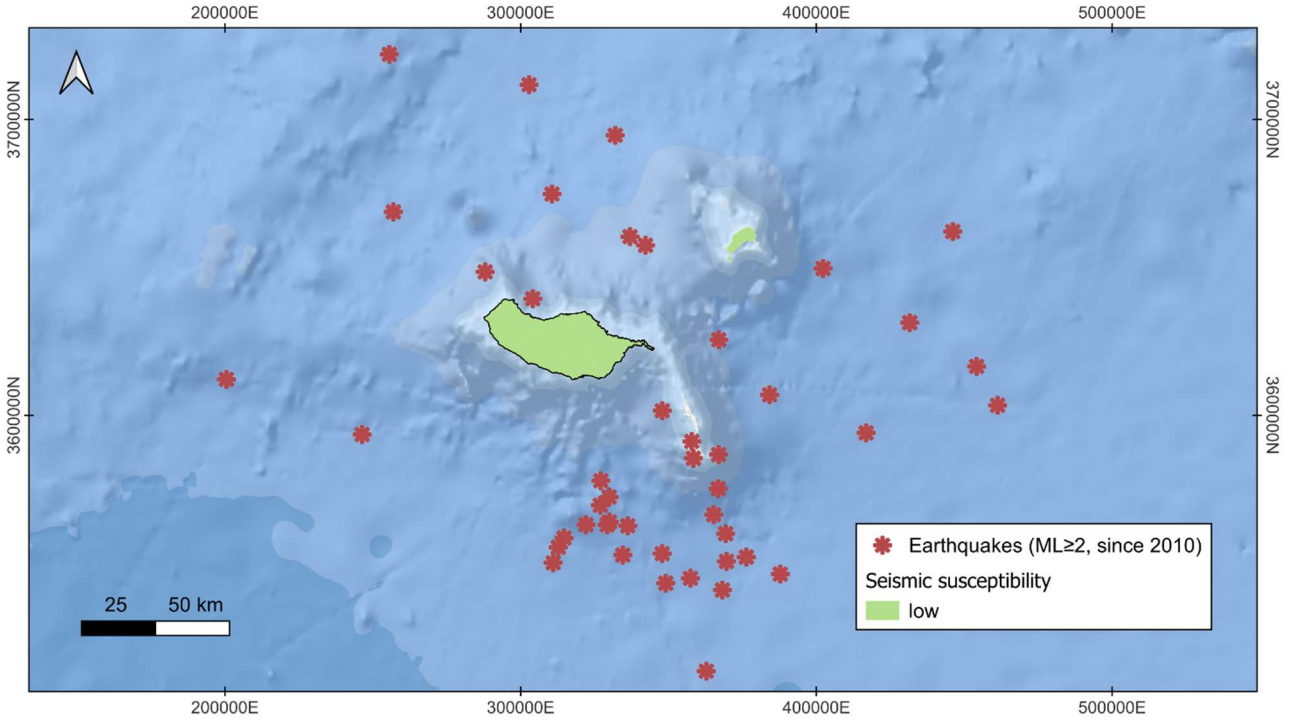

Figure 32 Seismic susceptibility of Madeira and earthquakes with M≥2.0 (ML) recorded since 2010. Data: ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Seismic events can impact critical water infrastructure by damaging storage reservoirs, treatment plants, and pumping stations through ground shaking and differential

settlement, leading to structural cracking or operational failure. Conveyance pipelines are vulnerable to rupture at joints, bends, and slope crossings due to ground displacement or shaking-induced stress, causing supply interruptions and leakage losses. Earthquake-induced landslides or rockfalls may further damage exposed infrastructure or obstruct access roads essential for emergency repairs and operational continuity.

Scenario modelling indicates that a high-magnitude offshore earthquake, similar to the 1755 Lisbon Earthquake, could cause structural damage, injuries, and cascading effects such as landslides, rockfalls, and fires triggered by gas leaks. This scenario has a low probability (return period >200 years) but high severity, resulting in an overall moderate seismic risk.

Volcanic risk

Madeira has no historical records of volcanic eruptions, and risk assessments rely on indirect indicators such as diffuse CO_2 emissions and elevated subsurface temperatures observed during tunnel and gallery excavations[110]. Minor gas emissions have occurred in the Ribeira Brava–Ribeira de São Vicente and Machico–Porto da Cruz tunnels, posing no danger to workers or users. However, in March 2000, excavation of the *Fajã da Ama* water gallery encountered a fault zone emitting high concentrations of CO_2 approximately 1700 m into the tunnel, causing worker loss of consciousness and highlighting potential localized geochemical hazards.

For critical water infrastructure, volcanic risk primarily involves exposure to diffuse gas emissions during construction or maintenance of tunnels, galleries, and groundwater intakes, posing health hazards to personnel and requiring ventilation or monitoring systems. Elevated groundwater temperatures in hydraulic tunnels such as *Levada dos Tornos*, *Pico Grande*, and *Encumeada* may affect material performance, structural integrity, and operational safety if temperature variations are significant.

Geomorphological and radiometric evidence indicates the most recent eruptions occurred between 6000 and 7000 years ago. However, due to the long recurrence intervals and lack of historic eruptions, a realistic eruption scenario cannot currently be defined. Accordingly, volcanic risk in Madeira is classified as low in both probability and severity.

5.4.5. Wildfires

Wildfires in Madeira are uncontrolled fires affecting forests, shrublands, and agricultural lands, primarily caused by human negligence or intentional ignitions under hot, dry, and windy conditions. Risk is highest along the southern slopes (Figure 33), particularly in Santa Cruz, Funchal, Câmara de Lobos, Ribeira Brava, Ponta do Sol, and Calheta, with frequent

large fires recorded in 2003, 2006, 2010, 2012, and 2016; resulting in over 3000 hectares burned[93].

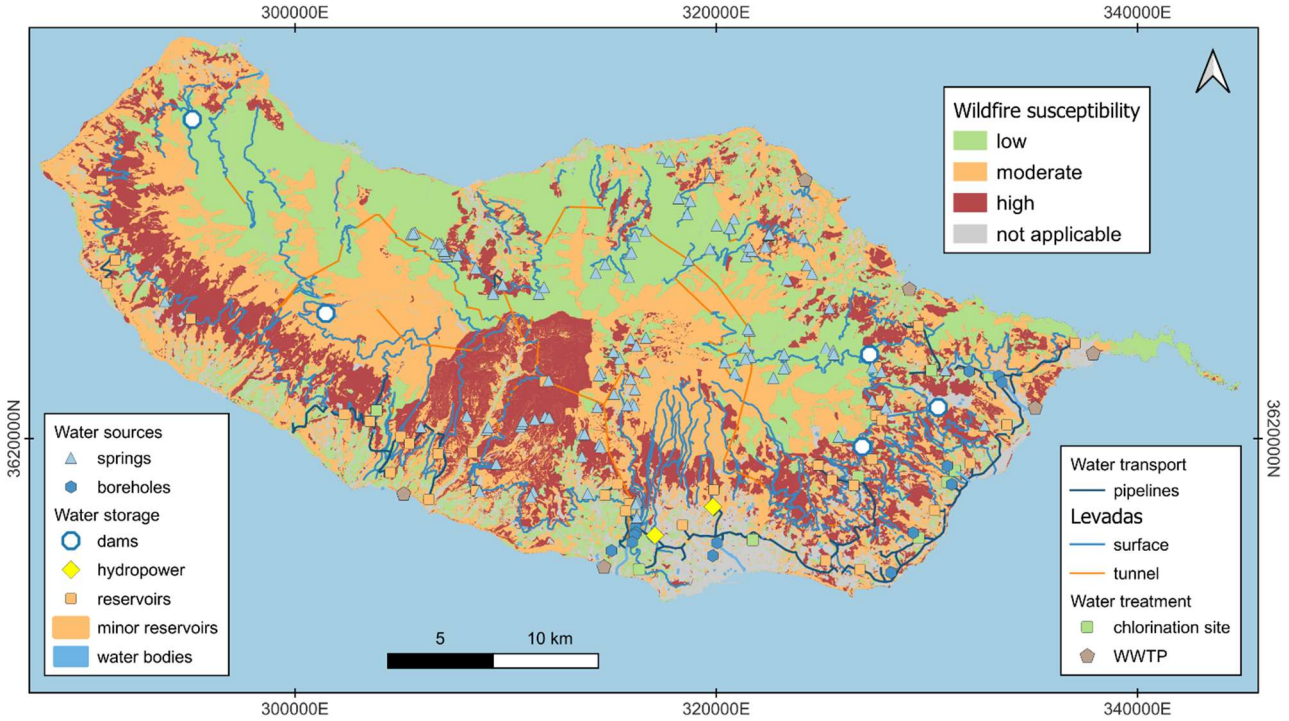

Figure 33 Wildfire susceptibility on Madeira. Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Wildfires impact critical water infrastructure by damaging intake catchments through vegetation loss, increasing erosion, sediment inflow, and turbidity in surface water sources. Burned areas produce ash and organic debris that degrade water quality and increase treatment requirements. Fires can directly threaten above-ground pipelines, pumping stations, or storage tanks located in exposed upland areas, particularly at the urban–forest interface. Post-fire rainfall events amplify landslide and debris flow risks, further endangering infrastructure integrity and access roads needed for operation and maintenance.

Scenario modelling indicates high wildfire probability (annual occurrence) and moderate severity, with rapid spread across steep slopes threatening residential areas, transport routes, and ecosystem services.

Climate projections[93] indicate that rising temperatures and declining precipitation will increase fire susceptibility, particularly at lower elevations where agriculture and urban areas are concentrated. While the Laurisilva forest is expected to remain relatively unaffected in the near term, altitudinal shifts in vegetation cover are anticipated over longer timescales. Agricultural abandonment is a key risk factor, as unmanaged land accumulates dry biomass that elevates fire intensity and spread. Consequently, areas experiencing rural decline are considered especially vulnerable to future wildfire events,

elevating exposure risks for water supply systems reliant on upland catchments and infrastructure corridors traversing fire-prone terrain.

5.4.6. Coastal hazards

Madeira's coastal zones, particularly densely urbanised seafronts, are highly exposed to overtopping and coastal flooding during extreme maritime events (Figure 34). These occur when storm surges and powerful waves breach natural or engineered barriers, inundating low-lying areas including ports, promenades, beaches, and resorts.

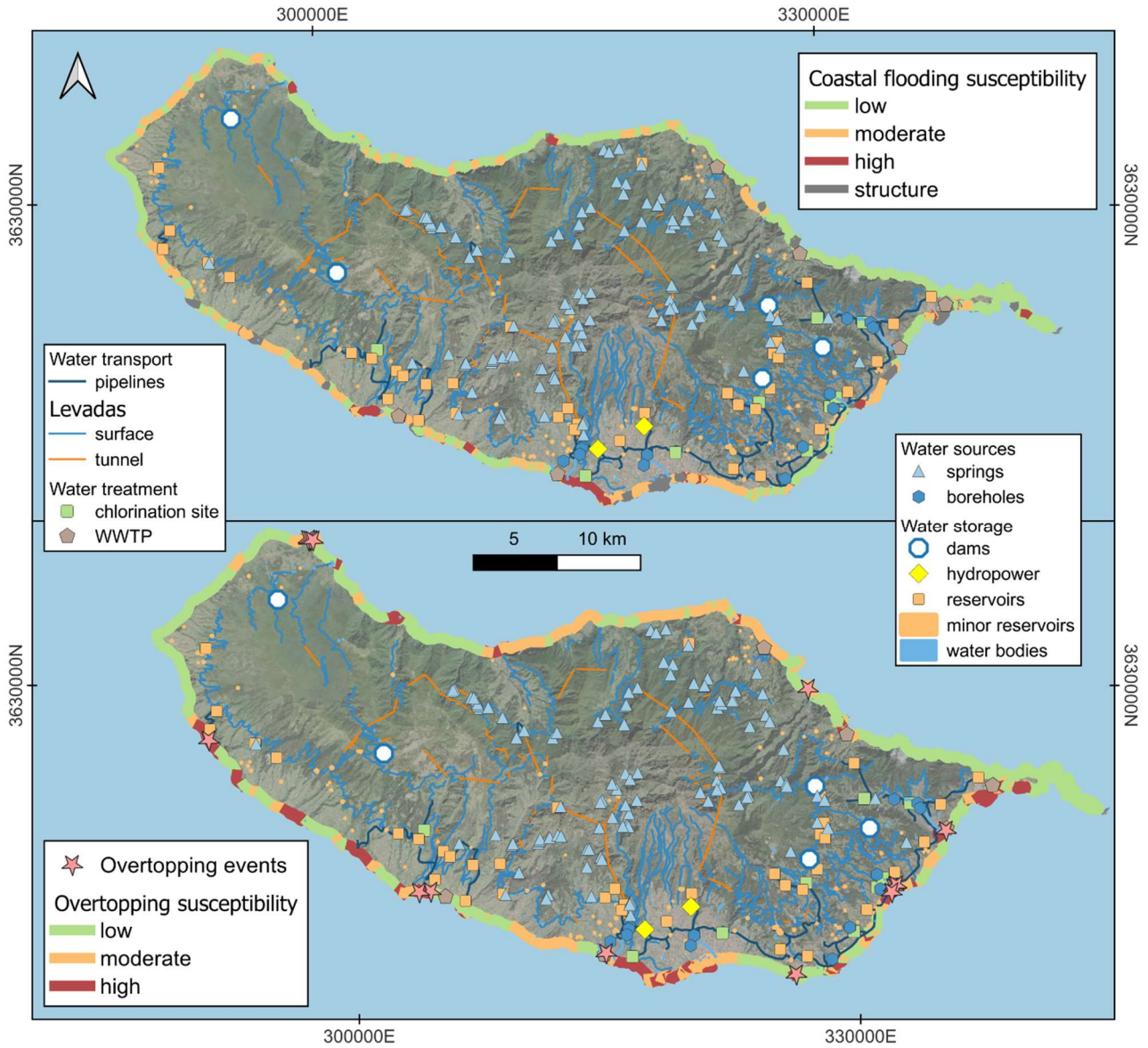

Figure 34 Madeira's coastal flooding susceptibility (top) and coastal overtopping susceptibility (bottom). Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

Sea-level rise projections[93] range from 35–50 cm under intermediate scenarios to up to 75 cm by 2100 under extreme emissions trajectories, reducing beach widths and increasing overtopping frequency. Recent events demonstrate this vulnerability: in 2013, overtopping damaged ports in Santa Cruz, Machico, and Funchal, causing one fatality; in 2014, a tourist

was swept away in Porto Moniz; and in 2018, a storm destroyed part of a beachside restaurant in Garajau.

Coastal hazards impact critical water infrastructure primarily by threatening pipelines, pumping stations, and WSS facilities located near shorelines, as well as port facilities essential for water supply logistics and emergency operations. Flooding and wave action can damage structural components, corrode materials through saltwater exposure, inundate electrical and mechanical systems necessary for operation, and obstruct access roads, delaying maintenance and emergency response. Ports are particularly at risk during overtopping events, compromising their role in importing equipment and materials needed for infrastructure repair and operational continuity.

