genesis

D3.1 Harmonised framework for Pilot evaluation and management

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Executive summary

Macaronesian Islands face acute water security challenges driven by climate change, population growth, and aquifer depletion. The GENESIS project addresses these through geologically-informed nature-based solutions (NbS) demonstrated across five Atlantic Island locations: Faial (Azores), Gran Canaria and El Hierro (Canary Islands), Madeira, and Cape Verde. This deliverable establishes a harmonised framework ensuring systematic, rigorous, and comparable evaluation across all demonstrators, enabling credible evidence generation about which NbS approaches work best under which conditions.

The value of multiple demonstrators depends critically on comparability of results. Without standardised protocols for site characterisation, monitoring, data collection, and performance evaluation, findings from different locations cannot be meaningfully synthesised. This framework provides that standardisation whilst maintaining necessary flexibility for site-specific contexts, covering the complete lifecycle from preliminary characterisation through monitoring installation, implementation, and performance evaluation.

The framework serves six interconnected objectives: enabling meaningful comparison through standardised methodologies; ensuring scientific rigour through quality assurance procedures; facilitating integration across GENESIS Work Packages; supporting adaptive management through systematic monitoring; building institutional capacity through practical guidance; and demonstrating compliance with EU standards including the Water Framework Directive. The framework provides the operational backbone linking all work packages—translating WP2's governance findings into practice, supplying WP4 with standardised hydrological data for modelling, delivering WP5 the cost and performance information for economic valuation, providing WP6 the empirical basis for policy recommendations, and enabling WP7's communication and dissemination activities.

The five demonstrators employ four distinct NbS typologies addressing specific hydrogeological contexts. Managed aquifer recharge through infiltration wells (Faial) suits fractured basalt aquifers with high transmissivity, bypassing limited surface infiltration capacity. Infiltration trenches (Gran Canaria) create hydraulic barriers against seawater intrusion through sustained recharge with reclaimed water from the Jinámar wastewater treatment plant, simultaneously addressing coastal aquifer protection and beneficial wastewater reuse. Surface infiltration basins (Madeira, Cape Verde) restore hydrological connectivity disrupted by urbanisation or capture episodic flows in ephemeral streams, delivering flood attenuation co-benefits alongside groundwater recharge. Multi-compartment well monitoring (El Hierro) enables adaptive management optimising natural compartmentalisation created by geological dikes without new construction.

This deliberate typology spectrum enables comparative assessment of performance, costs, co-benefits, and transferability across the range of conditions characterising Atlantic Islands. The demonstrators span critical contextual gradients including climate (humid Azores to semi-arid Cape Verde), development level (sophisticated infrastructure to resource-constrained contexts), and institutional capacity. The temporal distribution of implementation—El Hierro and Gran Canaria commencing Q1-Q2 2026, Faial and Madeira Q2-Q3 2026, Cape Verde Q4 2027—enables iterative methodology refinement with early learnings informing later implementations.

The assessment protocol balances standardisation against contextual adaptation through six core principles: standardised indicators measured using consistent methodologies; temporal consistency ensuring comparisons reflect genuine performance differences; spatial representativeness capturing key processes; multi-dimensional assessment spanning hydrological, water quality, ecological, social, and economic domains; baseline establishment enabling attribution; and transparency ensuring reproducibility.

Performance evaluation addresses five interrelated dimensions. Hydrological performance quantifies recharge enhancement, aquifer response, and water balance improvements, with demonstrator-specific targets recognising contextual differences. Water quality performance ensures infiltrated water maintains or improves aquifer quality, with parameters reflecting both regulatory requirements and intervention-specific considerations—Gran Canaria emphasises pharmaceuticals and microplastics addressing public concerns about reclaimed water, whilst Faial focuses on detecting saline water mobilisation. Ecological co-benefits assess habitat provision and biodiversity enhancement, particularly relevant for Madeira's urban demonstrator providing educational value and recreational amenity. Social acceptability tracks stakeholder perceptions and participatory engagement, building on WP2 baseline surveys establishing greater than 70% acceptability across all regions. Economic performance addresses whether NbS deliver water security at costs competitive with conventional alternatives, with demonstrator-specific benefits ranging from avoided desalination costs to flood damage reduction to agricultural productivity improvements.

Smart monitoring networks integrate automated sensors, cloud connectivity, and real-time visualisation providing continuous information whilst minimising manual labour. Network design addresses spatial coverage (upstream-downstream configuration, recharge zone coverage, depth profiling), temporal resolution (continuous hourly for critical parameters, periodic automated for stable dynamics, campaign-based for laboratory analyses), redundancy ensuring data continuity, and integration with existing networks where feasible.

The five demonstrators employ distinct equipment configurations reflecting operational contexts. Faial uses autonomous pressure transducers with monthly manual downloads appropriate for remote locations. Gran Canaria deploys multiparameter sondes, billing-grade flow meters, and real-time cellular telemetry through existing infrastructure. El Hierro employs three electromagnetic flow meters (one per compartment) with telecontrol system under development enabling real-time monitoring. Madeira features comprehensive vadose zone monitoring with fibre optic connectivity. Cape Verde uses portable meters with quarterly manual collection, balancing essential data acquisition with resource constraints.

Monitoring programmes balance comprehensive characterisation against practical constraints, with continuous automated monitoring capturing dynamic processes, monthly sampling campaigns providing water quality characterisation, and quarterly to annual surveys addressing expanded parameters and social acceptability. Quality assurance procedures ensure data meet accuracy and completeness standards through automated screening, manual review, and laboratory accreditation.

Implementation protocols provide standardised approaches ensuring demonstrators deliver intended performance whilst generating lessons informing future implementations. Design documentation requirements span conceptual design reports, detailed design packages, and as-built documentation. Construction and commissioning standards address contractor selection, quality control, functional testing, and operator training. Operational management employs routine procedures varying by typology, decision-making frameworks responding to monitoring evidence, and sustained stakeholder engagement.

Adaptive management embraces uncertainty through structured cycles of implementation, monitoring, evaluation, and adjustment. Performance-based triggers (consistent shortfalls exceeding 20% below targets, unexpected responses), regulatory compliance issues, stakeholder feedback, and external conditions (extreme events, land use changes) prompt diagnostic investigations identifying causes and potential modifications. Governance follows WP2 frameworks with minor adjustments under site manager authority, moderate modifications requiring stakeholder consultation, and major changes engaging full governance processes.

The framework explicitly supports replication through comprehensive documentation, transferable methodologies, and sustained engagement with prospective replicators. European and global replicators are being recruited through EFG and ALDA networks spanning eight EU regions, eighteen associations of local authorities, twenty-one municipalities, and eighteen geoscience organisations. Three replicator regions—Santa Maria and Graciosa (Azores) and La Réunion—are represented as formal consortium partners. Knowledge transfer activities include training, demonstration site visits, participation in GENESIS meetings, and access to the NbS data platform.

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1 Introduction

1.1 Background and rationale

Macaronesian Islands face acute and intensifying water security challenges driven by climate change, population growth, tourism pressure, and aquifer depletion. These volcanic island systems, characterised by limited surface water resources and heavy dependence on groundwater, require innovative approaches to enhance water storage, improve recharge, and build resilience against increasing climatic variability. Nature-based solutions (NbS) offer ecosystem-based approaches that can augment conventional water infrastructure whilst delivering multiple co-benefits including biodiversity conservation, erosion control, landscape restoration, and climate adaptation.

The GENESIS project—Geologically Enhanced Nature-based Solutions for Climate Change Resiliency of Critical Water Infrastructure—addresses these challenges through demonstration of geologically-informed NbS across four Macaronesian archipelagos: the Azores (Portugal), Canary Islands (Spain), Madeira (Portugal), and Cape Verde. Work Package 3 establishes demonstration sites (called demonstrators) where diverse NbS interventions will be implemented, monitored, and evaluated under varying geological, hydrological, and climatic conditions. These demonstrators serve as living laboratories generating empirical evidence about NbS performance whilst building regional capacity and demonstrating feasibility to stakeholders and decision-makers.

However, the value of multiple demonstrators depends critically on comparability of results. Without standardised protocols for site characterisation, monitoring design, data collection, and performance evaluation, findings from different locations cannot be meaningfully synthesised to generate robust conclusions about which NbS approaches work best under which conditions. Inconsistent methodologies would limit learning, reduce credibility of results, and undermine the project's contribution to advancing NbS practice in island contexts globally.

This deliverable establishes a harmonised framework for demonstrator site evaluation and management that ensures systematic, rigorous, and comparable assessment across all GENESIS demonstrators. The framework provides standardised protocols whilst allowing necessary flexibility to address site-specific geological, hydrological, and operational contexts. It covers the complete lifecycle from preliminary site characterisation through monitoring network installation, data collection and management, NbS implementation, and performance evaluation. By establishing common standards, the framework enables GENESIS to generate credible, comparable evidence about NbS effectiveness that can inform water management policy and practice across Macaronesia and similar island contexts worldwide.

1.2 Objectives of the harmonised framework

The harmonised framework serves multiple interconnected objectives essential for achieving GENESIS Work Package 3 goals:

- **Enable meaningful comparison of results across demonstrators.** By standardising assessment methodologies, performance indicators, and data collection protocols, the framework ensures that findings from the Azores can be directly compared with results from the Canary Islands, Madeira, and Cape Verde. This comparability allows identification of patterns, context-dependent factors influencing performance, and transferable lessons applicable across diverse island settings.

- **Ensure scientific rigour and credibility of evidence**. The framework establishes quality assurance and quality control procedures, calibration protocols, and data validation methods that ensure technical soundness of results. Rigorous methodology is essential for generating evidence that water authorities, funding agencies, and policy-makers will consider credible when making investment decisions about NbS deployment.
- **Facilitate integration and synthesis across Work Packages**. The framework connects directly to participatory governance models developed in WP2, providing protocols for stakeholder engagement in monitoring and adaptive management. It generates data that will inform hydrological modelling in WP4, economic valuation in WP5, and policy recommendations in WP6. Standardised data structures and documentation enable efficient integration across analytical activities.
- **Support adaptive management and continuous improvement**. By establishing systematic monitoring protocols and explicit performance evaluation criteria, the framework enables early detection of challenges, identification of necessary adjustments, and iterative refinement of NbS designs and operational procedures. Adaptive management is essential given uncertainties about novel interventions in understudied hydrogeological settings.
- **Build institutional capacity and knowledge transfer**. The framework provides practical guidance that consortium partners and local stakeholders can implement, building technical competence in site characterisation, monitoring design, and data management. Standardised approaches facilitate training, knowledge exchange between sites, and eventual transfer of methods to new contexts beyond GENESIS demonstrators.
- **Demonstrate compliance with EU standards and best practices**. The framework aligns with relevant EU directives including the Water Framework Directive, Groundwater Directive, and emerging guidance on managed aquifer recharge. It incorporates internationally recognised standards for environmental monitoring, data management (FAIR principles), and quality assurance, ensuring GENESIS results meet expectations for EU-funded research.

1.3 Linkages within Genesis

The harmonised framework for demonstrator site evaluation and management provides the operational backbone of GENESIS, linking the Work Packages and ensuring coherent implementation. It translates WP2’s findings on inclusive and adaptive governance into practice by embedding participatory monitoring, integrating social acceptability indicators, and involving stakeholders in data interpretation and adaptive management.

The framework supplies WP4 with the standardised hydrological data needed to model groundwater recharge, aquifer responses and water balance dynamics under different climate scenarios. Consistent data formats and monitoring protocols allow models to be calibrated and compared across sites, supporting robust scenario analysis.

For WP5, the framework delivers the cost, performance and ecological information required for economic and environmental valuation. It ensures that implementation costs, maintenance needs, ecosystem service benefits and social acceptability are documented in a comparable way, enabling cross-site assessment of cost-effectiveness.

The evidence generated also underpins WP6, providing the empirical basis for policy recommendations and upscaling strategies. Standardised evaluation helps identify which NbS approaches perform best under specific conditions, while documentation of challenges and enabling factors informs guidance on regulation, financing and capacity building.

WP7 draws on the monitoring results for communication and dissemination, with standardised reporting supporting comparative analyses, visual materials and open data practices.

The framework also links project phases vertically: site characterisation informs design; monitoring installation aligns with construction; and performance evaluation feeds into adaptive management and decisions on scaling. This integrated approach ensures that demonstrator sites operate as dynamic learning environments rather than static technical showcases.

2 Demonstrators characterisation

The GENESIS project implements its harmonised framework across five Atlantic Island demonstrators spanning the Macaronesian archipelagos—Azores (Faial), Canaries (Gran Canaria and El Hierro), Madeira, and Cape Verde. These demonstrators represent distinct hydrogeological contexts and nature-based solution approaches, offering complementary insights into groundwater management challenges facing volcanic island territories under increasing water stress. This chapter establishes the foundation for applying the assessment protocols defined in Chapter 3 and implementing the monitoring programmes detailed in Chapter 4.

2.1 NbS typologies and site selection

The GENESIS demonstrators employ four distinct nature-based solution typologies, each addressing specific hydrogeological contexts and water management objectives. Understanding the rationale behind typology selection enables transferability assessment and guides adaptation to other Atlantic Island contexts sharing similar challenges.

2.1.1 Aquifer recharge through infiltration wells

The infiltration well approach suits volcanic island contexts where fractured basalt aquifers provide high transmissivity but limited storage capacity. This geological configuration enables rapid transmission of infiltrated water through fracture networks whilst offering substantial void space within fracture systems and inter-lava flow contacts. Infiltration wells access deeper aquifer zones than surface infiltration methods, directly injecting water into saturated formations where storage potential is greatest and evaporation losses are eliminated [1, 2].

This typology proves particularly valuable where surface soils exhibit limited infiltration capacity due to compaction, fine-grained weathering products, or shallow restrictive layers. By bypassing the unsaturated zone, infiltration wells enable managed aquifer recharge even where surface infiltration would prove inefficient. The approach also minimises land area requirements compared to infiltration basins, an important consideration on islands where flat terrain suitable for surface infiltration is scarce and often committed to agriculture or development.

Site selection criteria for infiltration wells integrate multiple factors: aquifer transmissivity sufficient to accept injection volumes without excessive mounding, aquifer storage capacity adequate to retain injected water until natural discharge or planned abstraction occurs, proximity to water sources during surplus periods, and distance from abstraction points sufficient to prevent short-circuiting. Geophysical surveys characterise these subsurface properties, whilst hydrogeological testing quantifies hydraulic parameters and injection well design calculations determine required depths, screen intervals, and anticipated injection rates [3-5].

This typology is implemented at the Faial (Azores) demonstrator, where fractured basaltic formations provide excellent transmissivity but surface soils show limited infiltration capacity. The approach addresses groundwater sustainability challenges whilst minimising land requirements in an agricultural landscape.