Scenario modelling indicates high probability (annual occurrence) and moderate severity, resulting in an overall high coastal hazard risk classification. Climate change-driven sea-level rise and intensified storm patterns are projected to increase the frequency and severity of overtopping and flooding, further exposing coastal water infrastructure to damage and operational disruption.

Tsunami Risk

Tsunamis are rare but potentially high-impact hazards in Madeira, caused by sudden ocean-floor disturbances such as underwater earthquakes or landslides. The north coast is most exposed due to its orientation toward major seismic sources, including the Azores–Gibraltar Fault Zone and the Gorringe Bank. Historical records note the 1755 Lisbon Earthquake tsunami affecting Madeira, while local tsunami-like events include the 1930 Cabo Girão landslide, which generated waves that caused 19 fatalities in Câmara de Lobos[93].

Hazard mapping identifies high-susceptibility zones in coastal valleys, low-gradient areas near river mouths, urban seafronts, ports, and the airport (Figure 35). Scenario modelling indicates that a tsunami generated by a major offshore earthquake could reach Madeira's north coast within 40 minutes, breaching coastal defences, flooding river mouths, and damaging infrastructure, roads, and buildings. Although the island's steep coastal topography reduces inundation extent, potential fatalities and injuries may occur due to inundation, debris impact, and limited evacuation time.

Tsunamis impact critical water infrastructure by inundating coastal facilities and networks located near shorelines, damaging pipelines, and disrupting port operations vital for logistics and emergency response. Wave action can undermine structural foundations, corrode exposed materials, and deposit debris that blocks access routes, delaying repairs and operational continuity.

Risk assessments classify tsunamis as low probability (return period >200 years) but moderate severity (partially mitigated by steep coastal topography), resulting in an overall moderate risk for Madeira's coastal infrastructure and communities.

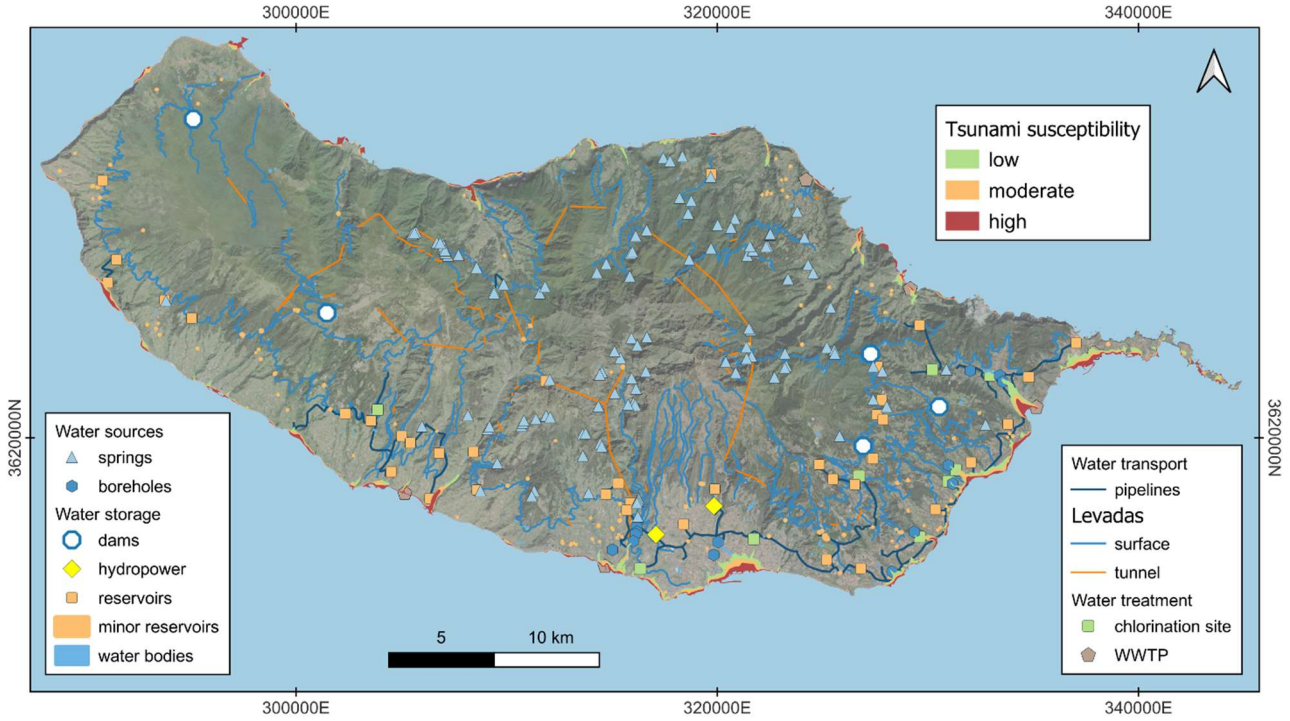

Figure 35 Tsunami susceptibility on Madeira. Data: IP-RAM SR de PC[92], ARRAM[93]. CRS: EPSG:5016 (PTRA08 / UTM 28N).

5.4.7. Climate change impacts

Climate change poses a significant threat to Madeira due to its small size, steep terrain, and limited natural resources, increasing vulnerability across essential systems such as water supply, energy, agriculture, transport, and public health. Many natural hazards in Madeira, including droughts, flash floods, landslides, and coastal erosion, are closely linked to climatic conditions, with observed increases in frequency and intensity likely reflecting early climate change impacts[93].

Future regional projections indicate a marked rise in extreme weather events. Downscaled climate simulations under the CLIMAAT II project[93] estimate a mean temperature increase of 1,3 °C to 3 °C and a reduction in annual precipitation by approximately 30% by 2100. These trends will intensify hydrological extremes, increasing drought severity and flash flood frequency, particularly in the southern and eastern regions. Reduced precipitation combined with higher temperatures will decrease surface runoff and groundwater recharge, directly affecting reservoir inflows, stream intake yields, and overall freshwater availability for urban supply, irrigation, and hydroelectric production.

Sea-level rise, projected to exceed 0,5 m and potentially reach 1 m above 1990 levels by 2100, will increase coastal flooding, overtopping, and erosion, particularly in low-lying areas

such as Ribeira Brava and Machico. Saltwater intrusion into coastal aquifers is expected to compromise freshwater quality and reduce available yields for potable water supply. Coastal water infrastructure, including pipelines, pumping stations, and wastewater networks located near shorelines, will face heightened risk of inundation, foundation erosion, and material corrosion due to prolonged saltwater exposure and more frequent storm surges.

Climate change could also indirectly affect critical water infrastructure by increasing wildfire frequency and severity, reducing catchment vegetation cover, accelerating soil erosion, and elevating sediment loads in surface water sources. This would raise treatment demands, clog intake structures, and reduce reservoir storage capacity due to sedimentation. Increased landslide risk linked to more intense rainfall events may damage pipelines, access roads, and embankments, disrupting distribution networks and isolating facilities.

Overall, climate change is projected to amplify environmental risks across Madeira, imposing severe challenges to water security, infrastructure resilience, and operational continuity. Integrated adaptation strategies, including improved water resource management, infrastructure design for climate robustness, catchment protection, and coastal zone planning, will be essential to safeguard critical water systems against escalating climatic stressors.

5.4.8. Madeira risk matrix

The table 4 summarises the classification of natural hazards in Madeira based on their probability (rows) and severity (columns), as presented in the Risk Assessment of the Autonomous Region of Madeira, IP-RAM (2023)[93]. It provides an integrated overview of the relative risk levels for each hazard, combining historical records with scenario-based assessments.

Flash floods are classified as an extreme risk due to their critical severity, while landslides, forest fires, coastal flooding and overtopping, and windstorms are high-risk hazards requiring prioritised mitigation measures. Droughts, tsunamis, and earthquakes are categorised as moderate risk, whereas coastal erosion, dam-break floods, and volcanic activity are considered low risk.

This classification supports strategic decision-making by identifying hazards that pose the greatest threat to Madeira's population and critical infrastructure, including water supply systems, and informs targeted vulnerability reduction and adaptation planning within the GENESIS project assessment framework.

Table 4 Risk classification matrix for natural hazards in Madeira, showing probability, severity, and corresponding risk levels (green: low, yellow: moderate, orange: high, red: extreme) adapted from IP-RAM (2023)[93].

Severity → Probability ↓	Residual	Reduced	Moderate		High	Critical
High	–	–	Landslides Forest fires Coastal flooding and overtopping		–	–
Medium–High	–	Droughts	–		Windstorms	Flash floods
Medium	Coastal erosion	–	–		–	–
Medium–Low	–	Dam-break floods	–		–	–
Low	Volcanic activity	–	Tsunami		Earthquakes	–

5.5. Summary of vulnerabilities and key conclusions

The assessment of Madeira Island confirms the presence of a territorially adapted but structurally vulnerable water supply system, shaped by steep volcanic terrain, uneven water availability, and historical adaptation practices such as the *levada* network. With a population of approximately 250 000 residents concentrated in water-stressed coastal zones, the island's infrastructure must support domestic supply, irrigation, and hydroelectric generation across a highly complex topographic and hydrological setting.

Water is sourced from a mix of surface and groundwater systems, including springs, galleries, levadas, and boreholes. While coverage and service levels are high, the system suffers from substantial inefficiencies, with physical and administrative losses exceeding 60%, and several municipalities exhibiting critical billing deficits. Infrastructure is dispersed and often difficult to access, with limited storage capacity, low redundancy, and aging distribution networks contributing to operational fragility. Despite institutional efforts to modernize systems through digital monitoring and pressure control, vulnerabilities persist across sectors and elevation zones.

Environmental exposure is significant due to the island's susceptibility to multiple natural hazards. Flash floods represent the most severe threat, followed by landslides, wildfires, droughts, and coastal flooding, each posing distinct risks to water intake, transport, treatment, and distribution components. Infrastructure located in flood-prone valleys, on unstable slopes, or near the coastline is particularly at risk, with climate change projected to intensify all major hazard drivers. Systemic weaknesses, such as inadequate monitoring, spatial fragmentation, and rural land abandonment, further elevate risk profiles.

Available hazard maps, infrastructure and population data, and technical literature have been cross-referenced to identify critical exposure and vulnerability patterns affecting Madeira's water systems. This assessment highlights the need for strengthened coordination across water management, land use, and hazard mitigation efforts, particularly given Madeira's scale, rugged terrain, and evolving climatic and demographic pressures. The island's experience demonstrates both the potential and limitations of long-standing adaptive infrastructure under intensifying environmental stressors.

6- FAIAL ISLAND

6.1. Introduction and environmental setting

Faial, part of the Central Group of the Azores archipelago in the North Atlantic Ocean, belonging to Portugal, covers an area of 173 km² and features the Caldeira stratovolcano, which reaches 1043 m in elevation (Figures 36 and 37). In 2021, Faial had a resident population of 14 331, with nearly half living in the main municipality of Horta, which has around 5600 inhabitants[111]. This results in a low population density across the island. The regional climate is temperate oceanic, with mild summers and consistently high humidity[112]. The economy is primarily based on livestock farming (milk, dairy and beef production) along with agriculture (flowers, fruits and vegetables, in a rising trend towards organic permaculture practices), fishing, and an expanding tourism sector[113].

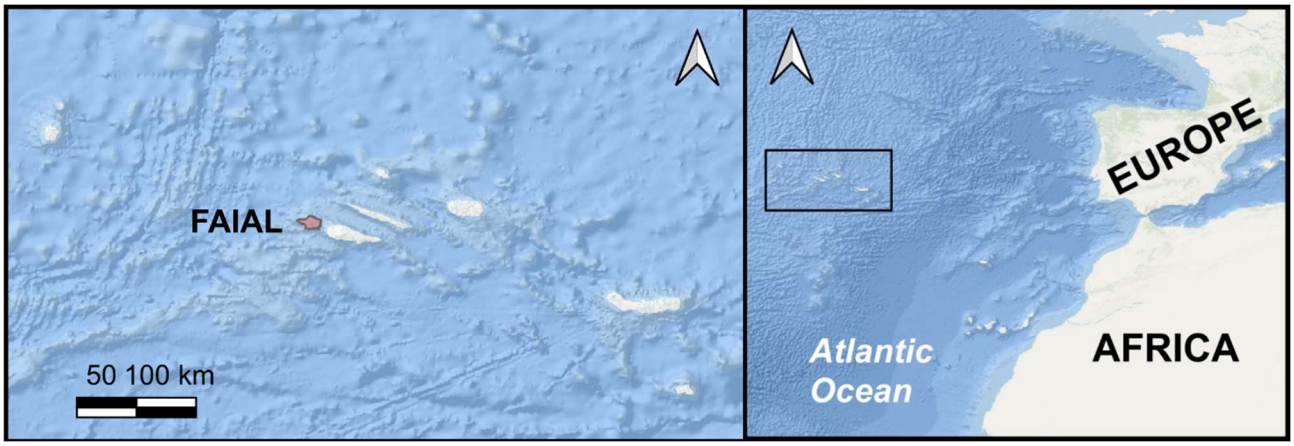

Figure 36 Faial's location within the Azores archipelago and wider regional context.

Like the other Azorean islands, Faial is of volcanic origin and lies on the diffuse tectonic plate boundary between the North American, Eurasian, and African (Nubian) plates. Its terrain consists of basaltic to trachytic (*sensu lato*) volcanic deposits, including lava flows, pyroclastic fall and flow (pyroclastic density currents) deposits. Fractured and permeable porous volcanic layers (clincker levels of lava flows, lava tubes, coarse pyroclastic fall deposits) lead to the formation of aquifers[31].

Under its temperate oceanic climate, Faial receives an average of 1633 mm of precipitation annually, with actual evapotranspiration totalling 561 mm. Surface water discharge is estimated at 1,12 × 10^8 m^3/year, and renewable groundwater resources total 74,1 hm^3/year[114]. Groundwater is the primary public water source, as is typical in the Azores. As on other Azores islands, Faial exhibits two main aquifer systems: the basal aquifer containing freshwater lenses floating above saltwater, and altitude aquifers of perched water bodies.

Following the new EU orientation, only two water bodies are defined: *Capelo* and *Central Volcano*. Recharge is driven by orographic rainfall, with higher altitude areas exhibiting the highest recharge potential. The coastal basal aquifer is productive but vulnerable to saltwater intrusion, which is worsened by overexploitation. Perched aquifers at higher elevations are more limited, that could be semi-confined or unconfined, and are often associated with seasonal water springs- Perched water bodies are most likely hydraulically connected to the underlying aquifers[115].

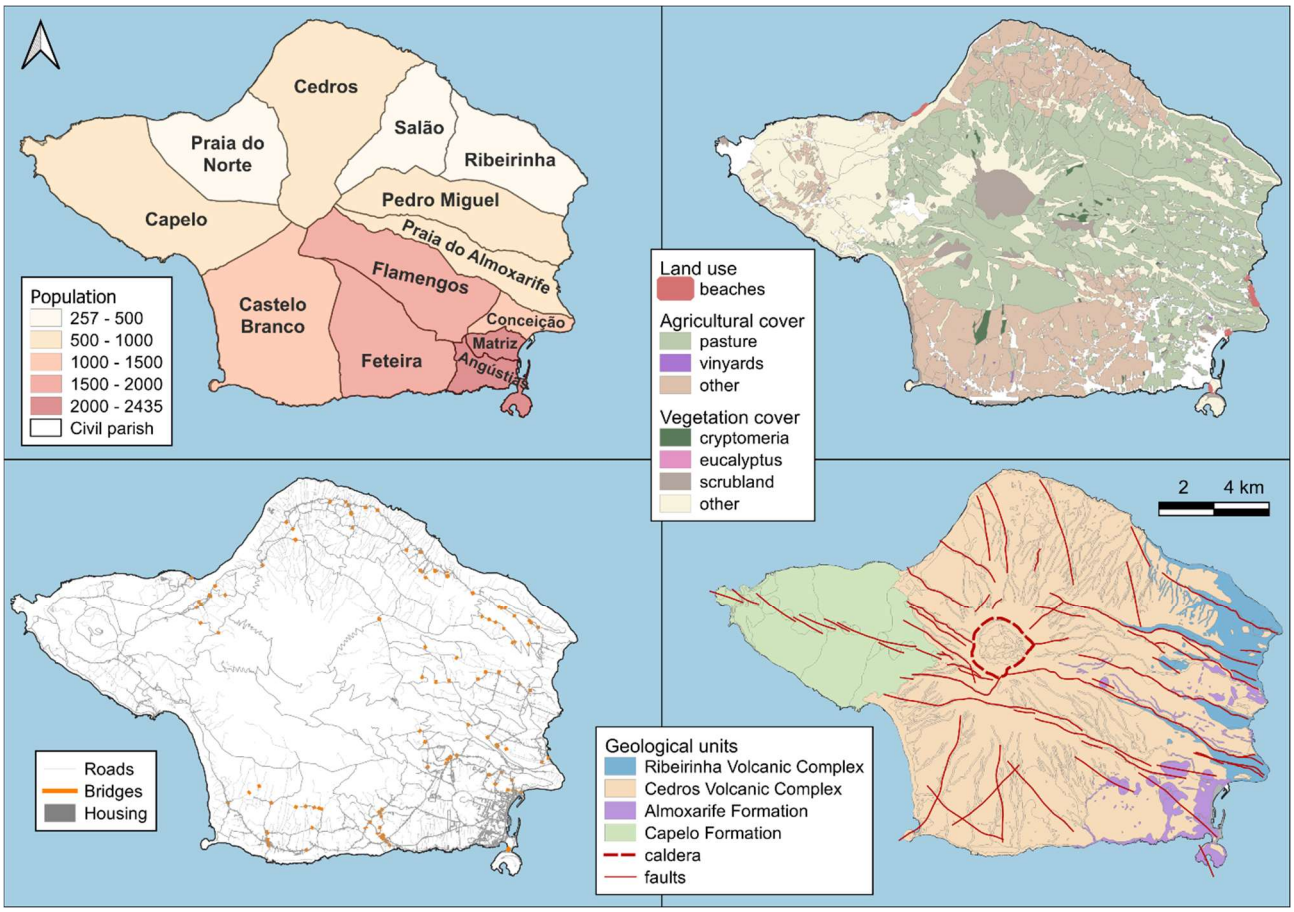

Figure 37 Faial Island: population, land use, infrastructure, and geology maps. Data sources: Secretaria Regional do Ambiente e Ação Climática (SRAAC), Governo Regional dos Açores; geology adapted from[116],[117] after[118]. Tectonic data from [117], [119], and [120]. CRS: EPSG:5015 (PTRA08 / UTM 26N).

6.2. Water supply system and infrastructure

Faial's water supply system includes springs, drilled wells, surface storage, and distribution infrastructure (Figure 38). The island is served by 57 springs and 14 boreholes, with 55 abstraction points supplying approximately 2,50 × 10^6 m^3/year[114]. Springs are predominant in high-elevation areas associated with volcanic deposits from the recent units of Caldeira Volcano, while the basal aquifer is accessed by boreholes and old tidal wells low-lying in coastal zones. The Caldeira Volcano (or *Central Volcano*) is regarded as a single aquifer, although highly compartmentalised due to its volcanic structure, including faults, dykes and the limited lateral extent of the deposits. This aquifer has very low hydraulic gradient

and high transmissivity (>1,16 × 10^{-2} m^2/s), providing reliable yields but increasing their vulnerability to rapid contamination and salinization due to overexploitation[114].

Water is distributed through seven independent systems, each serving approximately 2142 people. Urban use accounts for 85% of total consumption, followed by industry (7%) and agriculture (6%). However, only 40% of abstracted water reaches end users, with the remainder lost to leakage and network inefficiencies[114]. The *Furo das Cancelas* well is a critical source, operating at 5 m^3/h for over 50 years and supplying around 3000 residents, Horta Airport, a dairy processor, and a tourist accomodations[121].

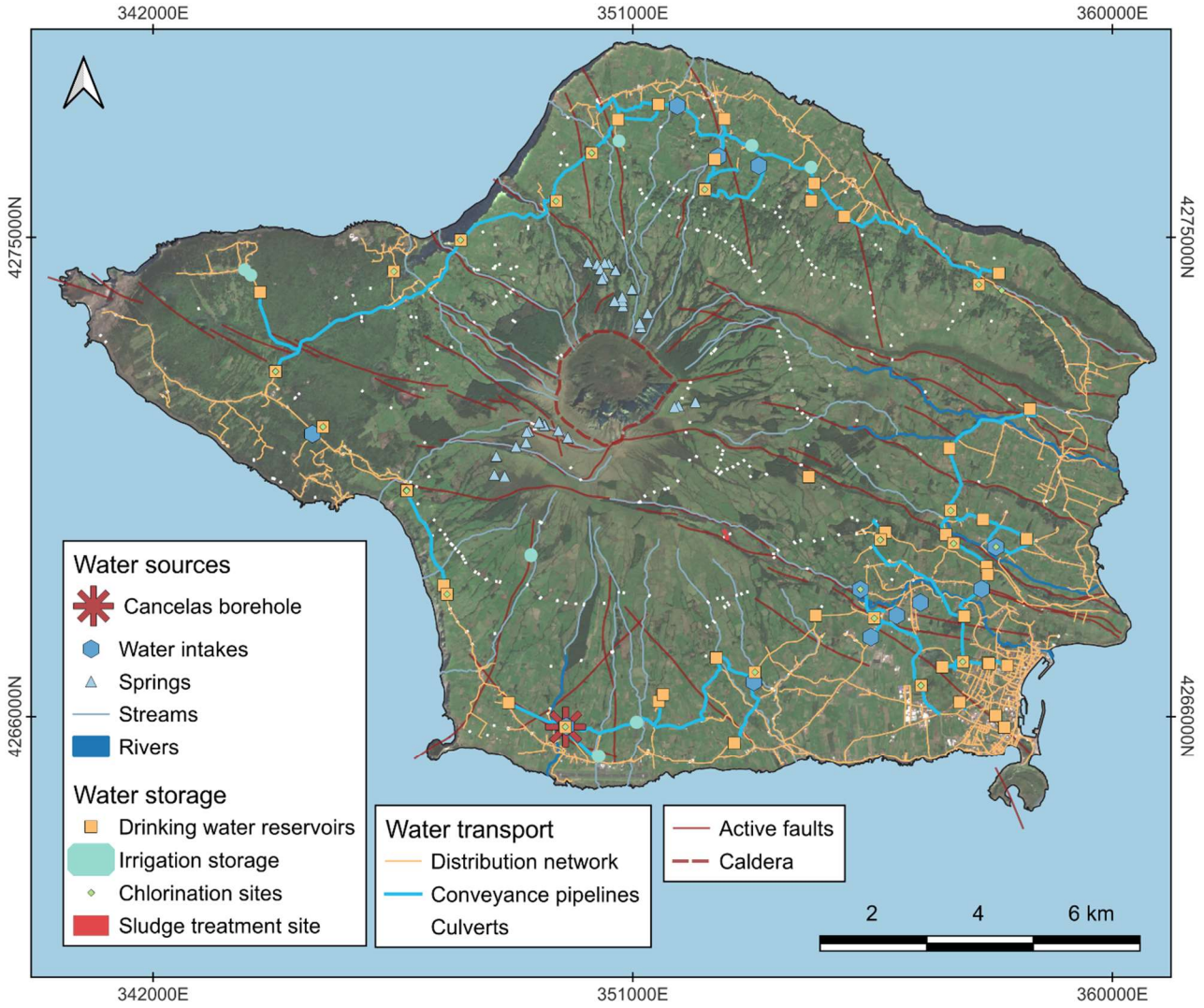

Figure 38 Faial water supply system and infrastructure. Data sources: Secretaria Regional do Ambiente e Ação Climática (SRAAC), Governo Regional dos Açores; Câmara Municipal da Horta;. CRS: EPSG:5015 (PTRA08 / UTM 26N).

Surface water is stored in small artificial ponds upstream, presently used for agricultural purposes, but would also support a planned Aquifer Storage and Recovery (ASR) system[121]. Treatment is limited to basic chlorination. Since 2006, a monitoring programme has sampled 10 wells and springs twice per year for water quality, along with two streams. Wastewater infrastructure remains inadequate: Faial generates over 5,14 × 10^5 m^3/year of

urban wastewater, yet only 10% of residents are connected to public drainage networks, with overall coverage reaching just 15% when including septic tanks[114]. This situation increases contamination risk.

6.3. Vulnerabilities and system weaknesses

Faial is exposed to seismic, volcanic, landslide, and coastal overtopping hazards. High rainfall combined with steep terrain increases the risk of flash floods and erosion. Coastal aquifers are susceptible to seawater intrusion, particularly in areas with high transmissivity and thin freshwater lenses. Although perched aquifers are less prone to salinization, they remain vulnerable to overexploitation and inadequate recharge protection[31,115].

A spatial proximity analysis in QGIS 3.40.11 (EPSG:5015) quantified exposure of Faial's water infrastructure to mapped active faults (Figure 38). Two components were evaluated: discrete facilities (boreholes, chlorination sites, reservoirs, sludge treatment ponds) and conveyance pipelines. Buffer distances of 10 m for conveyance pipelines and 100 m for discrete facilities were applied to represent the typical positional uncertainty of fault traces and to delineate near-fault influence zones consistent with the spatial footprint and vulnerability of each infrastructure type. Within a 100 m planar buffer of faults, 17/117 sites (15%) fall inside the threshold (mainly in Flamengos area, Figure 37), including six drinking water reservoirs, two chlorination sites, two boreholes, two artificial sludge treatment ponds, and five irrigation storage reservoirs. For conveyance pipelines, faults buffered by 10 m intersect 34/689 segments (5%), totalling 1,5 km of 69,9 km (2%) of network length. Localized crossings delineate potential points of functional disruption under fault movement or seismic loading.

Hazard data for Faial were obtained from The Flood Risk Management Plan (PGRIA 2022–2027)[122], coordinated by the *Secretaria Regional do Ambiente e Ação Climática*. This plan evaluates the effectiveness of flood-risk management measures implemented and revises risk classifications for the Azores in light of recent hydrometeorological events and projected climate impacts. The PGRIA reclassified and prioritized flood risks across the archipelago based on historical records of damaging floods between 2012 and 2018, identifying eleven river basins with elevated risk distributed across the islands of Flores, Terceira, Pico, São Jorge, and São Miguel. Faial is not included among the basins or coastal zones classified as having elevated flood risk, and consequently no fluvial flooding hazard maps are available for this island. Instead, the hazard coverage provided for Faial comprises coastal hazard zones and landslide susceptibility, which reflect the main geomorphological and climatic pressures relevant to the island. These datasets were used to evaluate the

spatial exposure of the water-supply infrastructure to slope instability and coastal hazards.

The landslide susceptibility map (Figure 39) shows that most of Faial falls within the lowest hazard category, with moderate to high susceptibility confined to steep slopes and erosional landforms. Areas classified as high landslide susceptibility are concentrated along coastal cliffs and ravines, as well as on the caldera rim and adjacent slopes. Comparison with the distribution of conveyance pipelines, reservoirs, and other supply assets indicates that no major infrastructure lies within high-susceptibility zones. Only limited pipeline segments intersect moderate-susceptibility terrain, suggesting that exposure of the water supply system to landslide processes is minor at the island scale.

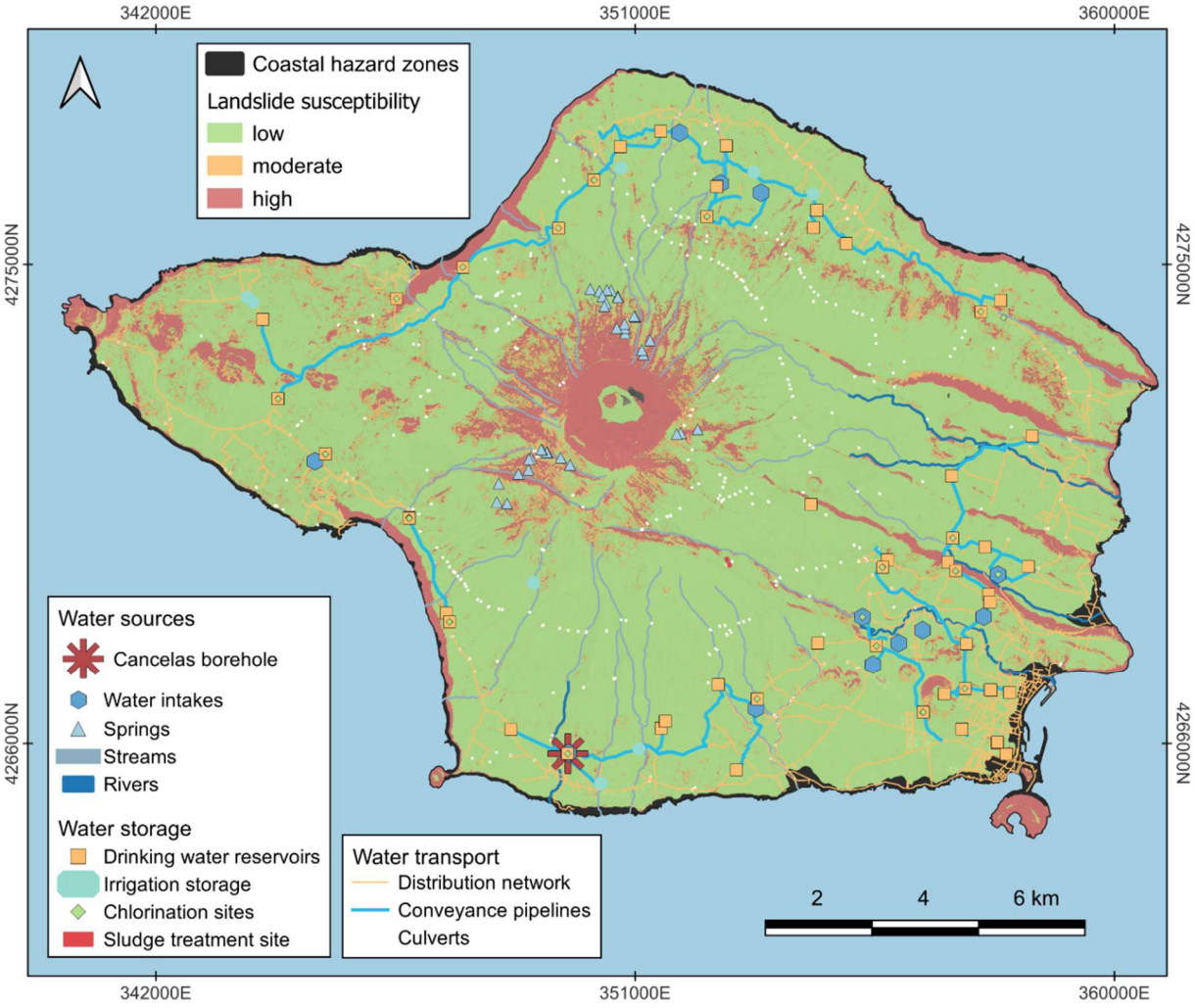

Figure 39 Landslide susceptibility classes and coastal hazard zones on Faial. Data source: PGRIA 2022–2027[122]; Secretaria Regional do Ambiente e Ação Climática (SRAAC), Governo Regional dos Açores; Câmara Municipal da Horta; TRISOLARIS. CRS: EPSG:5015 (PTRA08 / UTM 26N).