2.1.2 Infiltration trenches for coastal protection

The infiltration trench typology specifically addresses coastal aquifer salinisation, where creating positive hydraulic gradients through inland recharge counteracts seawater intrusion driven by over-abstraction. This approach requires sustained recharge volumes sufficient to alter regional hydraulic gradients, typically necessitating non-conventional water sources such as reclaimed wastewater, desalinated seawater, or imported surface water—resources that conventional infiltration basins relying on episodic stormwater cannot provide [4].

Infiltration trenches distribute recharge across linear features, creating barrier conditions that intercept seaward groundwater flow and redirect it toward abstraction zones requiring protection. The trench configuration maximises contact area between infiltrating water and aquifer materials, promoting efficient transmission into saturated zones whilst enabling inspection and maintenance access throughout the recharge distribution system. This approach offers greater reliability than point-source injection wells, where clogging or equipment failure affects entire system capacity, whilst avoiding the extensive land requirements of infiltration basins.

Site selection criteria must consider proximity to reclaimed water supply infrastructure, positioning relative to threatened abstraction wells, and hydraulic properties enabling efficient infiltration. Optimal locations intercept seawater intrusion pathways before they reach critical production wells, minimising conveyance distance from treatment facilities. Underlying geological conditions—permeable sediments overlying fractured volcanic rocks—facilitate vertical percolation and subsequent lateral transmission toward protected aquifer zones.

This typology is implemented at the Gran Canaria demonstrator, where the site's location between the Jinámar wastewater treatment plant and the coastal aquifer provides optimal positioning for intercepting seawater intrusion whilst enabling beneficial reuse of reclaimed water.

2.1.3 Surface infiltration basins for distributed recharge

Surface infiltration basins suit contexts where surface runoff from urban areas or ephemeral streams provides intermittent but substantial water volumes. This typology mimics natural recharge processes disrupted by urbanisation or land use changes, restoring hydrological connectivity through engineered landscape features that promote infiltration whilst providing co-benefits including flood attenuation, water quality improvement, and urban amenity.

Basin design balances multiple objectives beyond groundwater recharge: temporary storage volume sufficient for flood peak attenuation, infiltration capacity enabling basin recovery between storm events, sediment trapping that protects aquifer quality without excessive clogging, and landscape integration supporting ecological and social functions. This multi-functional approach reflects contemporary understanding that nature-based solutions deliver greatest value when designed for multiple services rather than single-purpose optimisation.

Site selection criteria for infiltration basins require level terrain or moderate slopes amenable to economical earthwork, soils with adequate infiltration capacity, locations capturing runoff from contributing catchments before conveyance to receiving waters, and sufficient distance from structures to prevent foundation saturation or stability concerns. In urban contexts, site selection must also consider land availability, ownership patterns, and integration with urban planning objectives, whilst in semi-arid contexts, ephemeral stream positioning determines basin locations [6-9].

This typology is implemented at two demonstrators addressing different contexts. Madeira's demonstrator captures highland stream water before it reaches the urbanised coast, reducing flood risks whilst enhancing recharge. Cape Verde's demonstrator employs multiple infiltration lagoons along the Ribeireta ephemeral stream system, capturing episodic runoff events for groundwater recharge in a water-scarce environment.

2.1.4 Multi-compartment well monitoring as virtual NbS

This approach illustrates that nature-based solutions extend beyond physical infrastructure to encompass adaptive management systems that optimise existing natural capital. The multi-compartment well monitoring typology does not construct new recharge pathways but rather enables more sophisticated exploitation of natural compartmentalisation created by geological dikes. This ”virtual” nature-based solution recognises that improving understanding and management of natural hydrogeological features can deliver water security benefits comparable to physical interventions whilst avoiding construction impacts.

This approach suits contexts where aquifer heterogeneity creates distinct groundwater compartments with varying recharge rates, residence times, and quality characteristics. Independent monitoring of each compartment enables adaptive abstraction management—preferentially drawing from compartments experiencing favourable recharge whilst reducing pressure on stressed units. This optimisation potentially extends overall aquifer yield whilst reducing environmental impacts compared to undifferentiated mixed abstraction.

Site selection criteria include existing infrastructure with access to multiple aquifer compartments, institutional capacity for adaptive management responding to monitoring evidence, and stakeholder willingness to adjust abstraction patterns based on real-time conditions. The approach proves particularly valuable where geological structures create natural compartmentalisation and where existing wells can be retrofitted with monitoring systems more economically than constructing new recharge infrastructure [10, 11].

This typology is implemented at the El Hierro demonstrator, where geological dikes create three hydraulically-independent aquifer compartments accessed by a single well. Enhanced monitoring enables adaptive management of abstraction rates from each compartment based on recharge conditions and quality parameters.

2.1.5 Typology selection framework

Selecting appropriate nature-based solution typologies for new contexts should consider hydrogeological conditions, water availability patterns, land constraints, institutional capacity, and stakeholder priorities through systematic multi-criteria assessment. High transmissivity fractured rock aquifers favour injection wells, coastal salinisation threats indicate barrier recharge systems, intermittent surface water availability suits infiltration basins, and existing infrastructure heterogeneity may enable monitoring-enabled optimisation.

The GENESIS demonstration portfolio spans this typology spectrum deliberately, enabling comparative assessment of performance, costs, co-benefits, and transferability across the range of conditions characterising Atlantic Islands. Lessons learned from these demonstrations—quantified through the monitoring programmes detailed in Chapter 4 and assessed via the protocols established in Chapter 3—will inform typology selection guidance for water managers facing similar challenges across Macaronesia and beyond.

Understanding not just the technical performance but also the social acceptability, institutional requirements, and co-benefit delivery of different typologies will prove essential for mainstreaming nature-based solutions into Atlantic Island water management practice [12-15]. The GENESIS demonstrators therefore serve not merely as technical pilots but as learning platforms advancing both scientific understanding and practical implementation capacity for this diverse family of sustainable water management approaches.

2.2 Overview of GENESIS demonstrators

The five GENESIS demonstrators progress through different stages of development, from completed permitting and advanced procurement in El Hierro, to pre-construction design in Faial, Gran Canaria and Madeira, to conceptual planning in Cape Verde. This temporal distribution enables the project to refine methodologies iteratively, with early learnings from more advanced demonstrators informing approaches at later-stage implementations. Each demonstrator addresses specific water security challenges through tailored nature-based solutions whilst contributing to the broader objective of developing transferable frameworks for Atlantic Island water management.

2.2.1 Faial

Context

The Faial demonstrator addresses groundwater sustainability in a volcanic island context where existing abstraction threatens the delicate balance between freshwater resources and seawater intrusion. The island's geology, characterised by fractured basaltic formations and pyroclastic deposits, creates complex groundwater flow patterns that require detailed characterisation before implementing managed aquifer recharge interventions.

Rationale

Infiltration wells were selected for Faial based on three critical factors: first, the fractured basalt aquifer exhibits high transmissivity enabling efficient water transmission through fracture networks; second, surface soils show limited infiltration capacity due to fine-grained weathering products and compaction; and third, land constraints in this agricultural landscape favour the small footprint of infiltration wells over extensive surface infiltration basins. This typology bypasses surface soil limitations whilst directly accessing the aquifer system.

Planned Nature-based Solution

The demonstrator will establish a managed aquifer recharge system using infiltration wells to enhance groundwater replenishment during periods of surplus rainfall. The intervention aims to increase storage capacity within the natural aquifer system, improving water security during dry periods whilst reducing pressure on existing abstraction points. The infiltration well(s) will be strategically located in the vicinity of the Cancelas well, a site selected for its favourable hydrogeological properties and accessibility for monitoring and operational management.

Geophysical survey programme

Understanding subsurface conditions requires comprehensive geophysical investigation to define the optimal location for infiltration wells with precision [16, 17]. LNEG (Laboratório Nacional de Energia e Geologia) has designed a survey combining two complementary techniques to maximise interpretive confidence (Figure 2.1). The programme comprises two long profiles of Electrical Resistivity Tomography (ERT) and 57 Time Domain Electromagnetics (TDEM) soundings across the study area.

The survey design strategically leverages existing information, which varies significantly across the demonstrator area. In the westernmost area, data availability is limited to sparse well logs, whilst the easternmost area benefits from historical geoelectrical data including vertical electrical soundings with dipole-dipole and Schlumberger arrays, alongside borehole descriptions and geophysical logs. The survey profiles and sounding locations have been positioned to integrate these datasets, creating a comprehensive subsurface model that spans areas of both data abundance and scarcity.

The geophysical survey contract has been signed by LNEG, with fieldwork scheduled to commence on 19 January 2026. This timeline reflects necessary coordination with multiple stakeholders, including obtaining permissions from landowners and ensuring adequate personnel from the Municipality of Horta (Câmara Municipal da Horta, CMH) to maintain safe working conditions for both field crews and livestock. The survey involves high-voltage electrical equipment, requiring careful safety management and stakeholder communication throughout the data acquisition period.

Procurement status

CMH is advancing procurement for the infiltration well construction through established public contracting procedures. The tender documentation is substantially complete, including the specification document and invitation to tender. However, launching the formal procurement requires completion of three critical technical documents currently in preparation: the detailed execution project with technical clauses, the health and safety plan, and the construction and demolition waste prevention and management plan. These documents are expected to be finalised by the end of December 2025, enabling tender launch in early 2026.

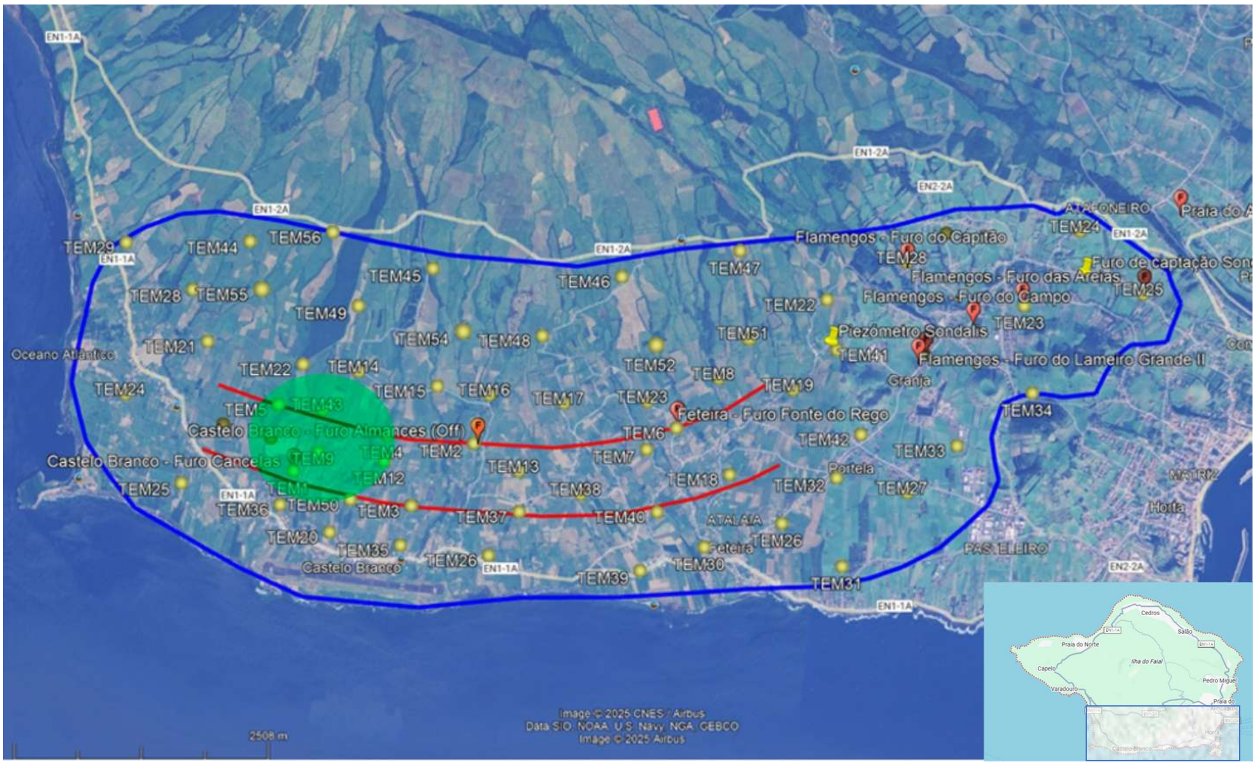

Figure 2.1: Aerial photograph showing the approximate location of the infiltration wells that would be constructed (green area) in Faial and the area covered by geophysical surveys (no scale).

Baseline monitoring requirements

The demonstration will focus monitoring efforts on the hydrological parameters most critical for assessing managed aquifer recharge performance. Piezometric levels constitute the primary indicator of aquifer response to infiltration, revealing both the spatial extent of recharge influence and the temporal dynamics of groundwater mounding and dissipation. Electrical conductivity measurements provide essential information on water quality changes, particularly detecting any mobilisation of stored salinity or intrusion of seawater that might occur as hydraulic gradients shift.

Monitoring equipment will consist primarily of autonomous data loggers combining pressure transducers for water level measurement with electrical conductivity sensors. These instruments enable continuous high-frequency data acquisition without requiring permanent power supply or telemetry infrastructure, appropriate for the installation's remote location. The selected instrumentation provides accuracy of ±0.5 cm for water levels and ±1% for electrical conductivity across the expected measurement ranges, meeting the performance specifications established in Chapter 4.

Land ownership and permitting

The installation site falls within the CMH jurisdiction, with the Municipality serving as both implementation authority and land manager for public domain areas. Ongoing coordination with private landowners addresses access rights for geophysical survey activities and subsequent construction access corridors. This collaborative approach ensures community support for the demonstration whilst respecting property rights and local livelihoods, particularly agricultural activities that characterise the landscape.

2.2.2 Gran Canaria

Context

The Gran Canaria demonstration addresses the critical challenge of coastal aquifer salinisation through artificial recharge with reclaimed water. The site is located in the island's eastern coastal zone, where intensive groundwater abstraction has created hydraulic conditions favouring seawater intrusion. This situation exemplifies a common threat facing many Atlantic Island aquifers, where limited recharge and growing demands have pushed exploitation beyond sustainable limits.

Rationale

Infiltration trenches were selected for Gran Canaria based on the specific need to create a hydraulic barrier against seawater intrusion. Unlike infiltration basins or wells that provide localised recharge, the linear trench configuration distributes recharge across a barrier positioned between the coastline and threatened abstraction wells. The availability of high-quality reclaimed water from the nearby Jinámar wastewater treatment plant enables sustained year-round recharge, essential for maintaining the hydraulic gradient necessary to repel seawater intrusion. This typology addresses both coastal aquifer protection and beneficial wastewater reuse, delivering multiple water management objectives simultaneously.

Planned Nature-based Solution

The intervention will construct infiltration trenches designed to recharge the coastal aquifer with high-quality reclaimed water from the Jinámar wastewater treatment plant. This approach simultaneously addresses two pressing water management challenges: reducing pressure on freshwater aquifers by providing an alternative supply source, and managing treated wastewater through beneficial reuse rather than ocean discharge. The infiltration system will be connected to the existing reclaimed water distribution network, enabling controlled injection rates responsive to both aquifer conditions and treatment plant output.

Design progress

Baseline conditions for the coastal aquifer have been established through an initial sampling campaign at identified monitoring points. This foundational dataset characterises current water quality parameters and hydraulic conditions against which recharge impacts can be assessed. Concurrently, the project team has compiled and processed reclaimed water quality data from the Jinámar treatment plant, evaluating its suitability for aquifer injection and identifying any parameters requiring attention during operational management (Figure 2.2).

The infiltration trench locations have been defined based on hydrogeological assessments and infrastructure constraints, with the connection point to the reclaimed water distribution network confirmed. The project has progressed to on-site staking-out, physically marking the positions of inspection chambers, pipelines, and ancillary infrastructure elements. This detailed field layout enables final verification of design assumptions and ensures construction can proceed efficiently once permits are secured (Figure 2.3).

Water quality monitoring programme

The demonstrator will implement comprehensive water quality monitoring spanning three critical points: the reclaimed water supply, the infiltration system, and the receiving aquifer. At the Jinámar treatment plant, routine monitoring occurs approximately every two weeks, measuring parameters including E. coli, pH, electrical conductivity at 25°C, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solids, turbidity, free residual chlorine, ammonium, nitrate, nitrite, total nitrogen, and total phosphorus. This monitoring frequency ensures early detection of any treatment performance variations that might affect aquifer recharge quality.

Every two years, the treatment plant effluent undergoes expanded characterisation including hardness, calcium, magnesium, fluorides, arsenic, cadmium, zinc, toluene, tributyltin, dioxins and furans, and naphthalene. This comprehensive suite addresses regulatory requirements for discharge to sensitive receiving environments, providing assurance that reclaimed water meets stringent quality standards before aquifer injection.

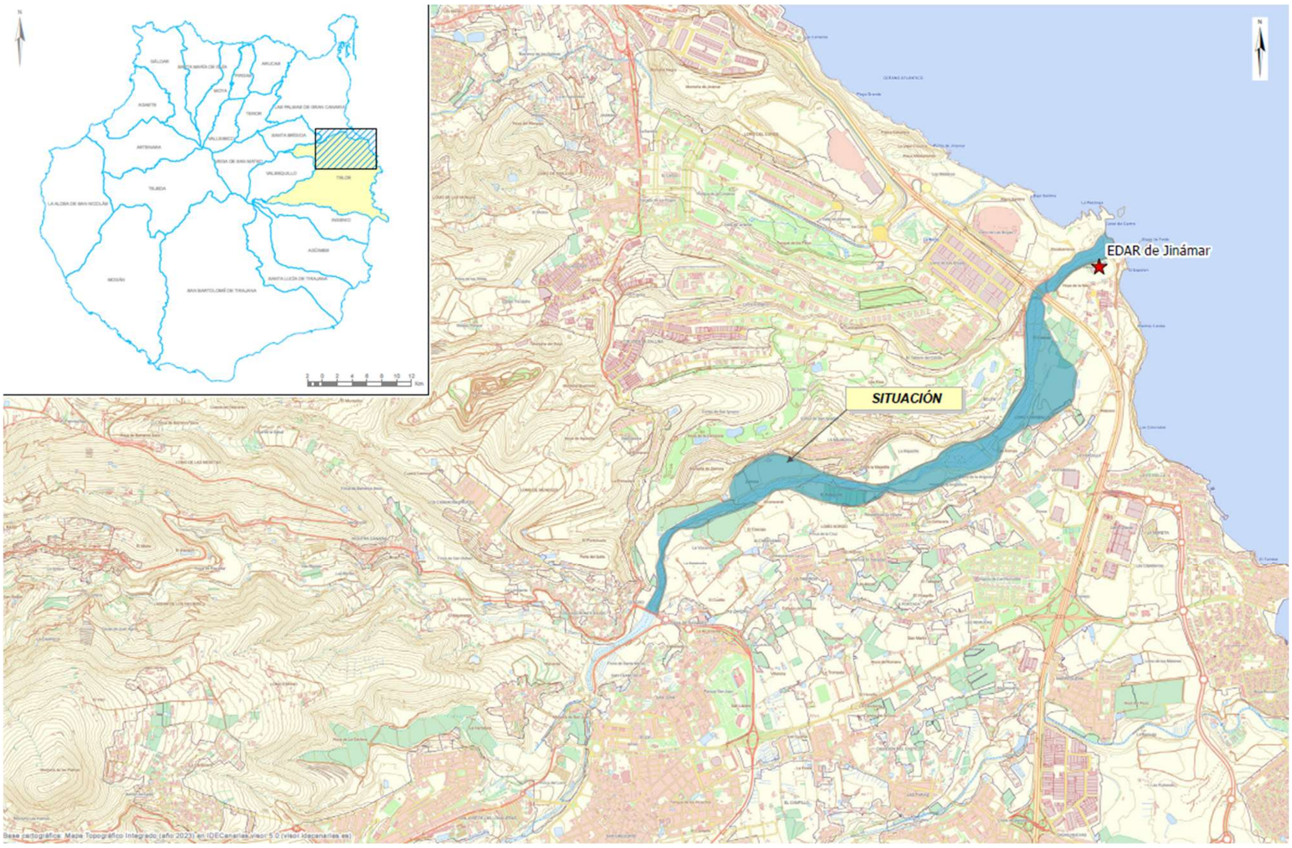

Figure 2.2: Topographic map of Gran Canaria showing the location of the water treatment plant and the basin where the infiltration trenches would be constructed (scale 1:20,000).

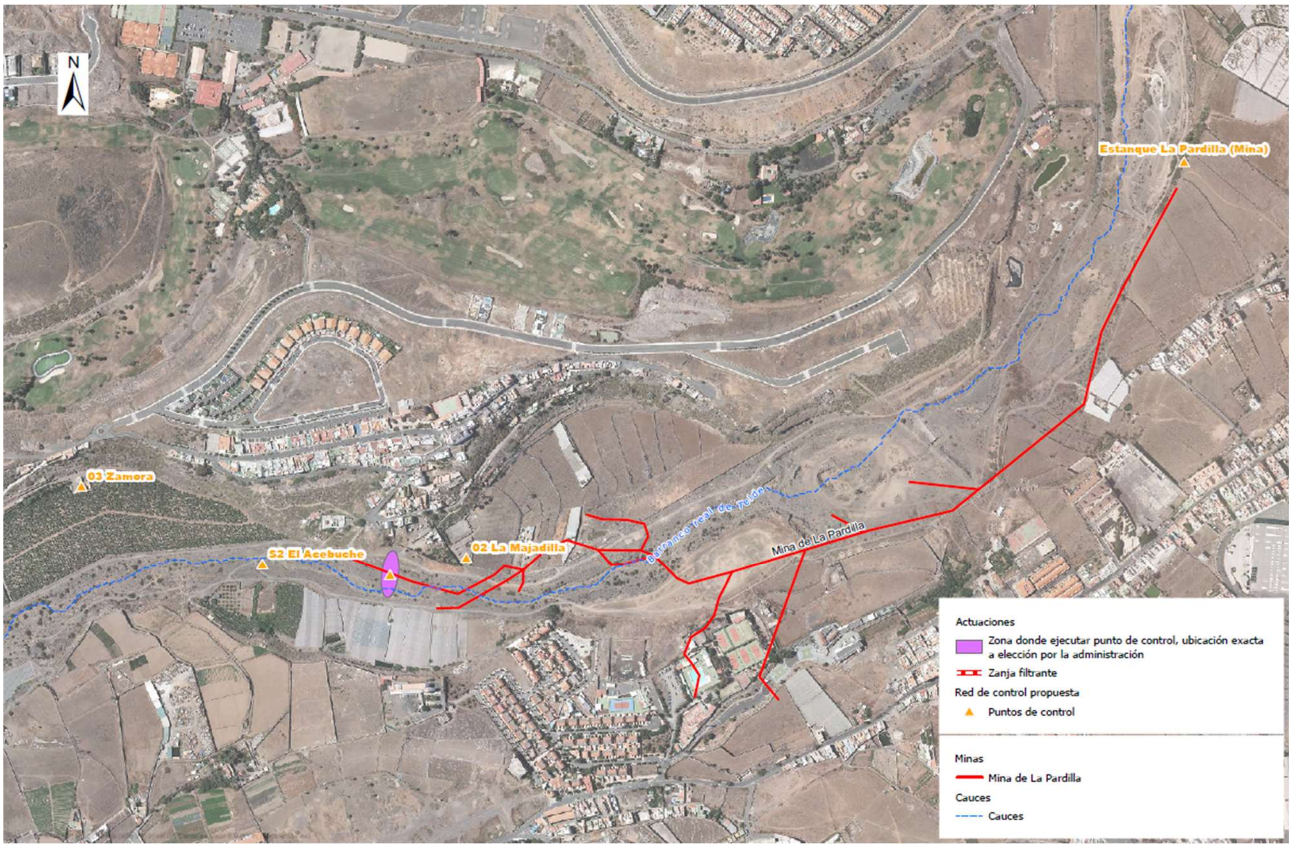

Figure 2.3: Aerial photograph map showing the location of the infiltration trenches and monitoring wells to be constructed (scale 1:5,000).

For all monitoring points including groundwater sampling locations, additional parameters will be measured at frequencies to be defined during operational planning. These include sodium, sodium adsorption ratio (SAR), chlorides, boron, sulphates, total organic carbon (COT), lead, potassium, bicarbonates, carbonates, settleable materials, mercury, orthophosphates, tetrachloroethylene (perchloroethylene), trichloroethylene, and total iron [18-20]. Special attention will be given to emerging contaminants of concern, including pharmaceuticals (diclofenac, caffeine, nicotine, erythromycin), pesticides (polar compounds including glyphosate), and microplastics (particularly PVC) [21]. This expanded monitoring programme reflects contemporary understanding of potential aquifer impacts from managed recharge with reclaimed water.

Critically, a sampling point will be incorporated directly at the injection point where water enters the infiltration trenches. This measurement location enables real-time verification of injection water quality and provides essential data for interpreting any changes observed in downstream aquifer monitoring wells.

Monitoring infrastructure

Following completion of construction works, the primary monitoring equipment will consist of water meters measuring injection volumes and flow rates. These instruments provide the operational data necessary for calculating recharge efficiency and managing injection operations within sustainable limits. The flow measurement system will integrate with the broader monitoring network described in Chapter 4, enabling correlation between injection volumes and aquifer response.

Land ownership and permitting

The infiltration installation will be constructed within the Hydrologic Public Domain, with the Water Council of Gran Canaria (Consejo Insular de Aguas de Gran Canaria) serving as both landowner and licensing authority (Figure 2.3). The Council has issued a formal communication confirming compatibility of the proposed intervention with the Insular Hydrologic Plan, representing a critical milestone in the permitting process. The project currently awaits final authorisation for occupation of the public domain, expected to be granted following standard administrative procedures.

This institutional arrangement, where water management authority and land ownership coincide, streamlines coordination and ensures alignment between the demonstration activities and broader island water resource planning. The integration within existing governance frameworks exemplifies the collaborative approach established in GENESIS WP2, facilitating knowledge exchange between research activities and operational water management entities.

2.2.3 El Hierro

Context

The El Hierro demonstrator implements innovative monitoring of a multi-compartment abstraction well serving a volcanic island with limited groundwater resources. The installation exploits three independent aquifer compartments, hydraulically separated by geological dikes—natural barriers formed during volcanic evolution that create distinct groundwater bodies with differing recharge rates and quality characteristics. Understanding and managing these compartments independently offers potential for optimising abstraction whilst minimising impacts on each aquifer unit.

Rationale

The multi-compartment monitoring approach was selected for El Hierro because the existing infrastructure already accesses three distinct aquifer compartments through a single well. Rather than constructing new recharge infrastructure, this typology leverages natural geological compartmentalisation to enhance water security through adaptive management. The approach recognises that optimising use of existing natural capital can deliver benefits comparable to physical interventions whilst avoiding construction costs, land requirements, and environmental disturbance. This virtual NbS proves particularly appropriate given El Hierro's limited land availability and the presence of infrastructure that can be enhanced through improved monitoring and operational sophistication.

Planned Nature-based Solution

Whilst the well infrastructure is already operational, the GENESIS intervention focuses on establishing comprehensive real-time monitoring that enables adaptive management of abstraction rates from each compartment. This approach transforms a conventional pumping installation into a sophisticated water resource management tool, where operational decisions respond to actual hydraulic and quality conditions rather than fixed schedules. The monitoring system creates opportunities for preferential abstraction from compartments experiencing favourable recharge whilst reducing pressure on those showing stress indicators.

Additionally, infiltration testing in recharge areas, combined with climate projections extending to 2100 (including precipitation, temperature, and evapotranspiration scenarios), enables simulation of well behaviour under future climate conditions. These analyses support calculation of safe abstraction yields accounting for climate change, providing design guidance applicable to similar volcanic island infrastructures facing uncertain hydrological futures.

Monitoring system

The monitoring system will continuously measure four critical parameters in each of the three aquifer compartments: electrical conductivity, temperature, pressure, and discharge (flow rate). This configuration enables detailed assessment of both water quality and hydraulic performance across the independent extraction zones, revealing how each compartment responds to pumping stress and natural recharge variations.

The monitoring infrastructure comprises three flow meters, three pressure sensors (manometers), and three temperature and water quality sensors—one complete set for each compartment. Additionally, one sensor installed approximately one year prior to project commencement continues recording conductivity and temperature of the mixed water from all three compartments, providing valuable baseline data characterising integrated system performance before compartment-specific monitoring begins.

Beyond the well installation itself, surrounding wells and boreholes are also being monitored using temperature, water level, and conductivity sensors. This expanded monitoring network reinforces hydrogeological understanding of the system, revealing regional groundwater dynamics that influence the multi-compartment well's performance and providing early warning of potential impacts on neighbouring abstractions.

Implementation status

The sensor monitoring mixed water from the three compartments has been operational for approximately one year, accumulating a valuable baseline dataset characterising integrated system performance. A technical site visit has been completed to define the civil works and technical requirements necessary for installing the nine new monitoring devices that will enable compartment-specific measurements.

The project currently awaits procurement of monitoring equipment, with delivery expected to require up to three months due to international logistics, customs procedures, and transport to this small island location. Minor civil works facilitating sensor installation are planned for January–February 2026, with final equipment installation anticipated around March 2026 once sensors arrive.

The telecontrol and data transmission system enabling real-time remote access to monitoring data requires a specific technical project, currently under development in parallel with equipment procurement. This system will integrate the El Hierro installation into the broader GENESIS data platform described in Section 4.3.4, enabling comparative analysis across demonstrators and facilitating knowledge exchange with water managers facing similar challenges on other Atlantic Islands.