The mapped coastal hazard zones on Faial (Figure 39) overlap with the waterfront of Horta, the island's largest settlement. No reservoirs, intakes, or treatment facilities are located within these zones; however, distribution pipelines crossing the urban area may be affected indirectly in the event of coastal flooding. At the island scale, exposure of the

critical water infrastructure to coastal hazards is negligible, but localized risk in Horta and other waterfront settlements underlines the need to account for indirect impacts on service continuity when coastal flooding scenarios are considered.

The spatial pattern highlights that while landslide processes remain a relevant hazard for Faial, particularly under extreme rainfall, the current configuration of the water supply system is largely situated outside the most vulnerable terrain. This suggests that landslides are unlikely to represent a primary systemic threat, though localized disruptions to distribution could occur in the event of slope failure intersecting pipeline corridors.

GENESIS climate projections for Faial indicate a notable increase in wind alerts, rising from approximately 6% of days in 2025 (around 1 in 17 days) to 17% by 2100 (roughly 1 in 6), representing the largest absolute growth among assessed climate-related risks. Alerts for hazardous coastal events are also projected to increase gradually, from 2,2% to 5,8% of days by the end of the century, equivalent to approximately one day per month. Apart from Gran Canaria, Faial is the only island where an increase is observed. This may be due to the exclusion of sea level or wave variables, which could lead to the model underestimating these risks. In contrast, alerts for intense rainfall are projected to decrease, although these results are still to be interpreted by meteorologists, as the projections under the RCP4.5 and RCP8.5 climate scenarios for the Azores indicate a rise in precipitation in the short-term (2010-2039) and medium-term (2040-2069)[123].

Groundwater salinization is a critical issue on Faial. Spring waters have low mineralisation, with conductivity values between 73 and 344 µS/cm, while boreholes reach up to 1359 µS/cm, exceeding legal limits, suggesting long-term aquifer residence times for the basal aquifer and seawater intrusion in coastal zones[124]. In some cases, seawater contributes up to 22,5% of groundwater composition, with coastal waters predominantly of the Na-Cl type. Beyond mixing processes, cation exchange and silicate weathering also alter groundwater chemistry[31]. Mitigation measures could include Aquifer Storage and Recovery (ASR), Managed Aquifer Recharge (MAR), chloride monitoring, and strategic inland well siting[31].

Aquifers on Faial differ in both productivity and vulnerability (Table 5)[115,124]. The current planning only considers two water bodies for the entire island, whereas in previous planning cycles (1st and 2nd), eight water bodies were considered. This new designation doesn't correspond to single aquifers, but rather to a set of aquifers with similar geology and geomorphology characteristics[125]. Without enhanced protection measures and infrastructure modernisation, ensuring Faial's long-term water security will remain challenging.

Table 5 Summary of the vulnerability assessment for Faial's water bodies (adapted from[115,124,125]).

Water body	Outcrop area (km^2)	Major aquifer type	Vulnerability notes
Capelo	27,10	Basal + high-altitude aquifer (mixed)	5 springs, 1 well; moderate volume; sensitive to overuse.
Vulcão Central	59,94	Basal + high-altitude + perched	Formed by: Pedra Pomes da Caldeira: High productivity; demands careful gate design in galleries to control flow around dykes Caldeira: 44 springs tapped Cedros-Castelo Branco: 5 springs, 4 wells; moderate risk of saltwater intrusion in peripheral basal units. Flamengos-Horta: 7 wells; highest risk of overexploitation and salinization; lowest natural storage volume Pedro Miguel: Very small yield; single well at risk of salt intrusion.
Indeferenciado	In previous planning, this was formed by Lomba – Alto da Cruz and Ribeirinha. Now they aren't strictly considered water bodies		

Although recharge zones generally have moderate to high capacity, few benefit from legal protection. Ongoing deforestation and the drainage of wetlands for expanding agricultural activities (pastoralism) continue to threaten recharge quality[115].

Water quality degradation presents a significant environmental concern on Faial. Surface waters, such as Flamengos Stream, exhibit high BOD_5, ammonium concentrations, and faecal coliform levels, along with degraded ecological indices. Monitoring results[114] classify 60% of springs as A1 (good quality) and 40% as A2 (moderate non-compliance) due to microbiological contamination. Overall, 35,1% of monitored water bodies across the island are in moderate to poor condition.

Infrastructure weaknesses are a critical aspect of Faial's water system vulnerability. Significant distribution losses, insufficient treatment of 91% of wastewater, and limited sewer coverage undermine system performance[114]. Additionally, aging infrastructure further elevates operational and contamination risks.

Planned improvements under the GENESIS project include implementing Aquifer Storage and Recovery (ASR) at *Furo das Cancelas* to stabilise hydraulic gradients using two to four injection wells with stored potable water. The system will feature digital sensors to monitor

pH, electrical conductivity, nitrate levels, flow rates, and energy consumption, with all data integrated into a Digital Twin platform. This monitoring framework will facilitate modelling aquifer vulnerability, including analyses of Ghyben-Herzberg lens dynamics.

6.4. Summary of vulnerabilities and key conclusions

Faial's water supply system is shaped by its small population, volcanic terrain, and reliance on sensitive groundwater reserves. Despite relatively high precipitation, the island's water balance remains fragile due to difficulties in accessing main water bodies, such as the basal aquifer, in areas where salinisation is less likely to occur (further inland), as well as the limited surface storage capacity, the seasonal fluctuations in demand, and growing exposure to multiple natural hazards. The island's aquifers, particularly those located in coastal zones, are vulnerable to seawater intrusion, overexploitation, and reduced recharge under projected climate change scenarios.

Key infrastructure elements include springs and boreholes distributed across two different systems, supplying urban, agricultural, and industrial consumers. However, systemic weaknesses persist. Significant distribution losses, insufficient wastewater treatment coverage, aging infrastructure and their poor localization, as they are frequently positioned on active faults which could lead to destructive earthquakes, limit the system's performance and resilience. The concentration of abstraction in areas with low to moderate recharge capacity and subject to seawater intrusion in the aquifers adds further pressure on water resources.

The chapter integrates available environmental, technical, and monitoring information to characterise vulnerability patterns across the system, while hazard data coverage is limited. The Faial case highlights the urgent need for integrated aquifer protection, modernisation of wastewater and supply infrastructure, and strategic adaptation to long-term salinization and recharge risks. Planned measures, such as Aquifer Storage and Recovery (ASR) combined with Digital Twin monitoring tools, represent important steps toward sustainable groundwater management and long-term water security.

7- SANTIAGO ISLAND

7.1. Introduction and environmental setting

The Cape Verde archipelago consists of nine inhabited islands located 455 km off the coasts of Senegal and Mauritania (Figure 40 and 41). Geographically, the archipelago is divided into two groups: *Barlavento* (windward) and *Sotavento* (leeward), referring to where the wind arrives and where it departs. The *Barlavento* group comprises Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boa Vista, while the *Sotavento* group includes Maio, Santiago, Fogo, and Brava. Except for Boavista, Sal, and Maio, the islands generally have rugged terrain, with elevations exceeding 1000 metres on several islands, and reaching up to 2882 metres on Fogo, the country's highest point[126]. The highest point of Santiago is Pico de Antónia, which reaches 1395 m a.s.l.[127].

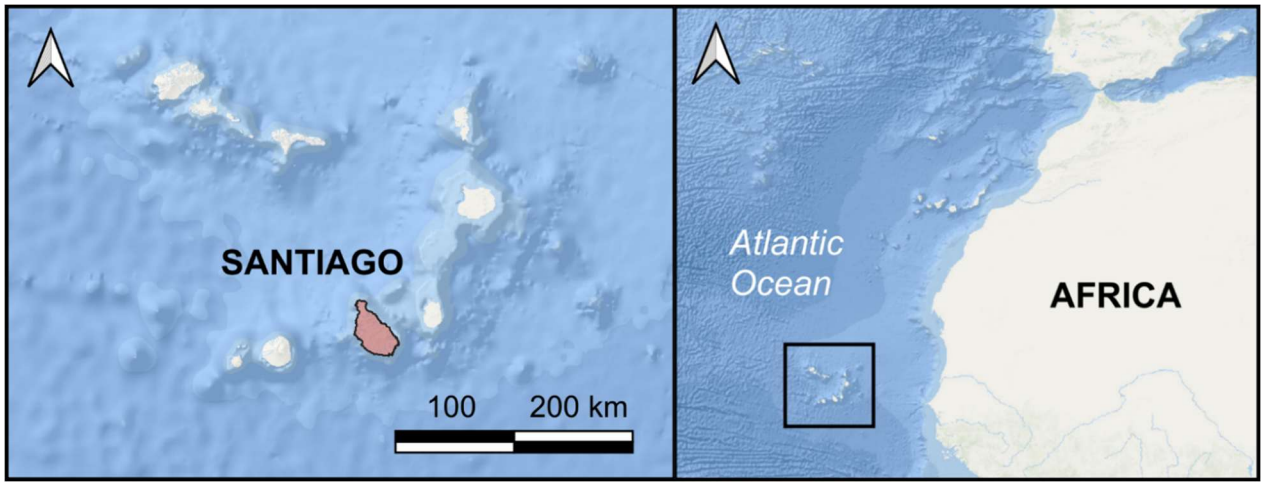

Figure 40 Santiago's location within the Cape Verde archipelago and wider regional context.

The archipelago was first discovered in 1460 by Italian and Portuguese navigators, with Santiago identified as the most suitable island for initial settlement, which began in 1462. Its strategic position along major Atlantic maritime routes linking Europe, Africa, and South America established Cape Verde as a historically significant port of call and logistical hub. This facilitated its early integration into global navigation networks and supported its long-standing role in the circulation of goods, people, cultures, and knowledge across continents[128].

As of 2021[129], Cape Verde had a total population of 483 628, of which Santiago accounted for 269 370 (56%), underscoring its demographic and strategic importance. Within Santiago, the municipality of Praia, which also serves as the national capital, had 142 009 residents, equivalent to 30% of the national population and 52% of Santiago's total. This demographic weight is paralleled by Santiago's agricultural role, as the island contains half

of Cape Verde's cultivable land, with 21 500 hectares of arable area corresponding to 52% of the national total[130,131].

Climatically, Cape Verde is within an arid to semi-arid climate zone, with higher elevations receiving increased rainfall due to trade wind interception. Annual average temperatures rarely exceed 25°C or fall below 20°C, while sea surface temperatures range from 21°C to 25°C[126]. The climatic stability of Cape Verde ensures the possibility of tourism throughout the year.

The islands were formed by volcanic activity associated with an oceanic hotspot[22]. The eastern islands originated between 10 and 20 million years ago, while the western islands, such as Santiago, are younger than 8 million years[132]. Some islands are ancient, now inactive basaltic shields, while others, including Ilha do Fogo, remain volcanically active with ongoing eruptions. Since 1500, Ilha do Fogo has experienced 27 eruptions, making it the most active island in Macaronesia, compared to 16 recorded in the Canary Islands. The most recent eruption began on 25 November 2014, releasing 53 000 tonnes of SO_2 within the first six weeks[133].

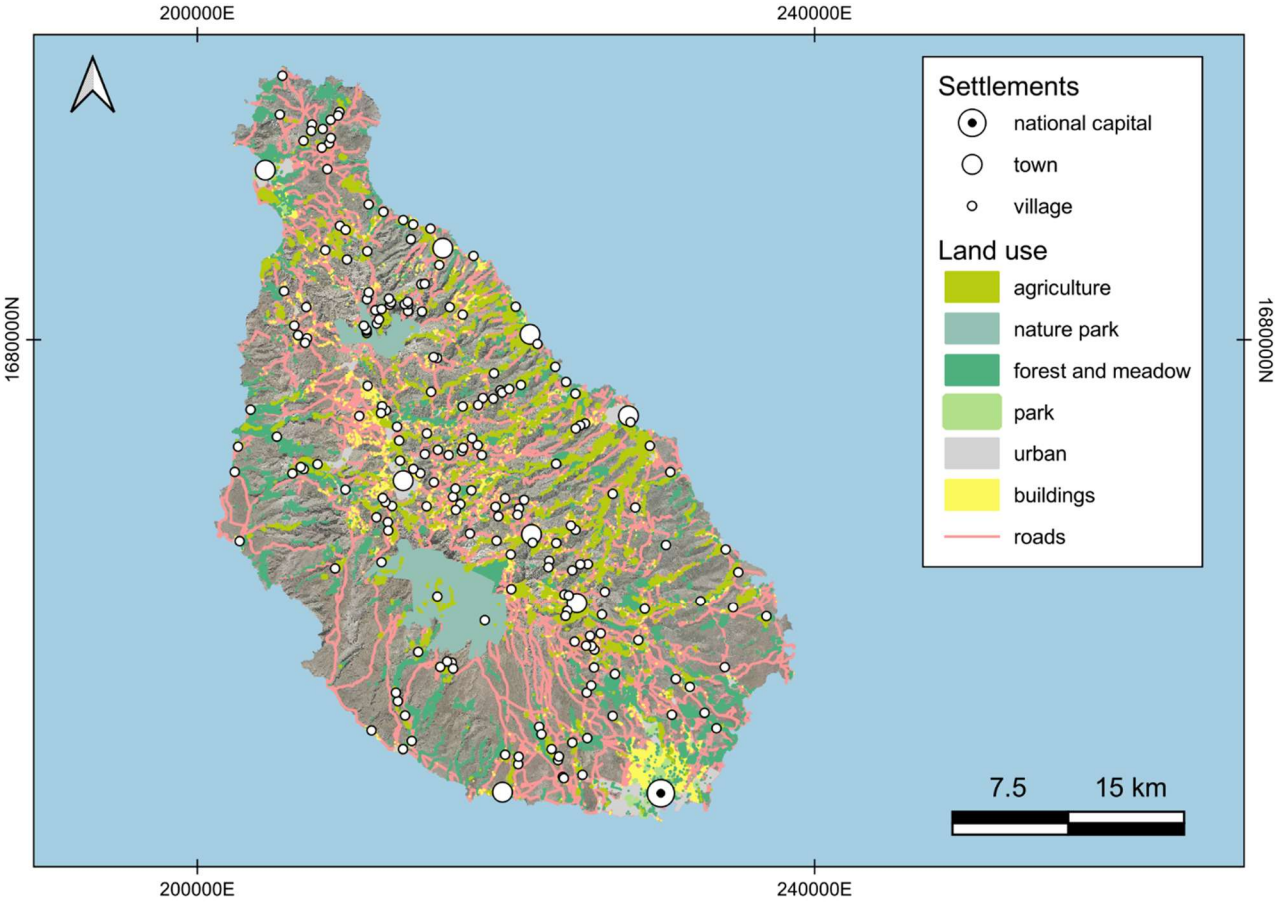

Figure 41 Land use, road network, and settlement distribution in Santiago[54,134]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.1.1. Climatic setting and atmospheric drivers of hydrology

Santiago Island, located in the southeastern part of the archipelago, has climatological and hydrogeological characteristics typical of Sahelian regions. Its seasonal patterns are driven by the movements of the Intertropical Front (ITF), which determines the onset of the wet season between August and November. Precipitation is irregular and strongly influenced by altitude, orientation, and morphology, ranging from approximately 170–190 mm/year at low elevations to 320 mm/year in mountainous areas. Some sources report averages up to 565 mm annually, with values exceeding 1000 mm at the summit and dropping below 100 mm along the coast[135–137]. Since the average precipitation ranges between 200 and 500 mm annually, the climate is classified as semi-arid[127].