Land ownership and permitting

The installation is of public ownership, belonging to the Island Water Council of El Hierro (Consejo Insular de Aguas de El Hierro), whilst operational management is carried out by a local irrigation community representing water users. This collaborative governance structure aligns operational decisions with stakeholder needs whilst maintaining public authority oversight of resource sustainability—a model reflecting the participatory water management frameworks explored in GENESIS WP2.

All required permits have been secured, including general administrative authorisations and the specific approval issued by the Mining Engineer responsible for the installation under Spanish Mining Law (Ley de Minas). From a regulatory perspective, the installation is fully authorised for the planned monitoring works, enabling the project to proceed directly to procurement and installation activities without administrative delays.

2.2.4 Madeira

Context

The Madeira demonstrator addresses urban water management challenges in the Municipality of Funchal, where impervious surfaces limit natural infiltration and concentrate stormwater runoff. Highland streams carry substantial flows that reach the urbanised coast rapidly, creating flood risks whilst representing lost opportunities for groundwater recharge. The intervention aims to enhance groundwater recharge by capturing this highland water before it reaches urban areas, whilst reducing downstream flooding risks.

Rationale

Surface infiltration basins were selected for Madeira based on the availability of intermittent but substantial surface water flows from highland streams, combined with the multiple co-benefits this typology delivers in urban contexts. Unlike infiltration wells that serve solely recharge functions, surface basins provide visible landscape features offering educational value, recreational amenity, and ecological habitat whilst delivering primary water management services. The urban setting benefits from this multi-functional approach, justifying land allocation and building community support through diverse value delivery. Additionally, the availability of suitable topography and land ownership by the Municipality of Funchal simplified site selection and permitting processes.

Planned Nature-based Solution

The project will construct a retention and infiltration basin designed to capture water from the initial reaches of torrential streams originating in the highlands (Figure 2.4) and promote gradual infiltration into underlying aquifers. This approach mimics natural recharge processes, creating hydrological connectivity between highland surface water flows and groundwater whilst providing temporary storage capacity that attenuates flood peaks during intense rainfall events.

The basin design integrates landscape and ecological functions, creating amenity value whilst delivering water management services. This multi-functional approach reflects contemporary understanding that NbS achieve multiple co-benefits beyond their primary engineering objectives, contributing to climate adaptation, biodiversity enhancement, and community wellbeing.

Design and procurement progress

The topographic survey of the construction site has been completed, providing the detailed elevation data necessary for final basin design and earthwork calculations. The University of Madeira (UMA) has launched a tender for the elaboration of the construction project, which will produce the detailed engineering drawings, specifications, and cost estimates required for proceeding to construction procurement. This phased approach enables expert input during the design phase whilst maintaining competitive bidding for construction services.

Figure 2.4: Topographic map showing the approximate location (red square) where the retention and infiltration basin would be constructed (scale 1:25,000).

Monitoring infrastructure

The demonstration will monitor parameters spanning the complete hydrological cycle from atmospheric inputs through surface storage to subsurface infiltration and downstream emergence. Precipitation measurement establishes the water balance input term, essential for calculating infiltration efficiency and assessing basin performance across varying storm characteristics. Temperature and evaporation data quantify atmospheric losses, refining water balance calculations and enabling assessment of seasonal performance variations.

Infiltration rate measurements within the basin characterise the rate at which captured stormwater percolates into underlying soils and aquifers, revealing whether performance meets design expectations and identifying any clogging issues requiring maintenance intervention. Discharge and flow measurements from the Tornos tunnel—a downstream groundwater emergence point—enable assessment of how enhanced infiltration translates into increased baseflow, demonstrating the broader hydrological benefits of the intervention beyond the immediate basin footprint. This comprehensive monitoring approach links atmospheric forcing with aquifer response through the intermediate stage of surface infiltration, creating a complete dataset for validating hydrological models and quantifying the effectiveness of urban infiltration basins as managed aquifer recharge tools. The monitoring programme will be refined during detailed design, incorporating the standardised protocols and equipment specifications established in Chapter 4.

Land ownership and permitting

The infiltration basin will be constructed on land owned by the Municipality of Funchal (Câmara Municipal do Funchal, CMF), which also serves as the licensing authority for the installation. A protocol between the UMA and CMF formalising collaboration arrangements awaits signature, expected to be completed during the early months of 2026. This institutional arrangement ensures strong municipal engagement with the demonstration, facilitating integration with broader water management strategies.

2.2.5 Cape Verde

Context

The Cape Verde demonstrator addresses water scarcity challenges facing the island of Santiago, where limited and highly seasonal rainfall creates extreme temporal variability in water availability. The intervention focuses on Ribeireta, an ephemeral stream system that conveys substantial runoff during intense rainfall events but remains dry throughout much of the year. Capturing and storing these episodic flows represents a critical opportunity for enhancing water security in this water-stressed environment.

Rationale

Surface infiltration lagoons were selected for Cape Verde based on the episodic nature of surface water availability in ephemeral stream systems, combined with practical constraints favouring simpler, more robust infrastructure over complex engineered solutions. Multiple lagoons distributed along the watershed provide redundancy against individual failures whilst maximising infiltration opportunity across diverse geological conditions. This typology requires minimal operational complexity and maintenance capacity, appropriate for resource-constrained contexts whilst delivering substantial co-benefits including flood mitigation, erosion control, and sediment trapping those recent extreme events demonstrated to be critically needed.

Planned Nature-based Solution

The project proposes constructing four infiltration lagoons positioned strategically along the Ribeireta stream system (Figure 2.5). These lagoons will capture runoff during rainfall events, promoting infiltration into underlying aquifers whilst reducing downstream flooding risks and erosion. The multi-lagoon configuration distributes storage capacity along the watershed, capturing flows from different sub-catchments and maximising infiltration opportunity through extended contact time between surface water and permeable substrata.

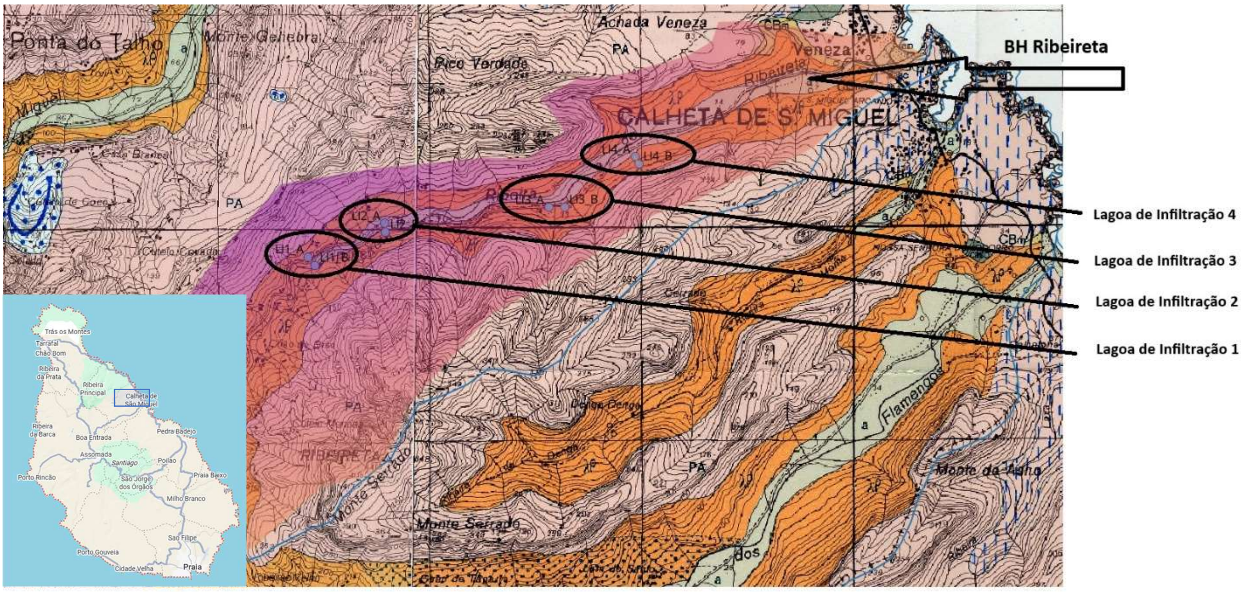

Figure 2.5: Geological map showing the hydrographic sub-basin of Ribeireta and the location where the four retention and infiltration basins would be constructed (scale 1:25,000).

Design progress

Recent extreme rainfall events on 13-14 November 2024 caused significant damage to infrastructure including roads, retention dikes, bridges, and dwellings in Ribeireta, underlining the urgent need for improved stormwater management in the study area. Field visits during the following week observed ongoing work clearing communication routes, cleaning stream channels, and de-silting existing dikes. These recent events provide valuable data on the watershed's hydrological response to intense rainfall and demonstrate the flood mitigation co-benefits that the proposed infiltration lagoons could deliver alongside groundwater recharge objectives.

The flooding also highlights the importance of designing infiltration structures to withstand extreme events whilst continuing to function effectively during more typical rainfall patterns—a design challenge requiring careful consideration of spillway capacity, structural stability, and maintenance accessibility. Subsequent field visits continue to assess recovery progress and refine understanding of site conditions, informing final lagoon positioning and design specifications.

Monitoring programme

Following construction completion, the demonstrator will monitor water quality parameters including pH, electrical conductivity, temperature, and total dissolved solids (TDS), characterising both infiltrating runoff and groundwater response. Infiltration capacity measurements will quantify the rate at which water percolates through lagoon substrata, essential data for assessing performance and identifying any maintenance requirements. Surface runoff velocity and volume of water stored in lagoons provide operational information on system hydraulics during rainfall events, enabling refinement of water balance calculations and assessment of flood attenuation effectiveness.

This monitoring programme focuses on parameters measurable with relatively simple instrumentation appropriate for remote field conditions with limited infrastructure support. The approach reflects practical constraints whilst ensuring sufficient data quality for demonstrating infiltration lagoon effectiveness and supporting transferability analyses to similar contexts throughout the Cape Verde archipelago and other semi-arid Atlantic Islands.

Implementation status

The Cape Verde demonstrator represents the earliest conceptual stage among GENESIS interventions, currently in planning rather than detailed design or procurement. This timeline reflects both the remote location and recent climate disruptions requiring infrastructure recovery before new construction can proceed. However, this later implementation schedule offers valuable advantages, enabling the project to incorporate lessons learned from more advanced demonstrators and to refine approaches based on emerging results from Azores, Canaries, and Madeira implementations.

Land ownership and permitting

Under Cape Verdean legislation, ephemeral streams constitute State property, with all proposed infiltration lagoons to be located within these public water domains. Following approval of the detailed proposals by the GENESIS consortium, the final design will be presented to the President of the Municipality of São Miguel for consideration and approval. The President has demonstrated support for the project since its initial presentation, indicating favourable prospects for securing necessary permissions and community backing.

Licensing follows a two-stage process: initial approval by the Municipality of São Miguel, followed by authorisation from the Ministry of Infrastructure. This hierarchical approach ensures both local government endorsement and national-level oversight of water infrastructure development, reflecting Cape Verde's centralised approach to water resource management whilst maintaining municipal involvement in implementation.

2.3 Baseline requirements

Comprehensive baseline characterisation establishes reference conditions against which intervention impacts can be assessed across all five demonstrators. Rather than duplicating detailed technical specifications, this section provides an overview of baseline requirements and their status across demonstrators, with comprehensive specifications integrated within the assessment framework detailed in Chapter 3.

2.3.1 Characterisation overview

Before implementing nature-based solutions and establishing monitoring programmes, each demonstrator requires baseline characterisation spanning physical, chemical, biological, and social dimensions. These baseline requirements create the foundation for the performance evaluation framework, enabling attribution of observed changes to interventions rather than natural variability or external drivers.

Baseline characterisation for GENESIS demonstrators is being conducted through coordinated efforts across multiple work packages. WP1 (Macaronesia Water Climate Risk Observatory) performs hydrogeological and climate characterisation, establishing aquifer geometry, hydraulic properties, natural recharge rates, existing groundwater flow patterns, and climate projections for all demonstrators. This work provides the physical foundation for understanding how nature-based solutions will interact with natural hydrological systems.

WP2 (NbS Mainstreaming and Social Engagement) characterises social and economic baselines through stakeholder surveys, focus group sessions, and economic assessments conducted at all demonstrators. This work, detailed in Deliverable D2.1, establishes baseline social acceptability (>70% across all regions), identifies implementation barriers (primarily financial and technical capacity constraints rather than cultural resistance), and documents existing water uses and economic dependencies. These social baselines enable assessment of how demonstrators affect community perceptions and deliver equitable benefits.

WP3 (this deliverable) integrates these baseline characterisation efforts, ensuring consistency with monitoring protocols, providing site-specific refinement where needed, and establishing the comparative framework enabling cross-demonstrator synthesis. Section 3.2 provides detailed technical specifications for baseline requirements across all five assessment dimensions (hydrological, water quality, ecological, social, economic), organised to support the performance evaluation framework.

2.3.2 Demonstrator-specific status

The five GENESIS demonstrators entered the project at different stages of characterisation and development, resulting in varying baseline completion status:

El Hierro, Gran Canaria, and Madeira have completed comprehensive baseline characterisation reports synthesising geophysical surveys (where conducted), aquifer testing, water quality assessments, and stakeholder analyses. These demonstrators benefited from pre-existing monitoring networks and historical datasets, accelerating baseline establishment. Their advanced baseline status enables earlier construction commencement and longer operational monitoring durations within project timescales.

Faial approaches baseline completion following geophysical survey execution scheduled for January 2026. The ERT and TDEM surveys will fill critical data gaps in subsurface characterisation, enabling final infiltration well positioning and design specification. Water quality and social baselines are complete, with geophysical surveys representing the final baseline milestone before construction procurement.

Cape Verde continues baseline characterisation activities alongside post-flood infrastructure assessment and conceptual design refinement. Whilst WP1 and WP2 activities established regional hydrogeological context and social acceptability, site-specific infiltration testing and detailed topographic surveys remain ongoing. The November 2024 flood events, whilst disruptive, provided valuable hydrological data characterising extreme event responses that will inform lagoon design and resilience specifications.

This temporal distribution of baseline completion enables iterative learning, with early-characterised demonstrators informing refinement of baseline protocols and parameter selection for later-stage implementations. The varying timelines create opportunities for adaptive improvement whilst ensuring all demonstrators ultimately operate within a consistent assessment framework enabling robust comparative analysis.

2.3.3 Baseline data management

All baseline data are documented following FAIR principles detailed in Section 4.3.1, ensuring discoverability, accessibility, and reusability by the broader scientific community and water management practitioners. Metadata include measurement methods, quality assurance procedures, data limitations, and uncertainty estimates. Spatial data are georeferenced and archived in standardised formats compatible with geographic information systems. Temporal data include precision timestamps enabling correlation with hydrological events and operational activities.