Precipitation occurs in isolated and intense events, which complicate water infiltration[127]. As a result, the island experiences quasi-periodic and sometimes severe droughts, intensified by high potential evapotranspiration. Temperatures show modest variation, with a mean minimum of 22°C in February and a mean maximum of 27°C in September. Winds are steady from the N–NE throughout the year, strongest between January and May, and contribute to marine aerosol transport, affecting groundwater salinity[135].

As there wasn't any historical storm data available for Santiago, patterns from the Canary Islands and the Central Azores group were used as proxies in the GENESIS climate projections. The results were then compared to the rest of the islands of Cape Verde, showing a slight increase in storm alerts for Santiago. Wind alerts, while remaining relatively infrequent, are projected to nearly triple, from 0,8% to 2,5% of days, implying an increase from a few events per year to around nine by the end of the century. Alerts for extreme temperatures show a slight rise, from 0,3% to 0,8%, still representing less than 1% of the year but potentially linked to more intense heatwave episodes. As with Faial, projections indicate the decrease of alerts for extreme rainfall, but this is still to be interpreted by meteorologists.

7.1.2. Geology and hydrogeology

Santiago's geology is entirely volcanic, comprising a complex volcano-stratigraphic sequence[135]. The main hydrogeological units include the Pico da Antonia eruptive complex (with terrestrial and submarine pillow-lava facies), the Monte das Vacas formation (characterised by pyroclastic cones), and recent Quaternary sediments. These overlie the low-permeability Ancient Internal Eruptive Complex (AIEC), composed of the Flamengo and Conglomeratic-Brechoide formations, which form an impermeable base.

The Pico da Antonia complex hosts Santiago's most significant aquifer, with high storage capacity and transmissivity values ranging from 10^{-1} to 2×10^{-2} m^2/s[137]. Its fissured and cavernous pillow lavas can yield up to 40 m^3/h, typically stabilising after initial drawdown[135]. The Monte das Vacas formation, exposed at the island's highest elevations (*Pico da Antonia*, *Serra Malagueta*), enhances infiltration due to good porosity and vertical permeability, with porosity reaching around 10% in the Tarrafal area, allowing drainage towards deeper, less permeable units[135].

The central groundwater reservoir, comprising the *Assomada* and *Pico da Antonia* formations, has a lenticular shape, thicker at the centre and thinning towards the coast. Recharge occurs through precipitation and fog condensation, while discharge takes place via springs, streams, or direct seepage into the sea[132]. Hydrogeological conditions vary considerably across the island due to geological heterogeneity and fracture distribution, which limit groundwater storage and movement. Many volcanic complexes contain more than 600 dykes per kilometre thicker than 3 m, accounting for up to 10% of rock volume and significantly reducing hydraulic conductivity[136]. Marine intrusion extends up to 4 km inland, highlighting the delicate balance between freshwater and seawater in coastal aquifers, where much of the population resides.

The island's steep terrain prevents the formation of permanent streams. This leads to rapid surface runoff and flash flooding during the rainy season, with torrents that can last from hours to days[127,131]. This runoff is responsible for the greatest water loss, exceeding evaporation. In this context, between 1981 and 1989, annual potential evapotranspiration (PET), was calculated using the Penman method, which reached up to 1650 mm in Trindade, municipality of Praia. The highest PET values are observed in May, coinciding with the driest month, showing the influence of wind and temperature on water loss[127].

Santiago's total annual surface water potential is estimated at approximately 168,4 million m^3, three times higher than the actual surface water availability of 56,6 million m^3/year, revealing a substantial gap between potential and actual volume, largely due to insufficient water capture infrastructures, and losing great volumes of water due to runoff[131].

In terms of groundwater availability of Cape Verde, Fogo Island has the largest surplus, followed by Santo Antão and Santiago. However, during drought years, Santiago frequently experiences a negative water balance, worsening supply constraints[127].

7.2. Water supply system and infrastructure

The water supply system (Figure 42) on Santiago is vital for public consumption, agriculture and economic activities. Praia, the capital of Cape Verde, and the country's largest urban centre, had a population of 145 000 inhabitants in 2021, a fourth of the national population[138,139]. Since most of the island's population lives in this city and depends on the local desalination plant for drinking water, irrigation, sanitation, and industrial use, desalinated water constitutes the main water source on the island[140]. The remaining population relies on groundwater sources and limited surface water[22,132].

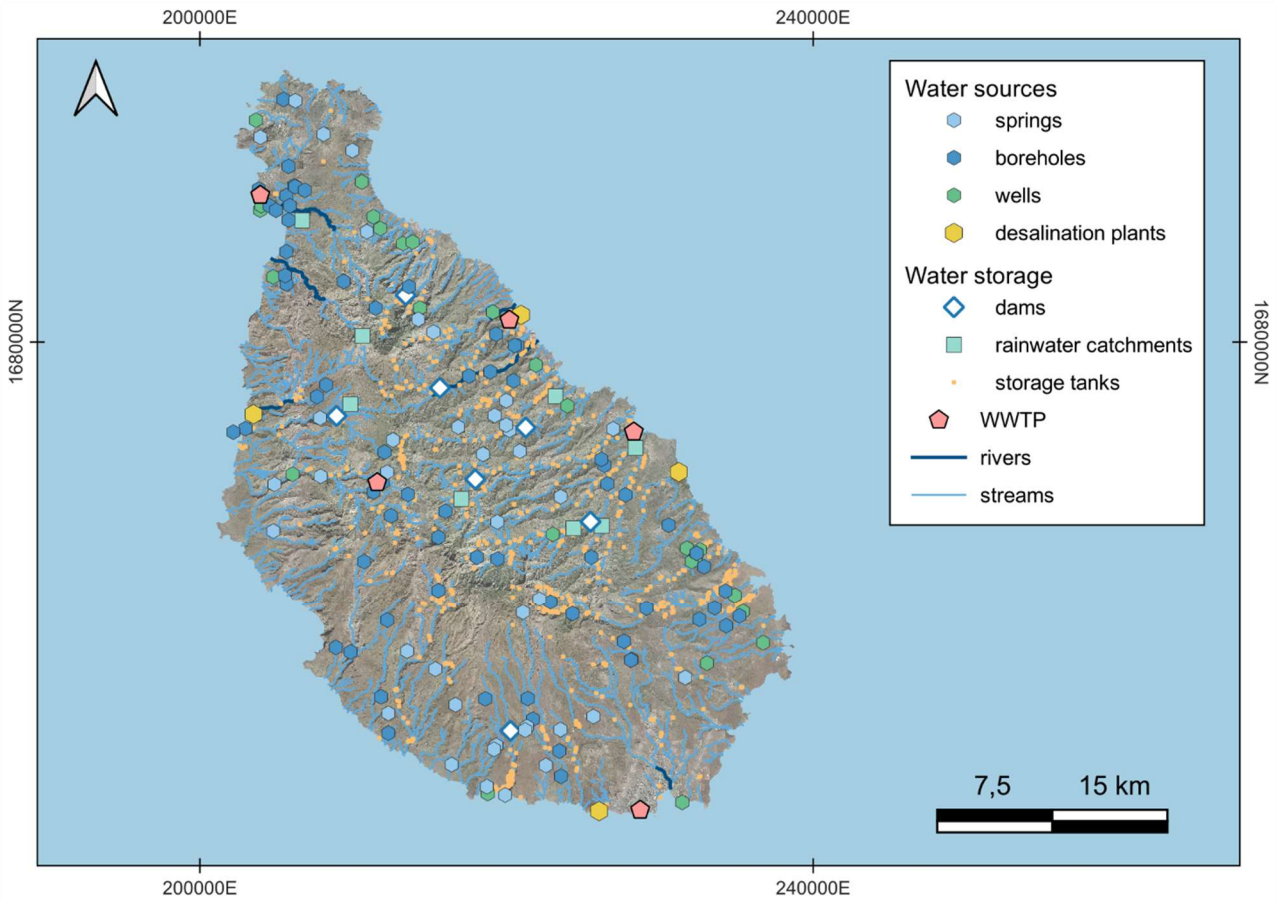

Figure 42 Waterways and water infrastructure in Santiago. Data source[54,134]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.2.1. Water sources and storage

The island extracts approximately 5,4 hm³ per year from groundwater using 223 boreholes, 29 wells, nine springs, and one gallery[22,132]. Desalination adds about 6 hm³ annually, mainly for urban supply in Praia, while surface water sources contribute around 3,25 hm³ per year, bringing total annual supply to approximately 15 hm³[141].

Groundwater

A total of 1199 springs have been identified at elevations between 3 m and 804 m, with about 70% located on the central plateau between the island's two main massifs, reflecting geological controls on spring distribution[132].

There are 780 boreholes, with diameters ranging from 200 mm to 600 mm and depths between 30 m and 270 m. Older boreholes use iron tubes, while newer installations use PVC, indicating material modernisation. Boreholes are typically situated near streams and coastal areas, although some are located on the plateau. Water from boreholes is often distributed by tanker trucks, particularly in areas lacking piped networks[132].

There are 1074 wells on Santiago, mostly located near the coast. They range in depth from 2,5 m to 15 m and are generally equipped with motor pumps, although some still use windmills or manual extraction systems[132].

Desalination

Desalinated seawater is a key component of the water-supply system in Praia and on Santiago, particularly in response to rising urban demand and constraints on groundwater availability. The seawater desalination plant operated by Electra S.A. in Palmarejo (Praia) had a nominal capacity of 5000 m³/day in 2007. The facility has since been expanded to 20 000 m³/day to meet the increasing demand of the island's capital[141–143].

Groundwater was the dominant water source in 2010, accounting for 87% of Santiago's supply[130], but the role of desalination has expanded steadily. In 2006, of the 2,12 million m³ of water treated by Electra, 1,61 million m³ originated from desalination, representing the majority of the treated volume[144]. By 2023, desalination accounted for 67% of water for human consumption, compared to 33% from groundwater[140].

However, concerns regarding groundwater quality near desalination plants have also been raised. In 2011, water quality analyses conducted with the support from the Government of Japan reported elevated concentrations of nitrates, total coliforms, and hardness in groundwater sources near the Praia and Santa Cruz facilities. However, parameters including pH, turbidity, nitrite, chloride, and fluoride remained within permissible limits for drinking water[145].

Surface water

Surface water plays a minor role due to the lack of permanent rivers. Runoff occurs only during intense rainfall events exceeding 25 mm per day and is captured in reservoirs where available. Retention structures such as dams are used to collect this runoff (Table 6), but their capacity decreases rapidly due to sedimentation from eroded, deforested, and overgrazed soils. In some cases, dam walls are raised after siltation, and water stored within

the porous sediments behind the dams is accessed using upstream drains, a practice similar to methods used in arid regions such as Fuerteventura, Namibia, Zimbabwe, Botswana, and Kenya[22].

Table 6 Main surface water reservoirs in Santiago, adapted from[146].

Reservoir	Municipality	Capacity (hm^3)	Dam height (m)
Poilão Dam	São Lourenço dos Orgaos	1,2	26
Salineiro Dam	Ribeira Grande de Santiago	0,56	26
Faveta Dam	Sao Salvador do Mundo	0,54	30
Saquinho Dam	Assomada, Santa Catarina	0,54	40
Barragem Principal	Sao Miguel	0,54	–
Flamengo Dam	Calheta de São Miguel, São Miguel	0,85	–
Figueira Gorda Dam	Santa Cruz	1,82	–

Barragem de Poilão is a brick dam located in the eastern part of Santiago Island, where it impounds Ribeira Seca, the island's largest river (Figure 43). The reservoir is primarily used for irrigation. However, significant sediment transport into the reservoir has severely impacted its storage capacity, which was reduced by nearly 50% between 2006 and 2013[146]. Despite this, the construction of dams on the island has offered relief to the farming sector, as their primary function is to provide irrigation for agricultural fields[127,147].

Figure 43 Poilão Dam, a critical component of Santiago's surface water infrastructure. Source[148].

7.2.2. Water transport, treatment, and distribution

Water is transported and distributed through a combination of pipelines, open canals, and tanker trucks. Canals and pipelines convey water by gravity or pumping, often operating under scheduled time restrictions for pumping and irrigation[132]. In urban areas such as Praia, more than 65% of households are connected to the piped network, which is primarily supplied by desalinated water[149]. In rural areas, coverage is much lower, and groundwater transported by tanker trucks remains a common source of supply[132,150].

Economic industries are mainly supplied through the public network in urban zones, while small industries in other municipalities depend largely on groundwater extracted from boreholes. Before distribution, water is disinfected using either 70% calcium hypochlorite or 35% sodium hypochlorite, with residual chlorine levels verified to ensure quality[132].

7.2.3. Wastewater

Santiago currently has five wastewater treatment plants (WWTPs) located in Praia (Palmarejo), Tarrafal, São Miguel, Santa Catarina and Santa Cruz (Pedra Badejo). Although these facilities constitute important infrastructure for sanitation and environmental protection, wastewater management across the island remains limited and underdeveloped[127]. The WWTPs face structural and operational challenges, including low household connection rates, insufficient wastewater inflows, and limited reuse of treated effluent. In many urban and rural areas, septic tanks and pit latrines remain the dominant sanitation systems, frequently contaminating groundwater and posing public health risks[127].

The Praia WWTP, located in Palmarejo, was built in 1997 and initially provided only pre-treatment and primary treatment, with effluent discharged into the sea through a submarine outfall[144]. The facility has since been rehabilitated, expanded, and modernized to include secondary treatment (activated sludge with extended aeration in sequencing batch reactors) and tertiary treatment (chlorine and ultraviolet disinfection), enabling water reuse. The sludge line was upgraded with a gravity thickener, mechanical dewatering, and a biogas recovery system, and a remote SCADA and PLC-based automation system was introduced to reduce manual operation[127]. Despite these improvements, the Praia WWTP operates far below its hydraulic capacity of 14 000 m^3/day. In 2014 it received only about 1000 m^3/day, corresponding to a household connection rate of approximately 7%. By 2017 inflows had increased to 3000 m^3/day[139]. According to data obtained from the National Water and Sanitation Agency of Cape Verde (ANAS), since 2020 the plant has treated 1304 m^3/day, indicating a decrease in the processed volume. This underutilization continues to

present operational challenges. More broadly, Santiago's wastewater infrastructure remains limited: in 2009 only 13% of households were connected to the sewer system, rising to 33% by 2021[132,151].

Besides Praia, Santiago's WWTPs in Santa Cruz (Pedra Badejo) and Tarrafal also face low connection rates and insufficient inflows. The Tarrafal WWTP, constructed under the local Sanitation Plan, uses lagoon technology with a nominal capacity of 1910 m³/day. The Santa Cruz facility treats up to 1500 m³/day, with part of its effluent reused for irrigation. Sludge treatment at both plants relies on drying beds[127].

Wastewater and solid waste are frequently discharged directly into streams, contributing to environmental degradation. Nationally, 13 WWTPs are in operation. Between 2019 and 2021, treated wastewater volumes ranged from 1,8 to 2,7 hm³/year[151]. Between 2022 and 2023 the only change in sewerage infrastructure was an increase in the total length of collectors, recorded on Santiago, indicating ongoing efforts to improve the service[140]. Wastewater reuse remains limited, representing a missed opportunity for advancing circular economy principles. Nevertheless, between 2019 and 2021 reuse increased from 0,31 to 1,19 hm³/year, reflecting gradual progress in promoting circular water use in Cape Verde[151].

7.2.4. Water management practices

Water management for springs, shallow wells, and surface runoff was traditionally governed by local community rules that established use priorities and regulations. Groundwater remains a critical source for water supply, especially in rural areas. However, its exploitation is not without issues, as saline intrusion into freshwater aquifers has severely impacted the availability of water for both domestic and agricultural use[138]. For this reason, in recent decades, however, public authorities have taken increasing control, introducing stricter measures to protect water resources. For example, to prevent salinization of coastal aquifers, public boreholes near the coast are limited to operating only 2–3 hours per day, and new coastal boreholes are prohibited[135]. This is critical, as a large portion of Santiago's population resides along the coast and depends on groundwater for their livelihoods. Urban areas such as Praia, have responded to this by prompting large-scale investments in brackish water desalination infrastructure[138].

Traditional water distribution remains widespread, particularly in rural agricultural areas where irrigation depends on water from boreholes and springs. Allocation is governed by locally maintained calendar systems, in which access is determined by the area of land cultivated rather than hydrological or technical criteria[152]. Farmers are assigned fixed periods of use, typically once per month, scheduled through rotational turns coordinated

by a local *meirinho* or, in the case of borehole systems, by a state-appointed *motorista*. These calendars are embedded in customary law and communal agreements, transmitted across generations and regarded as part of a property's inherited rights. Irrigation is generally applied through flood techniques every 15 to 30 days, allowing extended infiltration but resulting in inefficient water use. Informal exchanges, such as *troca de água* between relatives or neighbours, are common and introduce flexibility into an otherwise rigid structure. While the system reflects resilient communal governance and cultural continuity, it presents challenges for equitable allocation, efficient use, and long-term sustainability under increasing environmental stress.

Water access across Santiago remains unequal and, in many cases, insufficient (Table 7). Average consumption for households connected to the piped network is about 50 L/person/day. In contrast, users relying on public standpipes consume only 7–25 L/person/day with a mean of 15 L/person/day, well below the recommended minimum of 40 L/person/day[131].

Table 7 Water management in Santiago (as of 2011)[145].

Locality	Infrastructure	Population connected to WSS (%)	Water usage
Tarrafal	2 × 150 m³ water tanks (5:00–14:00h, alternating operations); 12 domestic wells	86%	75% domestic, 25% agriculture
São Miguel	35 reservoirs, 2058 m³ total capacity	65%	
São Salvador do Mundo	Springs; tanker trucks (from São Domingos, Santa Cruz)		
Santa Cruz	Desalination (Achada Ponta, 500 m³/day); 8 wells (1000 m³/day); 45 reservoirs	90% with taps + meters	
São Domingos	2 wells (500 m³/day); 54 reservoirs (11–200 m³)		
Praia	3 desalination plants. Key reservoirs: 1500 m³ (desalination site), 2500 + 1 000 m³ (Monte Babosa), 700 m³ (Eugénio Lima), 400 m³ (Achada São Filipe), 1500 m³ (Ponta d'Água), 400 m³ (Achada Grande Trás); ≈ 8000 m³ total		
Ribeira Grande de Santiago	4 wells (domestic + agriculture); 10 reservoirs (8–55 m³)		
São Lourenço dos Órgãos	14 reservoirs (domestic); 12–17 reservoirs (agriculture); 8 wells (dual use)	Rainy season: 60 % agricult., 40 % domestic. Dry season: reversed	
Santa Catarina		As of 2011, water supply capacity limited to 16 L/p/day	

Inequalities are most pronounced in peri-urban and rural areas, where communities depend on standpipes or water delivered by tanker trucks, both costlier and less reliable sources[127]. At the national level, 83% of the population has access to drinking water, but Santiago falls below this benchmark due to source-community distance, water cost, groundwater availability, and condition of infrastructure[131].

Water quality monitoring is comparatively well established on Santiago, with boreholes, wells, and selected surface sources tested three times per year. This system is considered generally satisfactory, whereas on other islands monitoring is sporadic, making water safety less certain[127].

7.3. Vulnerabilities and system weaknesses

Santiago's water resources and infrastructure face significant vulnerabilities arising from both natural conditions and human activities. The island's low and irregular rainfall limits aquifer recharge, making water availability fragile. When rain does occur, it is often brief and intense, resulting in rapid runoff that is largely lost to the sea rather than contributing to effective recharge or storage[22,135]. Soils, already degraded by deforestation and overgrazing, worsen this problem by accelerating erosion and sedimentation. Consequently, reservoirs fill with sediment quickly, shortening their useful lifespan and requiring repeated, costly interventions such as raising dam walls[22].

Groundwater systems are also highly vulnerable. Coastal aquifers are particularly at risk of saline intrusion, with seawater extending up to 4 km inland in some areas. This is mainly caused by overextraction, which lowers water tables and permits saltwater contamination of freshwater reserves[22,135]. Marine aerosols and salt dissolution further increase groundwater salinity. In certain zones, such as *Praia Baixo*, *Montenegro*, and *Charco*, brackish water remains the only available source for both domestic and agricultural use[135]. The volcanic geology, characterised by fractured and dyke-rich formations, complicates aquifer management by creating irregular flow paths and limiting storage potential in many areas[22].

Anthropogenic contamination further threatens groundwater quality. Key factors include diffuse pollution from agricultural fertilisers and phytosanitary products, discharge of human effluents, and free grazing of cattle and goats along streams and coastal areas, alongside saline intrusion resulting from excessive groundwater abstraction[132]. These pressures have worsened in recent years due to declining rainfall, reduced recharge, and the growing need for groundwater pumping to support irrigation, leading to additional lowering of water tables and expanded marine intrusion[132].

Management measures aim to reduce these vulnerabilities, though significant challenges remain. To limit saltwater intrusion, public boreholes near the coast are restricted to 2–3 hours of pumping per day, and new coastal boreholes are prohibited[135]. Despite these efforts, the delicate balance between freshwater and seawater in coastal zones requires continuous monitoring. The combined effects of climatic variability, geological complexity, land degradation, and human pressures make Santiago's water resources highly susceptible to both droughts and extreme rainfall events[22], highlighting the need for careful management, infrastructure adaptation, and long-term planning.

Water safety remains a critical issue on Santiago. Drinking-water supply is divided between two main entities: Electra Sul and Águas de Santiago (AdS). Electra Sul, a state-managed entity, provides treated desalinated water for urban use. AdS, under municipal management, supplies water from both groundwater and desalinated sources, but disinfection is applied only in part of its systems serving urban and rural areas. According to a 2023 report by ANAS (Agência Nacional de Água e Saneamento), none of the islands achieved the national target of 77% safe water, with Santiago reaching only 5%. Despite this, Electra Sul reported that 85% of its supply met safety standards, whereas AdS monitored only 8 of 41 required parameters, with an average compliance of 69%.

7.4. Natural hazards and exposure

Cape Verde ranked 32nd out of 177 countries in the World Risk Report 2017, due to its susceptibility, vulnerability and lack of coping capacities to natural hazards. However, by 2024 its position significantly improved, ranking 174th out of 193 United Nations member states, indicating notable progress in disaster risk reduction and resilience[153,154]. Despite this advancement, the country remains exposed to droughts, flash floods, landslides, earthquakes, volcanic eruptions and epidemics. Regarding Santiago, one quarter of the population lives in informal settlements, which are particularly exposed to climate-related hazards[155].

7.4.1. Flood risk

Santiago's geomorphology, characterized by steep slopes, high elevations, and small-scale river catchments, combined with irregular rainfall patterns, makes the island particularly susceptible to flash flooding. These flash flood events primarily affect valley floors, coastal zones, and low-lying urban areas, causing significant socio-economic and infrastructural damage (Figure 44)[156,157].

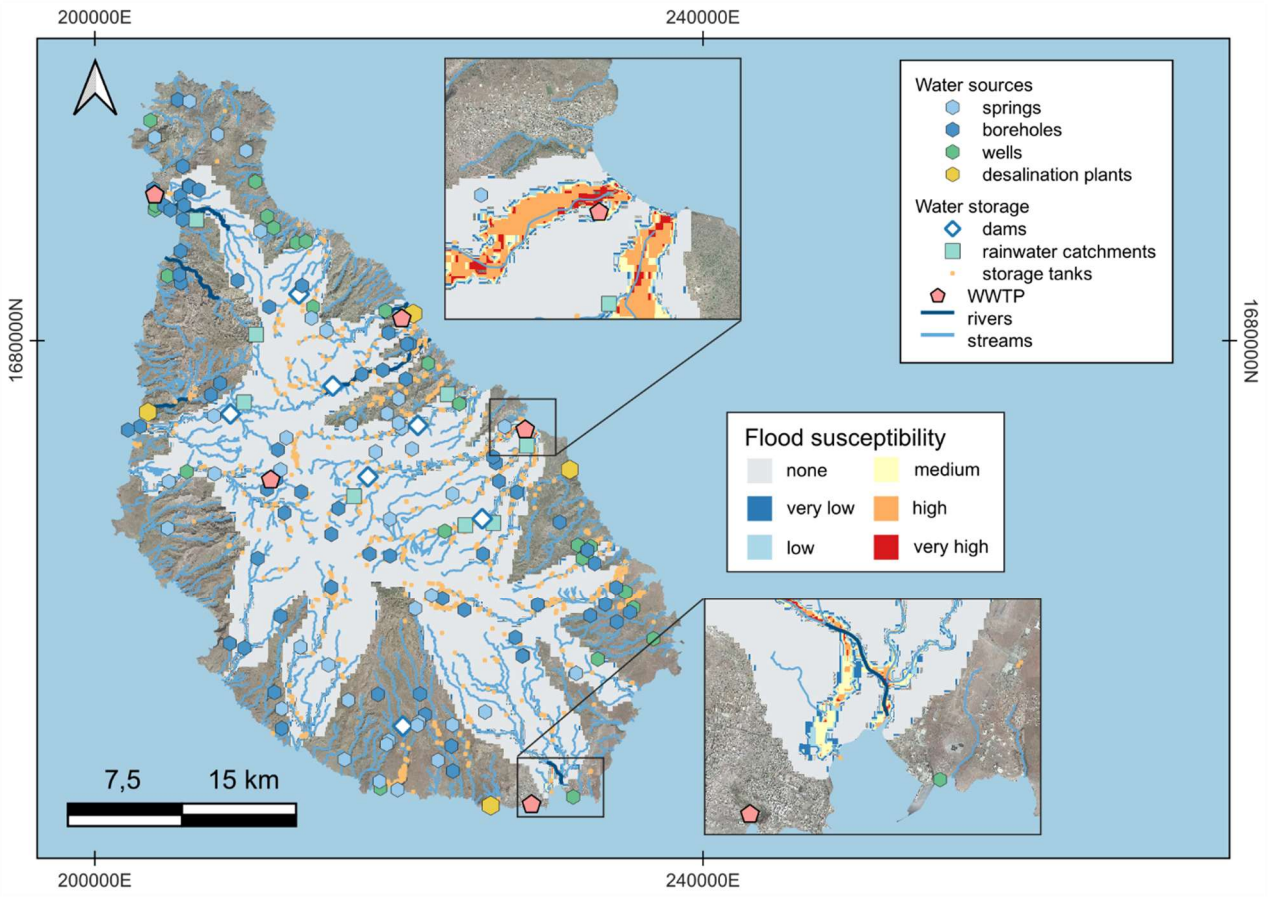

Figure 44 Flood-prone areas and susceptibility classes on Santiago. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

The highest flood risk period corresponds to the months of August to October, coinciding with the peak rainfall season. Flash flooding threatens over 150 000 people nationwide, with the majority located on Santiago Island[157]. Santiago, São Vicente, São Nicolau, and Santo Antão together make up 70–75% of the national population, but account for 98% of the flood-exposed population, underscoring the concentration of flood risk in these areas[155].

Precipitation hazard (storms)

Due to Santiago's semi-arid climate, there aren't storms often. However, when they do occur, they tend to be intense and temporary (Figure 45). These can lead to floods that affect valley floors, coastal zones and low-lying urban areas, causing significant socioeconomic and infrastructural damage[156,157].

In the capital city of Praia, critical infrastructure exposure to flooding is substantial, with an estimated 24% considered at risk. The vulnerability extends to transportation infrastructure as well; severe flood events could impact up to 90% of Santiago's road network, critically affecting connectivity and emergency response capabilities[155].

Historical events illustrate the magnitude of the risk: on September 8, 2015, intense flooding in Santiago resulted in extensive road damage, landslides, and destruction of agricultural lands and residential properties. Financially, it is estimated that approximately USD 550 million worth of buildings are exposed to flood hazards annually[157].

From an economic perspective, Santiago and São Vicente islands face a 1% annual probability of flood-related losses exceeding USD 37 million, which corresponds to 1,88% of Cape Verde's GDP. This highlights the significant economic vulnerability of the country's primary economic centres to extreme flood events[155].