Baseline reports synthesise these diverse datasets into integrated demonstrator characterisations, providing narrative descriptions accessible to non-specialist stakeholders whilst maintaining technical rigour. These reports constitute living documents, updated as monitoring continues and understanding deepens, rather than static snapshots. The baseline characterisation framework thus extends throughout the project lifecycle, continuously refining the reference conditions against which performance is assessed.

Detailed technical specifications for baseline requirements across all assessment dimensions are provided in Section 3.2, integrated within the performance evaluation framework to ensure consistency between baseline characterisation and operational monitoring protocols.

2.4 Preliminary fieldwork and survey protocols

Preliminary fieldwork establishes the observational infrastructure and initial datasets necessary for detailed design, implementation planning, and baseline monitoring programme development. These activities bridge conceptual planning and construction, ensuring interventions are founded on robust site-specific understanding rather than generic assumptions or extrapolated regional data. The following protocols provide standardised approaches adapted to specific demonstrator contexts through the worked examples provided.

2.4.1 Geophysical survey protocols

Where subsurface characterisation requires geophysical investigation [16], survey design should integrate multiple complementary techniques to reduce interpretive ambiguity. Electrical resistivity methods excel at detecting contrasts in groundwater salinity, lithological boundaries, and saturated zone geometry. Electromagnetic methods provide rapid spatial coverage and depth penetration, particularly valuable for reconnaissance surveys across extensive areas. Seismic methods resolve detailed stratigraphic architecture but require careful consideration of noise sources in inhabited areas.

Survey planning must consider both technical and practical constraints. Equipment logistics, access permissions, safety requirements, and stakeholder communication demand equivalent attention to scientific considerations. Survey timing should avoid periods when site conditions impede data acquisition—such as saturated surface soils limiting electrical contact for resistivity surveys or crop growth obscuring survey lines. Where surveys traverse agricultural land or sensitive habitats, protocols must minimise disturbance through careful equipment selection, timing coordination, and post-survey restoration.

Data processing should employ industry-standard software and inversion algorithms, with processing parameters documented for reproducibility. Interpretations should acknowledge uncertainty, particularly where multiple geological scenarios could produce similar geophysical signatures. Integration with direct observations from boreholes, outcrops, or test pits reduces interpretive ambiguity, creating constrained models more reliable for engineering design than geophysical data alone [22-26].

DEMONSTRATOR EXAMPLE: Faial geophysical survey

The Faial demonstrator exemplifies integrated geophysical survey design combining Electrical Resistivity Tomography (ERT) and Time Domain Electromagnetics (TDEM) to characterise subsurface conditions for infiltration well positioning. The survey comprises two long ERT profiles and 57 TDEM soundings strategically positioned to leverage existing information whilst filling data gaps.

In the westernmost survey area, limited historical data (only sparse well logs) necessitates higher TDEM sounding density to establish subsurface understanding. Conversely, the easternmost area benefits from historical geoelectrical data including vertical electrical soundings and borehole geophysical logs, enabling more targeted investigation. This adaptive survey design optimises resource allocation, intensifying investigation where uncertainties are highest whilst confirming existing interpretations where historical data provide foundation.

The survey faces practical challenges typical of agricultural volcanic island contexts: obtaining landowner permissions for access across multiple properties, ensuring adequate Municipal personnel for safety management given high-voltage electrical equipment, and coordinating timing with agricultural cycles to minimise crop impacts and livestock risks. The January 2026 fieldwork timing represents compromise between technical readiness, permission acquisition, and seasonal constraints.

This worked example demonstrates how standardised geophysical protocols adapt to site-specific data availability, access constraints, and stakeholder coordination requirements whilst maintaining technical rigour necessary for engineering design decisions.

2.4.2 Hydrogeological testing

Aquifer testing during preliminary fieldwork quantifies hydraulic properties governing groundwater flow and storage, essential parameters for predicting intervention performance. Test design should match monitoring well construction and pumping/injection rates to anticipated operational conditions, ensuring results are representative of future system behaviour. Constant-rate tests with sufficient duration to achieve quasi-steady-state conditions provide the most reliable parameter estimates, whilst step-drawdown tests reveal efficiency losses and near-well hydraulic behaviour [27].

Testing protocols must include comprehensive pre-test preparation: measuring static water levels across the monitoring network, calibrating pressure transducers, verifying data logger programming, and establishing baseline water quality. During testing, measurement frequencies should capture both rapid initial responses and longer-term trends, typically employing logarithmically-spaced intervals during early phases and arithmetic intervals during quasi-steady conditions.

Post-test analysis should employ multiple interpretive methods, comparing results to assess parameter estimate reliability and identify non-ideal behaviours such as boundary effects, partial penetration influences, or wellbore storage. Sensitivity analyses quantifying parameter uncertainty inform subsequent design conservatism and monitoring network optimisation. Where multiple observation wells provide spatial response data, inverse modelling can characterise aquifer heterogeneity and boundary conditions beyond simple analytical solutions.

DEMONSTRATOR EXAMPLE: El Hierro compartment testing

The El Hierro demonstrator's multi-compartment well requires specialised testing protocols to characterise the hydraulic properties of each dike-bounded aquifer unit independently. Testing involves sequential abstraction from individual compartments whilst monitoring response in surrounding observation wells, revealing compartment-specific transmissivity, storativity, and boundary conditions.

The dike structures separating compartments complicate standard aquifer test interpretation, as semi-permeable boundaries create responses differing from idealised infinite or closed boundary conditions assumed in analytical solutions. Testing protocols must therefore include long-duration observations (multi-day tests) enabling detection of boundary influences, combined with spatial monitoring revealing anisotropic responses indicative of dike orientation effects.

Climate projection integration requires additional testing to establish how compartments respond to recharge variations. Infiltration tests in upslope recharge zones, combined with compartment-specific abstraction tests, enable calibration of coupled surface-groundwater models simulating long-term sustainability under projected climate scenarios extending to 2100. This integration of standard hydrogeological testing with forward-looking climate adaptation planning exemplifies how preliminary fieldwork supports both immediate implementation needs and strategic resource management objectives.

2.4.3 Infiltration testing

For interventions relying on infiltration through surface soils or shallow sediments, preliminary testing quantifies infiltration rates under representative hydraulic conditions. Double-ring infiltrometer tests provide standard methodology for measuring infiltration capacity, with careful attention to initial saturation procedures and maintaining constant head conditions. Tests should be replicated across multiple locations capturing spatial variability, with replication intensity guided by coefficient of variation calculations from initial results.

Test interpretation must distinguish short-term infiltration rates—potentially influenced by soil structure disruption during excavation or initial saturation transients—from longer-term sustainable rates controlling operational performance. Extended duration tests spanning several days provide more reliable estimates of sustainable capacity than brief measurements, though practical constraints often limit test duration. Where feasible, monitoring soil moisture at depth during infiltration testing reveals whether observed surface infiltration rates translate into deep percolation or accumulate in shallow layers above restrictive horizons.

Infiltration test results inform both infiltration basin sizing and monitoring programme design. Where measured rates significantly exceed or fall short of design assumptions, basin dimensions or soil treatment specifications require adjustment. The spatial variability revealed through replicate testing determines required monitoring point density for adequately characterising operational performance variability.

DEMONSTRATOR EXAMPLE: Cape Verde lagoon infiltration assessment

The Cape Verde demonstrator requires infiltration testing across multiple proposed lagoon locations along the Ribeireta ephemeral stream system, as geological variability across the watershed likely creates substantial differences in infiltration capacity. Testing protocols must accommodate remote field conditions with limited infrastructure, favouring simplified double-ring infiltrometer methods over more equipment-intensive approaches.

The recent November 2024 flood events provide natural experiments complementing controlled infiltration testing. Observations of where flood waters infiltrated rapidly versus where they ponded or caused erosion reveal spatial patterns in soil permeability at scales difficult to assess through point measurements alone. Integrating these observational data with systematic infiltrometer testing at proposed lagoon sites creates more comprehensive understanding than either approach provides independently.

Testing must also address sediment dynamics, as ephemeral streams transport substantial sediment loads during flood events that could rapidly clog lagoon substrata. Test protocols therefore include assessment of sediment characteristics and potential filtration rates, informing design of sediment traps or pre-treatment features that will maintain infiltration capacity throughout operational lifetimes despite episodic sediment loading.

2.4.4 Water quality survey

Preliminary water quality surveys should analyse parameters spanning the complete suite identified in Chapter 3, establishing whether baseline conditions meet regulatory standards and identifying any quality concerns requiring special consideration during design or operation. Sampling protocols must follow standardised methods appropriate to each parameter, with particular attention to sample preservation, holding times, and chain of custody documentation.

For parameters exhibiting strong temporal variability—such as nutrients influenced by seasonal agricultural practices or microbial indicators responsive to recent rainfall—preliminary surveys should include multiple sampling events capturing different hydrological conditions. Where historical data exist, preliminary surveys should include overlapping parameters enabling continuity assessment and identification of long-term trends predating project activities.

Field measurements of unstable parameters—particularly pH, dissolved oxygen, electrical conductivity [28], and temperature—should occur immediately upon sample collection, before chemical or biological changes affect values. Portable instrumentation should be calibrated daily using appropriate standards, with calibration results documented in field records. Where field conditions are challenging, replicate measurements verify result reliability and identify potential instrument malfunction or operator error.

DEMONSTRATOR EXAMPLE: Gran Canaria reclaimed water baseline programme

The Gran Canaria demonstrator's use of reclaimed water for aquifer injection necessitates particularly comprehensive baseline water quality characterisation addressing both routine parameters and emerging contaminants of concern. The Jinámar wastewater treatment plant already conducts extensive monitoring under regulatory requirements, providing rich historical datasets characterising typical effluent quality and temporal variability. Preliminary surveys build upon this operational monitoring by expanding parameter coverage to include constituents potentially problematic for aquifer injection but not routinely monitored for ocean discharge. Pharmaceuticals (diclofenac, caffeine, nicotine, erythromycin), pesticides (polar compounds including glyphosate), and microplastics (particularly PVC) receive special attention given public concerns about aquifer contamination from reclaimed water sources.

The sampling programme includes not only treatment plant effluent but also groundwater at proposed injection locations and threatened coastal production wells, enabling assessment of natural baseline quality and detection capabilities for any quality changes attributable to injection. The sampling point incorporated directly at the infiltration trench injection entry provides critical verification that water entering the aquifer meets quality specifications, addressing community concerns about monitoring integrity and operational compliance. This comprehensive baseline quality programme, integrated with ongoing operational monitoring, exemplifies how demonstrators can leverage existing infrastructure and datasets whilst expanding coverage to address intervention-specific parameters and stakeholder concerns that standard regulatory monitoring may not encompass.

2.4.5 Quality control and assurance

All preliminary fieldwork must be documented through comprehensive field records capturing not only measured values but also contextual information essential for interpretation. Field forms should prompt recording of weather conditions, site access constraints, instrument calibration status, sample identification, and any unusual observations or deviations from planned protocols. Photographs provide permanent records of site conditions, equipment installations, and observed features difficult to describe textually.

Quality assurance during fieldwork includes field blanks, equipment blanks, replicate samples, and split samples distributed to different laboratories for inter-laboratory comparison [29-31]. These quality control measures quantify measurement uncertainty and detect systematic biases or contamination, establishing confidence levels for baseline datasets. Where preliminary fieldwork reveals quality concerns or unexpected results, additional investigation should occur before proceeding to design and implementation, ensuring interventions are founded on reliable site characterisation.

Survey results should be compiled into technical reports synthesising findings, identifying data gaps or uncertainties, and recommending any additional investigation necessary before finalising design. These reports constitute essential deliverables informing the transition from preliminary investigation to detailed design, construction, and operational monitoring phases described in Chapter 4.

3 Harmonised assessment protocol

3.1 Core principles

Meaningful comparison of nature-based solutions across diverse Macaronesian demonstrators requires balancing standardisation against necessary contextual adaptation. The harmonised assessment protocol achieves this balance through six interconnected principles that ensure scientific rigour whilst acknowledging real-world complexity.

Standardised indicators provide the foundation for comparison, with all demonstrators measuring identical core parameters using consistent methodologies. However, interpretation must recognise that baseline conditions, geological settings, and climatic contexts fundamentally influence what constitutes successful performance. A 20% increase in aquifer recharge represents excellent achievement in arid Cape Verde but modest success in the humid Azores. The framework therefore mandates both standardised measurement and contextual analysis, comparing sites to their own baselines and performance targets rather than imposing uniform absolute thresholds.

Temporal consistency ensures that comparisons reflect genuine performance differences rather than seasonal artifacts or inadequate monitoring duration. Multi-year monitoring spanning seasonal cycles and inter-annual climatic variability is essential for detecting patterns amidst natural hydrological noise. The framework establishes minimum monitoring durations—typically two to three years post-implementation—with standardised temporal protocols such as monthly sampling frequencies and seasonal campaigns. This temporal standardisation maintains comparability across sites implementing at different times whilst ensuring adequate data for robust statistical analysis.

Spatial representativeness addresses the challenge that NbS performance varies across intervention areas due to soil heterogeneity, topographic gradients, and distance from recharge sources. Monitoring networks must capture this spatial variability using consistent density and distribution principles adapted to site-specific geometries. The framework specifies approaches for sampling point placement, ensuring comparable spatial information quality whether monitoring a five-hectare infiltration basin or a fifty-hectare catchment intervention.

Multi-dimensional assessment recognises that NbS cannot be evaluated through hydrological metrics alone. Water quantity and quality improvements constitute primary objectives, but ecological co-benefits, social acceptability, and economic viability determine whether interventions achieve sustained implementation and scaling. Integrated assessment spanning these five dimensions generates comprehensive understanding whilst producing data supporting diverse analytical needs across GENESIS Work Packages. This holistic perspective distinguishes the framework from conventional water infrastructure evaluation focused narrowly on engineering performance.

Baseline establishment and comparative approaches provide the counterfactual necessary for attributing observed changes to interventions rather than external drivers. Well-characterised pre-implementation conditions establish reference points against which post-implementation performance is evaluated. Where feasible, paired monitoring comparing intervention and control areas strengthens causal inference by demonstrating that observed effects occur specifically where NbS are implemented. The framework specifies minimum baseline data requirements whilst encouraging control site approaches where practical constraints permit.

Transparency, data quality and reproducibility underpin scientific credibility and knowledge transfer beyond the GENESIS consortium. All monitoring activities follow documented standard operating procedures with explicit quality assurance and quality control protocols. Equipment specifications, calibration procedures, and analytical techniques are transparently described enabling independent verification and method reproduction by other researchers or practitioners. This transparency converts demonstration projects into rigorous scientific experiments generating publishable evidence rather than mere technical showcases.

These principles guide development of specific indicators, monitoring protocols, and evaluation procedures, ensuring that GENESIS generates credible, comparable evidence about which NbS approaches deliver best performance under which conditions.

3.2 Assessment dimensions and performance indicators

NbS generate multiple outcomes spanning hydrological, ecological, social, and economic domains. Comprehensive evaluation requires systematic assessment across five interrelated dimensions, each operationalised through specific measurable indicators.

3.2.1 Hydrological potential

Hydrological performance constitutes the primary objective for managed aquifer recharge interventions, quantifying how effectively NbS enhance groundwater storage, improve aquifer conditions, and contribute to water security. Assessment focuses on three interrelated aspects: recharge enhancement, aquifer response, and water balance improvements.

Performance Indicators

Recharge enhancement is quantified through direct measurement of infiltrated volumes where feasible (injection wells, instrumented basins) or estimated through water balance calculations where direct measurement proves impractical (distributed surface interventions). Recharge efficiency—the proportion of captured or diverted water successfully reaching aquifers rather than lost to evaporation, spillage, or surface runoff—provides the key performance metric. Target efficiencies typically range from 60-80% for surface infiltration basins to 85-95% for injection wells, though site-specific conditions and design choices influence achievable performance.

Aquifer response indicators reveal how recharge translates into improved aquifer conditions. Groundwater level increases in monitoring wells surrounding intervention areas demonstrate spatial extent and magnitude of recharge influence. Hydraulic gradient modifications, particularly in coastal settings, indicate effectiveness at counteracting seawater intrusion or altering flow pathways toward abstraction zones. Storage volume changes calculated from level increases and aquifer properties quantify additional water security provided. Response times—how rapidly aquifer conditions respond to recharge events—characterise system dynamics essential for operational management.

Water balance improvements at watershed or management unit scales demonstrate broader hydrological benefits. Baseflow increases in surface water features, spring flow enhancements, or extended seasonal flow duration indicate that aquifer recharge translates into sustained water availability. Reduced abstraction requirements from other sources or extended drought resilience demonstrate practical water security improvements delivered by interventions.

Baseline characterisation requirements

Establishing hydrological baselines requires minimum one-year pre-implementation monitoring capturing both wet and dry season conditions, though multi-year baselines provide stronger foundations for detecting change. Baseline characterisation must quantify natural recharge rates, seasonal groundwater level fluctuations, existing hydraulic gradients, and pre-intervention water balance components.

Spatial baseline coverage encompasses intervention areas plus buffer zones extending sufficiently to detect regional influences and distinguish intervention impacts from natural variations or other anthropogenic stresses. For infiltration basin or well interventions, monitoring networks typically extend 500-1000m from intervention centres, increasing to watershed scales for distributed interventions. Vertical profiling at multiple depths reveals three-dimensional aquifer responses where geological layering or density stratification create depth-dependent behaviours.

Temporal baseline monitoring employs frequencies matching operational monitoring protocols: continuous hourly measurements for water levels using pressure transducers, supplemented by manual verification measurements monthly. Flow measurements in surface water features employ continuous stage recording with rating curves, validated through periodic direct discharge measurements. Natural recharge estimates employ multiple independent methods (water balance, chloride mass balance, water table fluctuation) to constrain uncertainty.

Demonstrator-specific approaches

Faial: Primary indicator is piezometric response to infiltration well injection, targeting 0.5-1m water level increase within 500m radius during recharge operations. Electrical conductivity monitoring detects any saline water mobilisation from coastal interface due to artificial recharge mounding. Baseline characterisation includes geophysical surveys constraining aquifer geometry and properties, plus minimum one-year piezometric monitoring establishing natural variability patterns.

Gran Canaria: Hydraulic barrier effectiveness measured by stabilisation or reversal of seawater intrusion interface position in coastal monitoring wells. Injection volume measurements combined with aquifer response quantify recharge efficiency. Baseline characterisation leverages existing ITC monitoring network data, supplemented by coastal interface position surveys establishing pre-intervention intrusion extent.

El Hierro: Compartment-specific sustainable yield calculated from individual recharge rates and storage coefficients for each dike-bounded unit. Continuous monitoring of abstraction rates from each compartment reveals adaptive management effectiveness. Baseline includes one-year mixed-water monitoring (already completed) plus infiltration testing in recharge zones supporting climate-responsive yield calculations.

Madeira: Infiltration basin efficiency quantified by proportion of captured highland stream runoff successfully recharged versus lost to evaporation or overflow. Tornos tunnel discharge measurements detect downstream baseflow increases attributable to enhanced recharge. Baseline characterisation includes precipitation-runoff relationships, natural infiltration rates, and pre-intervention tunnel flows across seasonal variations.

Cape Verde: Lagoon performance during extreme events serves as indicator of flood attenuation co-benefit alongside groundwater recharge quantification. Natural infiltration losses during episodic flow events provide baseline against which lagoon-enhanced infiltration is compared. Simplified water balance approach appropriate for resource-constrained monitoring accommodates practical limitations whilst generating meaningful performance data.

3.2.2 Water quality

Water quality monitoring addresses whether infiltrated water maintains or improves aquifer quality, avoids mobilising contaminants from aquifer materials, and meets regulatory standards for beneficial use. Assessment spans physical-chemical parameters, nutrients, contaminants of emerging concern, and microbial indicators, with parameter selection reflecting both regulatory requirements and intervention-specific considerations.

Performance Indicators

Physical-chemical stability ensures that recharge operations do not degrade receiving aquifer quality. Temperature, electrical conductivity, pH, dissolved oxygen, and oxidation-reduction potential provide sentinel indicators of biogeochemical changes. Thresholds typically permit ±10% variation from baseline conditions, though regulatory standards may impose stricter limits. Major ion chemistry (calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate) characterises hydrochemical evolution and detects mixing with native groundwater or seawater.

Nutrient management proves particularly critical for reclaimed water applications or agricultural catchment interventions. Nitrogen species (nitrate, nitrite, ammonium), total nitrogen, phosphorus species (orthophosphate, total phosphorus), and dissolved organic carbon quantify nutrient loads and transformation processes. Performance targets generally aim to maintain concentrations below drinking water standards (nitrate <50 mg/L, nitrite <0.5 mg/L) whilst recognising that infiltration through vadose zones and aquifer residence typically reduces concentrations through denitrification and sorption processes.

Contaminants of emerging concern require attention where recharge sources may contain pharmaceuticals, personal care products, pesticides, or industrial chemicals. Parameter selection reflects source water characteristics and stakeholder concerns. Monitoring frequencies typically emphasise initial characterisation during commissioning, transitioning to annual or biennial monitoring once stable patterns emerge. Detection of concerning concentrations triggers increased monitoring and potential operational adjustments.

Microbial indicators assess pathogen risks, particularly for reclaimed water applications or surface water sources influenced by anthropogenic contamination. *E. coli* and total coliforms provide standard bacterial indicators, supplemented by virus indicators (coliphages) where direct potable reuse might occur. Groundwater monitoring typically demonstrates substantial pathogen removal during infiltration and aquifer passage, with performance targets of multi-log reductions (>3-log for bacteria, >2-log for viruses) common for managed aquifer recharge applications.

Baseline characterisation requirements

Water quality baselines require characterisation of both recharge source waters and receiving aquifer conditions. Source water characterisation emphasises parameters potentially problematic for injection, establishing whether pre-treatment is necessary and defining operational quality targets. Receiving aquifer characterisation establishes natural quality patterns and variability against which intervention impacts are assessed.

Baseline sampling frequencies balance adequate statistical characterisation with resource constraints. Monthly sampling for one year minimum provides reasonable temporal coverage for most parameters, with seasonal sampling (quarterly) acceptable for stable constituents exhibiting minimal temporal variation. Source waters with higher temporal variability (storm runoff, treatment plant effluent) may require more frequent baseline sampling (biweekly or event-based) adequately characterising quality ranges.

Parameter suites should address regulatory compliance requirements whilst including indicators specifically sensitive to anticipated intervention impacts. Standard suites include physical-chemical parameters (temperature, EC, pH, DO, turbidity), major ions, nutrients, trace metals (iron, manganese, arsenic where geological conditions suggest potential mobilisation), and microbial indicators. Expanded suites appropriate for reclaimed water applications add emerging contaminants, whilst agricultural catchment interventions emphasise pesticides and sediment-associated parameters.

Demonstrator-specific approaches

Gran Canaria: Comprehensive monitoring of pharmaceuticals (diclofenac, caffeine, nicotine, erythromycin), pesticides (polar compounds including glyphosate), and microplastics (particularly PVC) in reclaimed water injection addresses public concerns about aquifer contamination. Bi-weekly monitoring at Jinámar treatment plant provides source water characterisation, with monthly groundwater monitoring assessing aquifer impacts. Injection point sampling enables real-time quality verification before water enters aquifer, critical for maintaining stakeholder confidence.

Faial: Electrical conductivity monitoring as primary quality indicator detects any saline water mobilisation from coastal interface due to recharge-induced hydraulic mounding. Simplified parameter suite appropriate for clean freshwater sources emphasises major ions, nutrients, and basic physical-chemical parameters. Monthly sampling frequency balances adequate characterisation with resource constraints in remote island setting.

El Hierro: Compartment-specific quality monitoring reveals which dike-bounded units maintain better natural filtration or experience different contamination risks, informing preferential abstraction strategies. Continuous EC and temperature monitoring supplemented by monthly comprehensive sampling characterises quality variation across compartments, enabling adaptive management optimising both quantity and quality objectives.

Madeira: Runoff quality monitoring addresses potential contaminants from impervious surfaces including hydrocarbons, heavy metals (lead, zinc, copper from vehicle sources), and sediment. First-flush phenomena during storm events receive particular attention, as initial runoff typically carries highest contaminant loads. Event-based sampling during storm captures quality variations that fixed-frequency sampling might miss.

Cape Verde: Turbidity and sediment monitoring in lagoons quantifies water quality improvement through natural settling and filtration compared to direct stream abstraction. Simplified parameter suite focuses on physical characteristics, major ions, and microbial indicators, appropriate for resource-constrained contexts whilst addressing primary quality concerns. Quarterly sampling frequency reflects episodic flow events and practical access limitations.

3.2.3 Social acceptability

Social acceptability determines whether technically successful interventions achieve sustained implementation, replication, and integration into water management practice. Assessment addresses stakeholder perceptions, participatory engagement effectiveness, distributional equity, and institutional capacity development, recognising that social dimensions often determine long-term success more than technical performance alone [32, 33].

Performance Indicators

Stakeholder perception tracking employs repeated surveys documenting how awareness, understanding, attitudes, and trust evolve from pre-implementation baseline through operational phases. Indicators include perceived effectiveness (does it work?), environmental acceptability (is it safe?), procedural justice (was implementation fair?), and distributive justice (who benefits and who bears costs?). Longitudinal tracking reveals whether initial scepticism transitions to acceptance or whether concerns persist requiring ongoing engagement.

Participatory engagement metrics quantify stakeholder involvement breadth and depth. Participation rates in consultation meetings, workshop attendance, and monitoring programme contributions indicate engagement breadth. Influence on decision-making—instances where stakeholder input altered designs, operational procedures, or monitoring priorities—indicates meaningful participation rather than tokenistic consultation. Community ownership indicators, such as volunteer contributions to monitoring or maintenance, reveal deep engagement characteristic of successful collaborative governance.

Distributional equity assessment examines whether benefits and costs distribute fairly across stakeholder groups. Water security improvements should benefit previously underserved or vulnerable populations rather than concentrating advantages among already-privileged users. Environmental benefits should not impose disproportionate burdens (land use restrictions, access limitations, aesthetic impacts) on specific communities. Equity indicators employ social survey data, water access statistics, and economic impact assessments disaggregated by stakeholder categories.

Capacity development indicators document knowledge transfer and institutional strengthening. Technical training participation, professional skill development, and institutional protocol adoption quantify capacity improvements. Demonstration site visits, practitioner exchange programmes, and knowledge product utilisation indicate broader capacity building beyond immediate implementation partners. Sustained monitoring and adaptive management capacity beyond project timelines provides ultimate indicator of successful capacity development.

Baseline characterisation requirements

Social baselines employ mixed methods combining quantitative surveys, qualitative interviews, focus groups, and participatory mapping. Surveys establish baseline awareness, attitudes, trust, and willingness to support interventions across representative stakeholder samples. Response rates >30% provide adequate representation, with stratified sampling ensuring inclusion of diverse stakeholder categories (water users, regulatory authorities, environmental organisations, general public).

Qualitative methods capture nuanced perceptions, implementation barriers, and locally-specific concerns that structured surveys might miss. Semi-structured interviews with key informants (water managers, community leaders, technical experts) provide in-depth perspectives. Focus group discussions reveal social dynamics, shared concerns, and community priorities influencing acceptability. Participatory mapping exercises document existing water uses, valued ecosystem services, and perceived vulnerabilities, informing intervention design responding to community priorities.

Baseline social characterisation for GENESIS demonstrators was conducted through WP2 (NbS Mainstreaming and Social Engagement), documented in Deliverable D2.1. All five demonstrators completed stakeholder surveys and focus group sessions establishing baseline social acceptability >70% across all regions, identifying primarily structural rather than cultural barriers (financial constraints, technical capacity gaps, institutional fragmentation), and documenting high trust in scientific guidance and NGO facilitation.

Demonstrator-specific approaches

All demonstrators: WP2 surveys and focus groups established comprehensive social baselines before intervention implementation. Repeated surveys during operational phases (annual frequency) track perception evolution. Stakeholder reference groups established at all demonstrators provide ongoing participatory engagement platforms, meeting quarterly during active implementation and semi-annually during operational monitoring.

Faial: Agricultural landowner cooperation proved essential for geophysical survey access, requiring sustained engagement ensuring minimal disruption to farming operations and respect for property rights. Community concerns about potential impacts on agricultural water supplies addressed through transparent monitoring and communication about aquifer response to recharge operations.

Gran Canaria: Public perception of reclaimed water injection initially sceptical given concerns about aquifer contamination. Transparent comprehensive quality monitoring programme, including real-time injection point verification, addresses concerns through demonstrable protection. Community engagement emphasises scientific evidence of treatment effectiveness and natural attenuation during aquifer infiltration and residence.

Madeira: Urban demonstrator benefits from high visibility providing educational value and building broad public awareness. School programmes and interpretive signage leverage demonstration site for environmental education. Community surveys assess whether visible amenity improvements (landscaped basin, urban green space) enhance perceived value beyond technical water management benefits.

Cape Verde: Post-flood implementation context strengthens community support given demonstrated need for stormwater management. Participatory design process incorporated local knowledge about flow patterns and erosion vulnerabilities. Economic co-benefits from reduced flood damage and improved agricultural water security provide tangible value supporting continued community engagement.

El Hierro: Collaborative governance between public water authority and local irrigation community exemplifies participatory management model detailed in WP2. Adaptive abstraction management responding to compartment-specific conditions requires sustained user engagement and trust in monitoring evidence informing operational decisions.