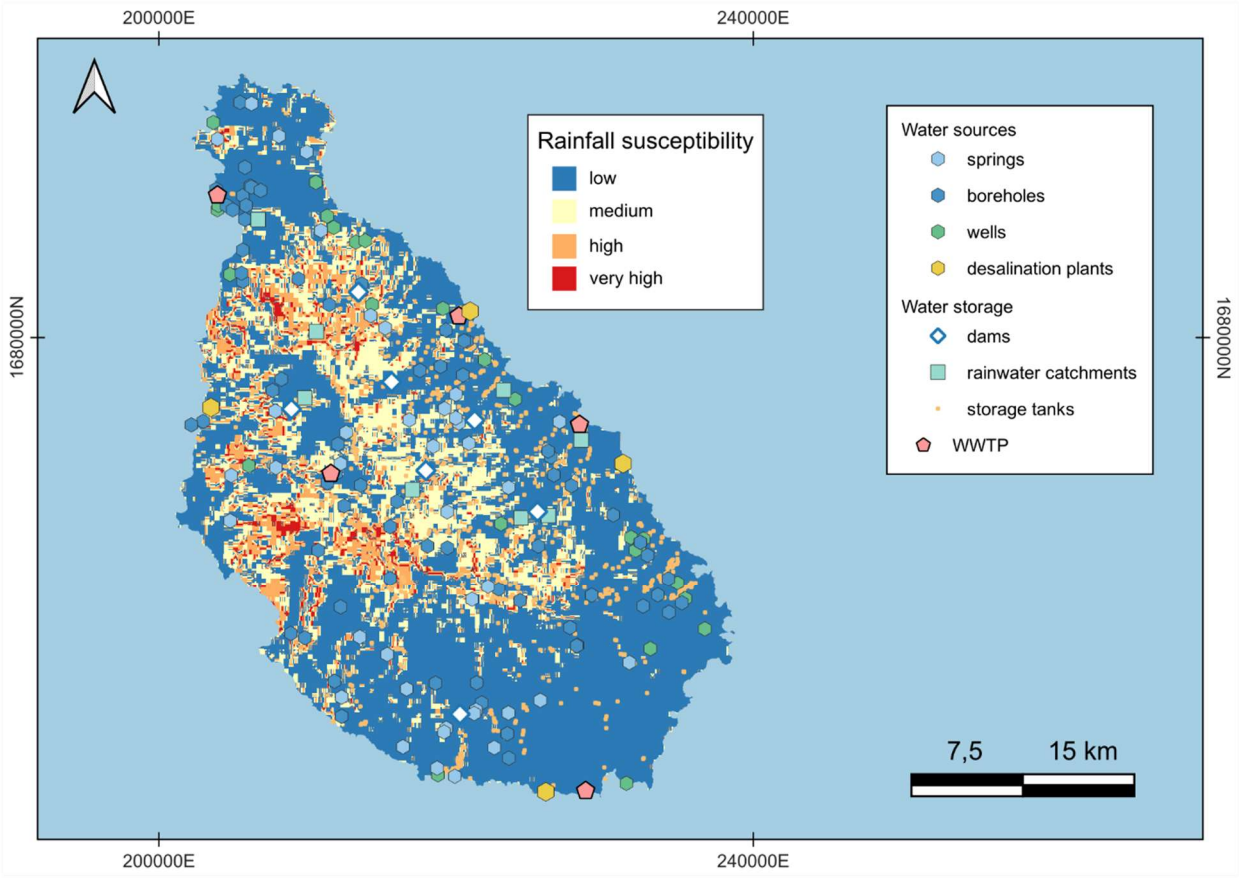

Figure 45 Precipitation (storm) hazard susceptibility on Santiago. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.4.2. Drought risk

Cape Verde has a long history of drought events, which have led to famine and forced migration, resulting in high mortality rates and significant impacts on the people's livelihoods[156]. Santiago is particularly vulnerable, exhibiting one of the highest rainfall deficits among the archipelago's islands. This deficit is especially pronounced in the southern region of Santiago, around Praia, while the northern and higher parts of the island experience comparatively lower drought risk[157] (Figure 46).

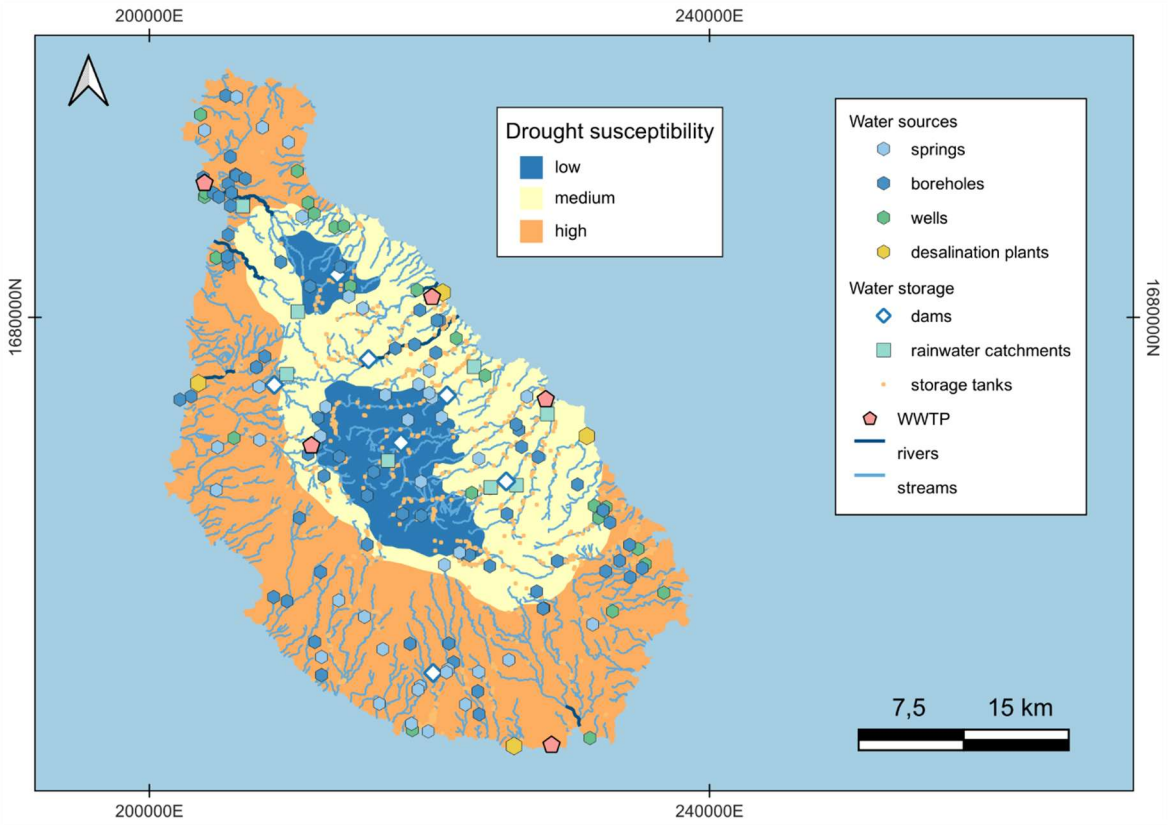

Figure 46 Drought susceptibility on Santiago. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

Economically, droughts have severely affected Santiago's agricultural sector, with annual income losses exceeding USD 8 million and an average agricultural income decline of approximately 15% per year[157]. Over the past century, Cape Verde has experienced ten major droughts, historically resulting in famine and population displacement. However, in recent years, famines have been largely averted due to increased food imports and humanitarian aid, despite ongoing drought occurrences[157].

Between 2017 and 2022, an extended drought period placed up to 10% of the national population at risk of food insecurity. Unlike flood exposure, which is concentrated primarily in Santiago and Santo Antão, drought risk is more evenly distributed across the islands[155].

In response to the prolonged drought and successive poor agricultural seasons, the Government of Cape Verde declared a national water emergency in January 2020. The emergency measures implemented included[159]: temporary restrictions on water consumption; reduction of authorized water withdrawal volumes; modifications to water usage methods; suspension or revocation of water usage rights; reprioritization of water supply allocation; changes to operational procedures in production plants and sanitation services.

7.4.3. Slope movements and landslide risk

Landslides in Santiago are primarily triggered by flash floods, which documented impacts critical infrastructure, such as roads and dams[156]. The island is generally classified as having a moderate landslide hazard (Figure 47), but associated damages remain significant. Annual losses to the building stock is estimated to exceed USD 150 000, while damage to energy generation facilities could be more than twice as high, averaging USD 350 000 per year[157].

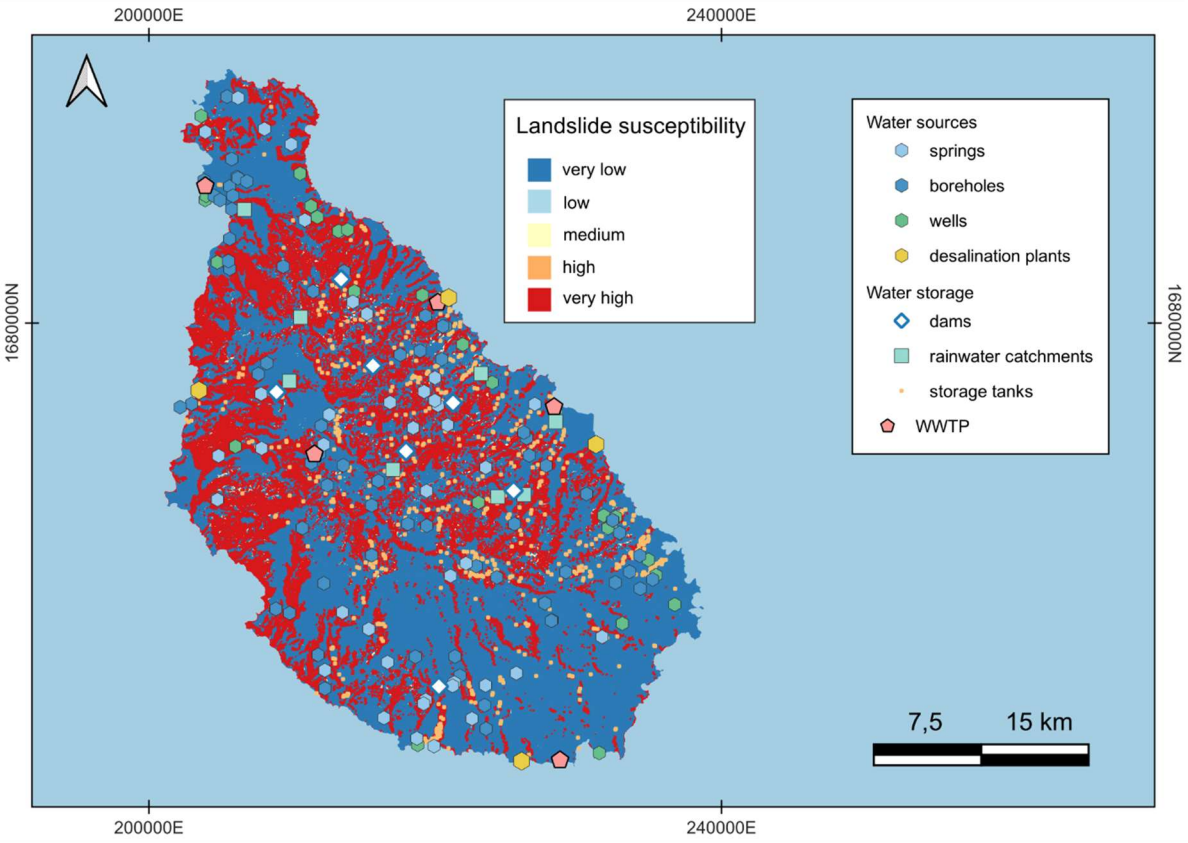

Figure 47 Landslide susceptibility on Santiago. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.4.4. Seismic and volcanic risk

The islands with the highest levels of seismic and volcanic activity are Fogo, Brava, and Santo Antão. The most recent eruption occurred on 23 November 2014 on Fogo Island, originating along an SSW–NNE fissure on the eastern flank of Pico Novo in the Chã das Caldeiras region. The event caused the complete destruction of housing and community infrastructure in Portela and Bangaeira, requiring full reconstruction and generating substantial economic losses[156].

Seismicity in Cape Verde is typically shallow and concentrated to the west of the archipelago, although the highest hazard levels are recorded on the eastern islands, reflecting the spatial complexity of tectonic risk in the region[157]. Santiago is classified as having low seismic susceptibility (2% probability of exceeding damaging ground shaking[157]), but probabilistic hazard modelling indicates four susceptibility classes across

the island, reflecting exposure to regional seismic sources and local amplification (Figure 48).

Santiago is not volcanically active, but it remains susceptible to volcanic ashfall. The northern part of the island can be affected during eruptions on neighbouring islands due to prevailing wind patterns[157]. Ash deposition can obstruct drainage systems and disrupt the functioning of the water supply system.