3.2.4 Economic performance

Economic performance addresses whether nature-based solutions deliver water security and co-benefits at costs competitive with conventional alternatives, generate positive benefit-cost ratios justifying public investment, and create economic opportunities supporting sustained implementation. Assessment spans direct costs, water security benefits, co-benefit valuation, and broader economic impacts.

Performance Indicators

Direct cost indicators quantify capital expenses (design, construction, equipment, permitting), operational expenses (energy, maintenance, monitoring, personnel), and infrastructure lifespan. Unit cost metrics (cost per cubic metre recharged, cost per hectare-metre storage created, cost per capita served) enable comparison across interventions and against conventional alternatives. Cost-effectiveness indicators relate expenditures to performance outcomes, enabling identification of design or operational factors influencing economic efficiency.

Water security benefits constitute primary economic value, quantified through replacement cost approaches (cost of alternative supply sources), damage cost avoided (economic losses prevented by improved water availability), or willingness-to-pay assessments (value users place on supply security). Benefits include reduced abstraction costs, extended drought resilience, delayed or avoided need for supply augmentation infrastructure (desalination, inter-basin transfers), and enhanced agricultural productivity or tourism revenue from reliable water supply.

Co-benefit valuation quantifies economic value of environmental and social outcomes beyond direct water security. Flood damage reduction from infiltration basin storage capacity employs damage-frequency curves and property value data. Ecosystem service values employ benefit transfer methods, stated preference surveys, or revealed preference analysis depending on data availability and resources. Recreational and amenity values employ travel cost methods, hedonic pricing of adjacent properties, or contingent valuation surveys. Educational value from demonstration and capacity building, though difficult to quantify monetarily, can be documented through participation metrics and knowledge product utilisation.

Broader economic impacts encompass employment generation during construction and operations, local procurement multiplier effects, tourism or property value increases from environmental improvements, and economic diversification through water security reducing vulnerability to drought impacts. Input-output analysis or computable general equilibrium modelling quantify indirect economic effects, though simpler approaches documenting direct employment and local expenditure provide adequate indicators for most applications.

Baseline characterisation requirements

Economic baselines quantify pre-intervention costs and benefits enabling post-implementation comparison. Water supply costs (energy, infrastructure maintenance, treatment) establish reference against which recharge-enabled savings are measured. Economic value of existing water uses (agriculture, tourism, municipal supply) establishes baseline from which improvements are assessed. Infrastructure replacement costs and failure probabilities inform valuation of extended infrastructure lifespan or delayed capital investment through improved water security.

Economic baseline data often derive from administrative records, utility financial statements, and regional economic statistics rather than requiring dedicated field surveys. Where primary data collection is necessary, stakeholder surveys can incorporate economic modules addressing willingness-to-pay for improved service reliability, agricultural input costs and revenues dependent on water availability, and perceived property values related to water security and environmental amenities.

Economic baselines for co-benefits require quantification of pre-intervention conditions for valued services. Flood damage costs based on historical events or hydrological models establish reference for quantifying damage reduction. Recreational use patterns and values from comparable sites inform benefit transfer for amenity improvements. Ecosystem service baseline values employ benefit transfer from meta-analyses or stated preference surveys where resources permit original research.

Demonstrator-specific approaches

Gran Canaria: Economic benefits include reduced need for desalination (high energy costs) through reclaimed water reuse, delayed or avoided seawater intrusion requiring expensive wellfield relocation or abandonment, and extended productive life of existing coastal abstraction infrastructure. Comprehensive cost data from ITC enables robust economic analysis comparing infiltration trench approach to conventional alternatives (seawater desalination, inter-island water transfers).

Faial: Economic benefits emphasise avoided seawater intrusion risks threatening domestic water supplies critical to island economy. Relatively low operational costs (no pumping energy, minimal maintenance) improve benefit-cost ratios compared to more energy-intensive conventional approaches.

El Hierro: Economic benefits arise from optimised abstraction management potentially extending aquifer yield without additional infrastructure investment. Avoided costs of developing alternative supplies or restricting agricultural withdrawals provide measurable economic value. Monitoring and control system costs compared against benefits from improved resource management enable economic performance assessment of virtual NbS approach relative to physical infrastructure alternatives.

Madeira: Multiple co-benefit streams complicate but enrich economic analysis. Flood damage reduction from storm storage quantified through hydrological modelling and property value data. Urban amenity improvements assessed through property value hedonic analysis or stated preference surveys. Educational value from school programmes and public outreach documented through participation metrics. Multi-benefit economic analysis demonstrates value proposition for urban NbS potentially uncompetitive on water security benefits alone.

Cape Verde: Economic benefits include flood damage reduction, agricultural productivity improvements from enhanced water security in water-scarce environment, and avoided costs of post-flood reconstruction. Limited resources for comprehensive economic analysis favour simpler approaches: direct cost documentation, employment generation quantification, and qualitative assessment of flood protection and water security benefits valued highly by community despite limited quantitative economic data.

3.3 Standardised evaluation framework

The assessment dimensions and performance indicators detailed above operate within a structured evaluation framework ensuring systematic, comparable assessment across all five GENESIS demonstrators. This framework specifies monitoring frequencies, data analysis protocols, reporting standards, and decision triggers for adaptive management.

3.3.1 Temporal evaluation structure

Demonstrator evaluation proceeds through four temporal phases, each with distinct monitoring intensities and assessment objectives:

- **Commissioning phase** (first 3-6 months post-construction) emphasises system function verification and initial response characterisation. Monitoring frequencies exceed long-term operational levels, capturing transient responses as infiltrated water first contacts aquifer materials or as constructed ecosystems begin establishing. Weekly to bi-weekly comprehensive sampling reveals water quality evolution, whilst continuous automated monitoring characterises hydraulic responses. This intensive commissioning monitoring identifies operational issues requiring adjustment whilst establishing performance baselines for subsequent evaluation.
- **Early operational phase** (months 6-24 post-commissioning) transitions to standardised operational monitoring whilst maintaining enhanced attention to performance trends. Monthly comprehensive sampling and quarterly ecological surveys provide adequate temporal resolution for detecting patterns whilst reducing resource requirements compared to commissioning intensity. This phase generates first performance assessments against targets, identifies seasonal patterns, and enables preliminary evaluation of whether interventions deliver anticipated benefits.
- **Mature operational phase** (months 24+ post-commissioning) employs routine operational monitoring with periodic intensive campaigns addressing specific questions. Continuous automated monitoring continues for critical parameters (water levels, flow rates, basic quality indicators), whilst comprehensive sampling transitions to quarterly or seasonal frequencies adequate for detecting long-term trends without excessive resource commitment. Annual ecological surveys document community development trajectories. Biennial campaigns addressing emerging contaminants or specialised parameters maintain comprehensive understanding without continuous intensive effort.
- **Adaptive evaluation cycles** occur throughout all phases, following quarterly to annual frequencies depending on demonstrator complexity and performance concerns. These structured evaluations synthesise accumulated monitoring evidence, compare performance against targets, assess whether adaptive management interventions improved outcomes, and identify adjustments warranted by emerging understanding or changing conditions.

3.3.2 Cross-demonstrator comparative analysis

Comparative analysis synthesising results across demonstrators employs statistical methods appropriate to available sample sizes and data characteristics. Temporal trend analysis within individual demonstrators uses time series methods (Mann-Kendall tests, Sen's slope estimators) detecting significant patterns whilst accounting for serial correlation. Comparison of demonstrator performance employs analysis of variance or non-parametric equivalents (Kruskal-Wallis tests) determining whether performance differences exceed natural variability.

Multivariate approaches relating performance to site characteristics, design features, or operational practices employ regression analysis, principal components analysis, or machine learning methods depending on data structure and analytical objectives. These analyses identify factors most strongly influencing performance, revealing whether geology, climate, design choices, or management approaches explain performance variability across demonstrators.

The table below summarises minimum monitoring durations and frequencies enabling robust comparative analysis across the five GENESIS demonstrators despite varying implementation timelines.

Table 3.1: Monitoring phase timeline and duration for GENESIS demonstrators.

Demonstrator	Commissioning	Early operational	Mature operational	Total Duration
El Hierro	Q2 2026 (3 mo)	Q3 2026 - Q2 2027	Q3 2027 - Aug 2028	27 months
Gran Canaria	Q3 2026 (3 mo)	Q4 2026 - Q3 2027	Q4 2027 - Aug 2028	24 months
Faial	Q1 2027 (3 mo)	Q2 2027 - Q1 2028	Q2 2028 - Aug 2028	20 months
Madeira	Q2 2027 (3 mo)	Q3 2027 - Q2 2028	Q3 2028 - Aug 2028	18 months
Cape Verde	Q4 2027 (3 mo)	Q3 2027 - Aug 2028	N/A	12 months

Notes: ● All dates shown as quarters (Q1-Q4) and years (2026-2028) representing planned commencement or completion times subject to permit approvals, construction scheduling, and equipment procurement. ● The 3-month commissioning phase occurs immediately following construction completion and monitoring equipment installation, with intensive monitoring characterising initial system response before transitioning to early operational phase. ● Total duration varies significantly across demonstrators (27 months for El Hierro to 11 months for Cape Verde) reflecting sequential implementation schedule within constrained project timescales.

This temporal distribution enables all demonstrators to achieve minimum operational monitoring within project timescales, adequate for detecting seasonal patterns and preliminary performance trends. Earlier-implementing demonstrators generate longer time series supporting more robust statistical analysis and greater confidence in long-term performance projections.

3.3.3 Performance targets

Performance targets balance ambition with realism, established through combination of modelling predictions, analogue site performance, and stakeholder priorities. Hydrological targets derive from water balance modelling and aquifer simulations predicting recharge efficiency and aquifer response magnitudes. Water quality targets reference regulatory standards supplemented by risk-based thresholds for parameters lacking established standards. Ecological targets employ reference site conditions or restoration ecology benchmarks adapted to site-specific possibilities. Social targets derive from WP2 baseline surveys, typically aiming to maintain or improve already-high acceptability levels (>70%). Economic targets employ benefit-cost ratios >1.0 as minimum threshold, with ratios >2.0 considered strong performance justifying replication investment.

Target achievement triggers celebration and potential operational optimisation seeking further improvements. Target shortfalls trigger diagnostic evaluation identifying whether underperformance reflects design limitations, operational issues, inadequate understanding of site conditions, or unrealistic expectations. This diagnostic assessment informs adaptive management decisions: operational adjustments addressing correctable issues, design modifications for future implementations learning from experience, or target revision where initial expectations proved unrealistic given site constraints.

3.3.4 Decision triggers for adaptive management

Monitoring evidence triggers adaptive management responses through pre-established decision rules balancing responsiveness against excessive intervention reacting to natural variability. Three trigger categories prompt escalating responses:

- **Informational triggers** (performance 10-20% below targets) prompt enhanced monitoring and diagnostic assessment without immediate operational changes. These modest deviations may reflect natural variability, seasonal patterns, or temporary conditions requiring understanding before action.
- **Management triggers** (performance >20% below targets or regulatory exceedances) prompt operational adjustments within authority of site managers: injection rate modifications, timing changes, maintenance interventions, or enhanced stakeholder communication. These operational responses occur rapidly (within weeks of trigger detection) addressing correctable issues before they escalate.
- **Governance triggers** (sustained performance >30% below targets, major regulatory violations, significant stakeholder conflicts) prompt formal evaluation engaging broader stakeholder groups and potentially requiring design modifications or fundamental operational changes. These major responses follow deliberative processes balancing technical analysis with stakeholder input, typically requiring months for proper evaluation and consensus building. The governance structures established through WP2 provide frameworks for these major adaptive decisions.

3.4 Reporting and documentation standards

Consistent reporting standards ensure that demonstration results are accessible, comparable, and reusable by diverse audiences ranging from consortium researchers to water management practitioners to policy makers. The GENESIS reporting framework employs tiered approach producing multiple product types serving distinct needs.

3.4.1 Monitoring reports

Quarterly data reports summarise monitoring results from each demonstrator, providing factual documentation without extensive interpretation. Reports include time series plots, summary statistics, comparison against baseline conditions and performance targets, quality assurance summaries, and brief notes on operational status or unusual conditions. Standardised templates ensure consistency across demonstrators whilst allowing flexibility for site-specific emphasis. These working documents support internal project coordination and provide raw material for subsequent performance assessment reports.

3.4.2 Performance assessment reports

Annual performance assessment reports synthesise accumulated evidence evaluating demonstrator performance against established targets across all five assessment dimensions. These analytical documents employ statistical methods assessing significance of observed changes, diagnose factors influencing performance variability, and provide preliminary conclusions about intervention effectiveness. Recommendations for adaptive management or monitoring programme refinements arise from performance assessments, informing operational decisions. Assessment reports target technical audiences including consortium researchers, water management professionals, and regulatory authorities requiring rigorous evidence.

3.4.3 Comparative synthesis reports

Comparative synthesis reports occurring at project mid-point and conclusion integrate results across all five demonstrators, identifying performance patterns, contextual factors influencing outcomes, and transferable principles informing future implementations. These strategic documents address questions about which NbS typologies perform best under which conditions, how design and operational choices influence outcomes, what monitoring approaches prove most informative, and where knowledge gaps require additional research. Synthesis reports target diverse audiences including technical specialists, policy makers, and funding agencies evaluating NbS as water security investments.

3.4.4 Stakeholder communication

Plain language summaries, infographics, and interactive visualisations translate technical findings for general audiences including communities hosting demonstrations, broader public stakeholders, and media. These communication products emphasise practical implications, co-benefits, and lessons learned whilst minimising technical jargon. Demonstrator-specific factsheets provide concise overviews suitable for site visits or public events. Project websites and social media maintain ongoing communication channels updating stakeholders on progress and emerging results.

3.4.5 Data and metadata publication

All monitoring data, supporting documentation, and analytical code are published in open-access repositories following FAIR principles detailed in Section 4.3.1. Comprehensive metadata enable other researchers to understand, evaluate, and reuse GENESIS data. Version control and persistent identifiers (DOIs) ensure long-term accessibility and proper attribution. This commitment to open data reflects recognition that demonstration value extends beyond immediate project objectives to enable ongoing research, support future implementation planning, and contribute to global understanding of NbS performance.

4 Integrated monitoring, data management and implementation

4.1 Smart monitoring networks

Smart monitoring networks integrate automated sensors, cloud-connected data transmission, and real-time visualisation to provide continuous, high-resolution information about NbS performance whilst minimising manual labour requirements. The five GENESIS demonstrators employ varied monitoring approaches reflecting their distinct typologies, infrastructure contexts, and resource constraints whilst maintaining sufficient standardisation to enable comparative analysis.

4.1.1 Network design

Effective network design balances comprehensive spatial and temporal coverage against practical constraints of budget, installation complexity, and maintenance demands. Monitoring networks must capture key hydrological and water quality processes across the full intervention area and surrounding zone of influence through strategically positioned sensors addressing multiple spatial scales from local point measurements through site-scale water balance to regional-scale aquifer response [19, 25, 30, 31, 34].