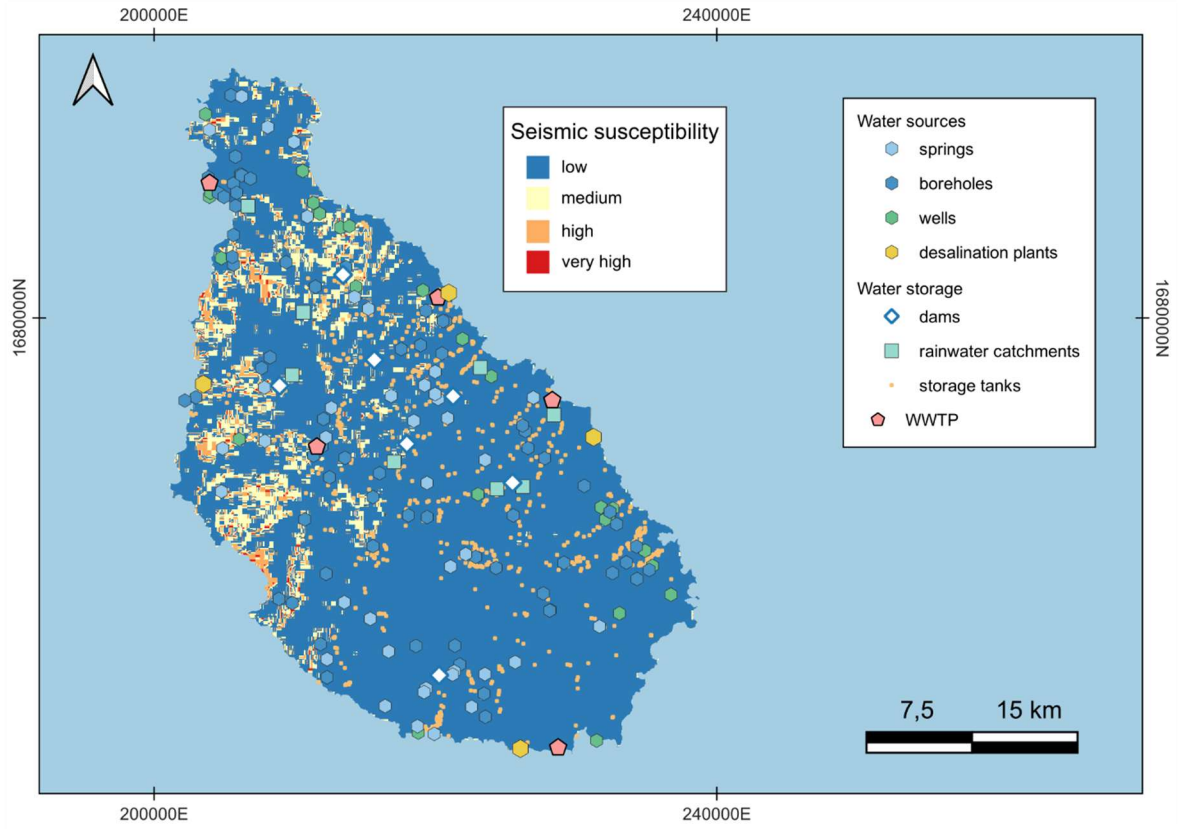

Figure 48 Seismic susceptibility on Santiago derived from probabilistic hazard modelling, reflecting exposure to regional seismic sources and local amplification. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.4.5. Wildfires

Santiago has the most extensive forest and shrubland cover in Cape Verde, totalling approximately 26 500 ha, equivalent to 27% of the island's surface area. The most ecologically significant areas are the humid forests located above 400 m a.s.l. on the northeastern-facing slopes, which benefit from horizontal precipitation associated with moist trade winds. This process enhances soil moisture, groundwater recharge, and overall water availability[155]. Forests in the arid and semi-arid sectors of Santiago also contribute to environmental stability by protecting soils against wind and water erosion, improving fertility through organic matter accumulation and nitrogen fixation, and sequestering atmospheric CO_2. They additionally provide essential resources such as fodder for livestock and fuelwood for rural communities[155]. Despite these functions, Santiago's forests are increasingly susceptible to wildfires (Figure 49). Between 2010 and 2015, the island

recorded 163 events, corresponding to 44% of the national total[153]. A multicriteria analysis of wildfire susceptibility[138] identifies anthropogenic factors (agricultural burning, waste incineration, inadequate forest management), geomorphological factors (slope), climatic factors (wind, solar exposure), and biological factors (forest species, accumulation of woody residues, presence of foreign species) as key determinants of ignition risk[138].

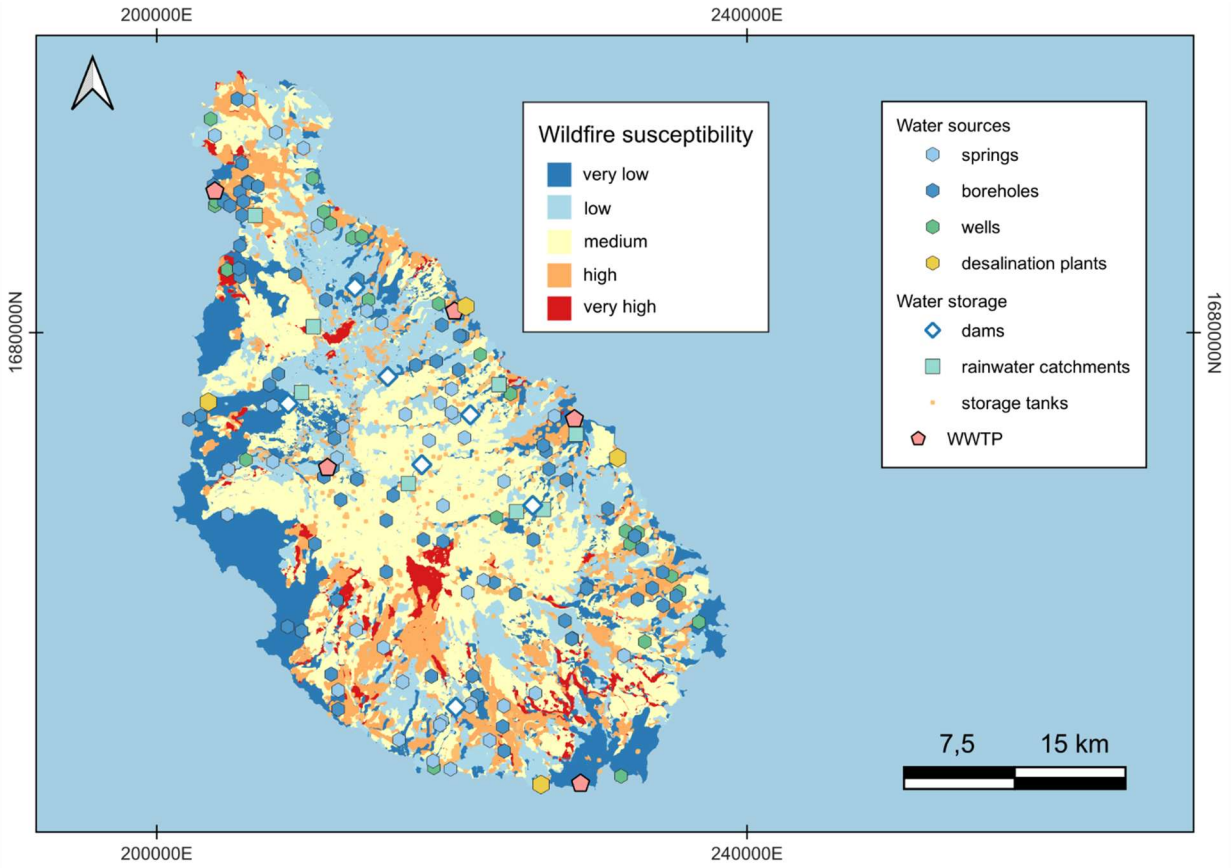

Figure 49 Wildfire susceptibility on Santiago. Data source[54,134,158]. CRS: EPSG:32627 (WGS 84 / UTM 27N).

7.4.6. Coastal hazards

Climate change-driven sea-level rise is increasing saltwater intrusion into soils and coastal aquifers on Santiago. This process threatens freshwater availability, reduces agricultural productivity, and affects ecosystem functioning in low-lying coastal zones. The problem is intensified by unregulated coastal urban expansion, where sand extraction for construction has been widespread. This activity weakens natural coastal barriers and accelerates salinization of soils and groundwater, further reducing the resilience of coastal ecosystems and water resources[156]. In addition, critical coastal infrastructure on Santiago, particularly in the transport sector, is increasingly at risk. Rising sea levels and coastal erosion threaten access to essential services such as hospitals, schools, and emergency facilities, thereby heightening the vulnerability of coastal communities to climate-related hazards[155].

7.5. Summary of vulnerabilities and key conclusions

Santiago is Cape Verde's largest and most densely populated island, home to over half the archipelago's population and hosting the national capital, Praia. Its water supply system is heavily reliant on groundwater abstraction, supported by desalination and limited surface water capture. However, the island's arid to semi-arid climate, combined with geological and land degradation constraints, poses major challenges to water resource availability, quality, and long-term sustainability. Infrastructure includes hundreds of boreholes, wells, springs, and a growing network of treatment and distribution facilities, with desalinated water playing a central role in urban supply. Yet coverage remains uneven: rural areas continue to depend on tanker delivery and traditional distribution systems. Surface storage structures, such as reservoirs and dams, are critically impacted by erosion-driven sedimentation, reducing their operational lifespan and storage capacity.

Santiago's hydrogeological vulnerability is shaped by fractured volcanic geology, low recharge rates, and widespread saline intrusion in coastal aquifers. Overextraction, land use pressures, and diffuse contamination further compromise groundwater quality, while episodic extreme rainfall events contribute to rapid runoff, erosion, and limited infiltration. Wastewater and sanitation infrastructure remain underdeveloped, particularly in rural areas, increasing environmental and public health risks. Despite Santiago's role as the political and economic centre of Cape Verde, it continues to face limited water availability, high runoff, saline intrusion, and unequal access. Existing infrastructure, including dams and desalination plants, has mitigated some of these constraints; however, long-term water security depends on improved resource management, upgraded infrastructure, and more equitable distribution systems, especially for vulnerable communities in rural and peri-urban areas.

8- CONCLUSIONS

This report presents a vulnerability assessment of critical water infrastructure systems across six volcanic islands in Macaronesia, designated as demonstrator sites for the GENESIS project: La Palma, Gran Canaria, and El Hierro (Canary Islands); Madeira; Faial (Azores); and Santiago (Cape Verde). Despite differences in geography, demography, and hydrological context, the islands exhibit common exposure patterns and systemic constraints.

8.1. Vulnerability and resilience patterns

All assessed water supply systems are exposed to a range of natural hazards, including volcanic activity, seismic events, landslides, flash flooding, wildfires, coastal hazards, and emerging climate-related stressors such as heatwaves, prolonged droughts, and intensified rainfall variability. These threats directly affect critical components such as desalination plants, coastal wells, groundwater and surface water reserves, conveyance infrastructure, distribution networks, galleries, wells, reservoirs, dams, wastewater treatment plants, and sewerage networks. Common vulnerability drivers include aquifer overexploitation, groundwater salinization, limited surface storage capacity, reliance on energy-intensive pumping, terrain instability, and interdependencies across essential services. In contrast, resilience is supported by decentralised gravity-fed conveyance, aquifer compartmentalisation, cross-zone supply redistribution within the island, and strategically distributed storage reservoirs.

Coastal infrastructure, including desalination plants, coastal wells, and energy-dependent pumping stations, is particularly exposed to marine intrusion, storm impacts, and cascading service disruptions. Groundwater-dependent systems exhibit resource pressure due to overextraction, salinization, and declining recharge rates. In several cases, such as Faial and Santiago, aquifer degradation is further compounded by limited surface storage capacity and insufficient wastewater treatment coverage.

Topographically complex islands such as Madeira, El Hierro, and La Palma face additional challenges associated with landslide-prone terrain and the need to adapt infrastructure to unstable slopes and steep gradients. At the same time, all islands exhibit adaptive features shaped by historical water use practices and physiographic constraints. These include decentralised systems centred on local springs and galleries, gravity-based conveyance networks, and, in some cases, operational redundancies such as multiple distribution reservoirs, pumping infrastructure, and the capacity to transfer water from resource-

abundant zones to areas with higher demand or limited availability. In systems characterised by low population density and fragmented settlement patterns, such as those of El Hierro, Faial, La Palma, and Santiago, efficiency is supported by low overall demand and close proximity between supply sources and consumption areas. Nonetheless, most systems remain sensitive to disruptions affecting critical abstraction points or conveyance corridors.

8.2. Methodological constraints and institutional data gaps

The assessment was shaped by significant variability in data availability, technical documentation, and institutional coordination across the study areas. In the Canary Islands (La Palma, Gran Canaria, and El Hierro), collaboration with local water authorities enabled the development and use of detailed geospatial datasets and infrastructure inventories, allowing full integration with the GENESIS cascading-effects engine. For Madeira, Faial, and Santiago, the analysis relied more heavily on literature review and the generation of new cartographic datasets based on available documentation and partner inputs.

These differences influenced the depth, resolution, and comparability of system characterisations. In several cases, specific infrastructure components were partially documented or not spatially resolved, constraining the granularity of impact evaluations. This variation highlights not only technical and physical limitations but also informational and institutional asymmetries that affect the quality and applicability of resilience planning.

Addressing these disparities requires investment in harmonised infrastructure inventories, integrated monitoring systems, and improved data governance. Strengthening institutional frameworks and supporting local technical capacity will be essential to ensure more equitable and actionable infrastructure risk assessments across Macaronesia, particularly in outermost and resource-constrained regions.

8.3. Application of the GENESIS cascading-effects engine for infrastructure risk prioritisation through scenario modelling

Integration of the GENESIS cascading-effects engine provided critical insight into the dynamics of indirect infrastructure failure. Across all modelled scenarios, including seismic events, coastal flooding, wildfires, and volcanic eruptions, indirect impacts, particularly on irrigation and energy services, frequently exceeded the extent of direct physical damage. Crops were consistently identified as highly sensitive to service losses originating outside agricultural zones, and the area indirectly affected by cascading losses was significantly

larger than the area directly impacted by the initiating hazard. The analysis highlighted high-criticality nodes, such as diesel storage tanks in La Palma or elevation-dependent conveyance systems in El Hierro, whose disruption can trigger system-wide service degradation. In addition, climate projections, particularly for wildfire scenarios under GENESIS 2100 conditions, demonstrated substantial amplification of cascading impacts. The modelling approach thus proved valuable for identifying system-level vulnerabilities, prioritising protection measures, and informing future resilience planning. In future applications, the tool may support stakeholder engagement and preparedness planning by enabling shared understanding of system-wide risk propagation.

8.4. Integrated recommendations for adaptive and resilient water infrastructure management

Strengthening the resilience of critical water infrastructure in Macaronesia requires sustained attention to both long-term resource constraints and hazard exposure, building on existing safeguards while identifying opportunities for targeted improvement. Based on the assessment findings, the following areas merit continued reinforcement and systematic evaluation:

- Ensuring that coastal infrastructure, including desalination plants and seawater intakes, is adequately protected through appropriate siting, structural measures, and the maintenance of sea-defence systems such as wave barriers, elevation buffers, or erosion protection, depending on local risk conditions;
- Evaluating and, where needed, enhancing distribution and contingency reserves storage capacity through the maintenance and strategic siting of reservoirs and potable water reserves;
- Maintaining the operational continuity of energy-dependent water infrastructure by ensuring backup generation capacity, protected transmission, and exploring integration with hybrid backup systems combining diesel and renewables where feasible in critical locations;
- Verifying the structural integrity of pipelines and pumping infrastructure in landslide- and erosion-prone areas, and reinforcing them where hazard mapping or scenario modelling indicates elevated risk;
- Expanding and maintaining automated monitoring of aquifer dynamics, including abstraction levels, salinity trends, and flow variability, to support adaptive resource management and early warning systems;

- Applying and periodically reviewing climate-resilient and hazard-adaptive design standards in infrastructure planning, construction, and rehabilitation processes.

These recommendations should be adapted to the specific environmental conditions, risk profiles, and institutional capacities of each island. Their implementation, supported by cascading-effects modelling insights, harmonised data practices, and strengthened inter-sectoral coordination, can enhance long-term service continuity, increase operational flexibility, and inform proactive risk governance across the Macaronesian region.

The combined findings of this report highlight the interdependence of water, energy, and environmental systems in volcanic island territories. With increasing frequency and intensity of climate-related and geophysical hazards, ensuring the continuity of essential services, particularly those supporting potable water, irrigation, and wastewater management, is central to long-term adaptation and risk management planning. Strengthening resilience will require not only targeted structural measures informed by scenario-based modelling and vulnerability assessments, but also sustained efforts to improve cross-sectoral coordination, expand real-time monitoring capacity, and enhance institutional preparedness, in line with the cascading and interconnected nature of systemic vulnerabilities demonstrated through the GENESIS methodology.

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