Spatial coverage follows upstream-downstream configuration with monitoring points positioned to establish background conditions, observe processes within the intervention area, and assess downstream impacts. For infiltration-based systems, monitoring wells distributed across the anticipated recharge mound capture spatial heterogeneity in aquifer response whilst verifying design assumptions about zone of influence. Multi-level monitoring wells or sensors at multiple depths characterise vertical flow dynamics, identifying perched water tables or confining layers that influence three-dimensional recharge processes.

Temporal resolution varies according to parameter dynamics and data requirements. Continuous high-frequency monitoring at hourly or finer intervals captures water levels, meteorological parameters, and key water quality indicators in critical locations. Periodic automated monitoring at daily to weekly intervals addresses parameters with stable dynamics or lower priority for real-time decision-making. Campaign-based sampling at monthly to quarterly frequencies provides laboratory water quality analyses, ecological surveys, and stakeholder perception assessments requiring human intervention.

Critical monitoring points include redundant sensors or backup systems ensuring data continuity during equipment failures, with multiple sensors measuring the same parameter enabling identification of sensor drift or malfunction through comparison. Initial monitoring networks focus on core indicators and critical processes with capacity for expansion if results identify unexpected dynamics or additional research questions emerge. Where regional meteorological stations, hydrological monitoring networks, or water quality surveillance programmes exist, GENESIS monitoring integrates with these systems through data sharing agreements rather than duplicating existing efforts—exemplified by Gran Canaria's integration with ITC's existing telemetry infrastructure and El Hierro's connection to surrounding observation well networks.

4.1.2 Instrumentation specifications

All demonstrators utilise compatible instrumentation enabling comparison whilst allowing site-specific selection based on local availability, costs, and technical support. Water level monitoring employs submersible pressure transducers or radar sensors with accuracy of ±0.5 cm and 1 mm resolution, using vented cables for atmospheric pressure compensation in wells or non-vented sensors with barometric correction for surface water. Water quality multiparameter sondes measure temperature (±0.1°C), electrical conductivity (±1% accuracy), pH (±0.1 units), dissolved oxygen (±0.1 mg/L), oxidation-reduction potential (±5 mV), and turbidity (±2%), with anti-fouling systems enabling continuous deployment and data logging capacity supporting minimum 30-day autonomous operation.

Soil moisture sensors using time-domain or frequency-domain reflectometry achieve ±2-3% volumetric water content accuracy, installed at multiple depths (typically 20, 50, 100 cm minimum) to capture vadose zone dynamics. Meteorological stations measure precipitation (0.2 mm resolution), air temperature and humidity (±0.3°C and ±3% RH), wind speed and direction (±0.3 m/s and ±3°), and solar radiation (±5% accuracy) following WMO siting standards. Flow measurement employs electromagnetic or turbine meters for pressurised systems achieving ±2% accuracy for critical applications like billing-grade injection monitoring, whilst V-notch weirs or flumes provide ±5% accuracy for routine surface water measurement.

The five GENESIS demonstrators employ distinct equipment configurations reflecting their operational contexts. Faial uses autonomous pressure transducers combined with electrical conductivity sensors (Diver CTD series) requiring no telemetry infrastructure, appropriate for the remote agricultural setting with monthly manual downloads providing adequate temporal coverage. Gran Canaria deploys pressure transducers in coastal monitoring wells supplemented by multiparameter sondes (YSI EXO2 equivalent) at injection and key monitoring locations, with one electromagnetic flow meter (±2% billing-grade) on the reclaimed water supply line, all connected via real-time cellular telemetry through ITC’s existing network infrastructure.

El Hierro’s multi-compartment well employs three electromagnetic flow meters (one per compartment) providing ±2% accuracy for operational management, complemented by three pressure sensors and three temperature-conductivity sensors enabling compartment-specific monitoring, plus one sensor operational for approximately one year providing mixed-water baseline data. The telecontrol and data transmission system under development (Q1 2026) will enable real-time remote monitoring and integration with the GENESIS data platform. Madeira’s urban demonstrator includes multiparameter sondes in the infiltration basin and downstream tunnel sampling points, V-notch weir for overflow measurement, and soil moisture sensors at three depths in multiple profiles (TDR technology) characterising vadose zone infiltration dynamics, with real-time connectivity via municipal fibre optic infrastructure once construction completes.

Cape Verde employs simplified monitoring appropriate for resource constraints and remote location, using staff gauges for manual water level readings, portable meters for field measurement of pH, electrical conductivity, temperature, and total dissolved solids during quarterly site visits, and manual rain gauges with periodic readings. This approach balances essential data collection with minimal equipment costs, maintenance requirements, and technical complexity whilst providing adequate information for demonstrating infiltration lagoon effectiveness in episodic flow capture and groundwater recharge.

4.1.3 Installation and calibration protocols

Groundwater monitoring wells follow ISO 5667-22:2010 standards with minimum 50mm diameter for sensor deployment (100mm preferred for multiparameter sondes requiring maintenance access), screens positioned to intercept target water-bearing zones identified through characterisation, clean silica sand filter packs extending 0.5m above and below screens, bentonite annular seals preventing surface water short-circuiting, and protective surface completions. Well development through pumping or surging continues until turbidity drops below 5 NTU and water chemistry stabilises, typically requiring several well volumes. Sensors are positioned at mid-screen depth using suspension cables with strain relief at wellheads preventing movement during maintenance operations.

All sensors receive factory calibration before deployment with certificates documenting traceability, supplemented by field verification confirming performance under actual deployment conditions. Water level sensors are compared against manual steel tape measurements at multiple depths spanning expected range, water quality sondes are calibrated using buffer standards for pH (pH 4, 7, 10), water-saturated air or sodium sulphite zero checks for dissolved oxygen, and standard solutions spanning expected range for electrical conductivity and turbidity. Flow meters are verified against volumetric measurements or reference meters where possible, meteorological sensors are compared against certified reference instruments. Post-installation monitoring includes enhanced weekly verification during the first month confirming sensors operate correctly and data quality meets specifications, with systematic documentation of calibration results, sensor serial numbers, installation details, and survey coordinates creating permanent records.

4.1.4 Cloud-connected data systems

Real-time data transmission employs communication technologies matched to site infrastructure and data requirements. Cellular telemetry provides cost-effective connectivity where mobile networks offer adequate coverage, enabling hourly to daily data transmission with modest power requirements suitable for solar-battery systems—employed at Gran Canaria and planned for Madeira leveraging existing mobile and fibre optic infrastructure respectively. El Hierro’s telecontrol system under development will utilise cellular connectivity supplemented by satellite backup for reliability in the island location. Faial’s remote agricultural setting and Cape Verde’s resource constraints dictate autonomous logging with manual downloads during monthly and quarterly site visits respectively, with data uploaded via web interface to the central platform.

The GENESIS data platform provides centralised infrastructure for data ingestion, storage, quality control, processing, visualisation, and distribution following modern cloud-native design. Data ingestion APIs accept diverse formats and transmission protocols from field telemetry systems, manual uploads from autonomous loggers, and bulk imports from laboratory information management systems, with robust parsing handling varied date-time formats and units. PostgreSQL with PostGIS spatial extension provides structured storage for time-series sensor data, spatial monitoring network geometries, quality control flags, and associated metadata, with time-series optimisation ensuring efficient query performance for large datasets spanning years of high-frequency measurements.

Automated quality control algorithms flag suspect data based on range checks, rate-of-change limits, redundant sensor comparisons, and spike detection as detailed in Section 4.2.4, with flagged data remaining in database with associated quality codes enabling manual review without data loss. Data processing pipelines compute derived parameters (groundwater level changes relative to baseline, recharge efficiency from water balance components), temporal aggregations (hourly to daily to monthly statistics), and spatial interpolations (kriged water table surfaces from well networks). Web-based visualisation interfaces present monitoring data through interactive time-series plots, map displays of spatial patterns, and automated report generation producing standardised summaries for quarterly coordination meetings and annual performance assessments.

Demonstrator integration proceeds sequentially reflecting implementation timelines. El Hierro achieves first full integration (Q1 2026) with telecontrol system design and API development demonstrating real-time data streaming and remote operational control capabilities. Gran Canaria follows (Q2 2026) through API integration with existing ITC telemetry systems, leveraging established infrastructure for seamless data flow. Madeira integrates during commissioning (Q3 2026) with high-bandwidth fibre optic connection enabling image streaming and rapid data delivery. Faial begins ongoing manual data uploads (Q2 2026 following geophysical survey and well installation) with processed data files uploaded monthly via web interface. Cape Verde initiates ongoing uploads (Q4 2027 following construction) using mobile application for offline data entry during quarterly field visits with subsequent synchronisation.

4.2 Monitoring programme

The monitoring programme defines what parameters are measured, at what frequencies, using which methods across the five GENESIS demonstrators, balancing comprehensive characterisation enabling robust performance assessment against practical constraints of budget, personnel availability, and analytical capacity.

4.2.1 Continuous automated monitoring

Continuous monitoring employs unattended sensors with automated data logging and telemetry, capturing high-frequency data characterising dynamic processes and enabling near-real-time operational management. Groundwater levels measured at hourly minimum frequency (15-minute where rapid responses anticipated) provide the core indicator for all five demonstrators, with monitoring wells distributed across anticipated zones of influence capturing spatial heterogeneity in aquifer response. Measurements continue through both recharge operations and quiescent periods characterising response dynamics and dissipation, with reference wells beyond zones of influence providing control data distinguishing intervention effects from regional trends.

Surface water stage and flow monitoring at 15-30 minutes intervals quantifies infiltration basin inflow and outflow at Madeira, revealing capture efficiency and overflow frequency whilst downstream baseflow measurements indicate enhanced groundwater discharge. Cape Verde’s ephemeral stream responses during storm events characterise flood attenuation benefits, though resource constraints may limit instrumentation to manual observations supplemented by photographic documentation. Soil moisture profiles monitored hourly at multiple depths (minimum 20, 50, 100 cm) characterise vadose zone dynamics and deep percolation at Madeira’s urban demonstrator, with distributed profiles capturing spatial variability across the infiltration basin revealing hydraulic properties and preferential flow paths.

Water quality multiparameter sondes operating at hourly frequency (15-minute during commissioning or events) measure temperature, electrical conductivity, dissolved oxygen, pH, oxidation-reduction potential, and turbidity at critical locations. Gran Canaria employs injection point monitoring verifying source water quality before aquifer entry, addressing public concerns through transparent continuous verification, whilst near-field monitoring wells detect immediate quality responses to recharge operations. El Hierro's compartment-specific monitoring reveals quality differences across dike-bounded units guiding adaptive abstraction management, whilst Faial's combined pressure-conductivity sensors detect any saline water mobilisation from coastal interfaces. Meteorological parameters measured at 10-minutes to hourly frequencies establish atmospheric forcing for water balance calculations, using on-site measurements where microclimatic variations are significant (Madeira's urban setting) or integrating with regional networks where representative (Faial and Gran Canaria via existing IPMA/AEMET stations).

Monitoring frequencies vary across demonstrators reflecting operational contexts and resource constraints. Faial employs hourly water level and conductivity monitoring across 6-8 wells with autonomous logging, Gran Canaria operates hourly measurements across 12 coastal wells plus 6 sonde locations with continuous injection line flow monitoring, El Hierro captures hourly data per compartment plus regional observation wells, Madeira implements hourly monitoring in basin and observation network with 15-minutes inflow-outflow measurements, whilst Cape Verde relies on weekly manual water level readings where wells are available given quarterly site access limitations.

4.2.2 Periodic sampling campaigns

Periodic sampling campaigns address parameters requiring laboratory analysis or exhibiting slower temporal dynamics, with frequencies balancing adequate temporal coverage for detecting trends against analytical costs and personnel demands. Monthly campaigns provide comprehensive water quality characterisation with groundwater sampling from monitoring well networks measuring major ions (calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate), nutrients (nitrate, nitrite, ammonium, phosphate), and field parameters (temperature, electrical conductivity, pH, dissolved oxygen, alkalinity). Gran Canaria employs an enhanced monthly suite adding chemical oxygen demand, total organic carbon, trace metals (iron, manganese, lead, zinc), and microbial indicators (*E. coli*, total coliforms) addressing reclaimed water [35-42] injection concerns, whilst surface water sampling at Madeira and Cape Verde characterises highland stream source water, basin standing water, and downstream discharge or lagoon water during wet periods.

Quarterly campaigns expand monitoring network coverage to boundary wells or regional monitoring points establishing context beyond immediate demonstrator areas, employ depth-specific sampling in multi-level wells characterising vertical stratification, and extend parameter suites addressing emerging contaminants of concern. Gran Canaria conducts quarterly pharmaceutical and personal care product screening during the first year (transitioning to semi-annual thereafter) alongside bi-annual pesticide sampling during agricultural seasons, reflecting potential contaminant sources in reclaimed wastewater. All demonstrators include extended trace metals panels and stable isotopes (δ^{2}H, δ^{18}O) for source water fingerprinting on annual or bi-annual basis, whilst Madeira emphasises polycyclic aromatic hydrocarbons and heavy metals from urban runoff with quarterly sampling during the first year transitioning to event-based monitoring thereafter. Ecological sampling occurs quarterly during establishment phases (first two years) documenting vegetation colonisation success and habitat development at Madeira and Cape Verde, transitioning to annual surveys once communities stabilise.

Semi-annual and annual campaigns provide comprehensive hydrochemistry characterisation with full major and trace element analysis, stable isotopes, and potentially radioisotopes (tritium for age dating) revealing aquifer mixing and residence times. Gran Canaria conducts semi-annual comprehensive pharmaceutical and microplastic screening addressing persistent public concerns about groundwater contamination from reclaimed water sources. Event-based sampling responds to storm events (Madeira and Cape Verde automated samplers or rapid response teams collecting flow-weighted composites or time-series discrete samples characterising first-flush effects), operational tests during commissioning examining system response to varied injection rates or timing, and incident response to elevated contaminant detection or stakeholder concerns requiring enhanced characterisation.

Sampling frequencies reflect demonstrator-specific contexts, with Faial conducting monthly groundwater sampling across 6-8 wells using standard parameter suite, Gran Canaria implementing bi-weekly monitoring matching existing EDAR protocols across 12 wells with enhanced organics suite, El Hierro sampling three compartments plus regional wells monthly with standard suite, Madeira monitoring basin and observation network monthly with urban runoff emphasis, and Cape Verde conducting quarterly rather than monthly campaigns given access constraints whilst maintaining annual comprehensive characterisation appropriate for resource limitations.

4.2.3 Water sampling protocols

Consistent sampling protocols ensure comparable data quality across demonstrators and temporal sampling events, following established standards (ISO, USGS, national guidelines) adapted to site-specific conditions [29, 30, 43]. Groundwater sampling employs low-flow purging as the preferred method, positioning pump intake at mid-screen depth with pumping rates below 500 mL/min maintaining minimal drawdown whilst monitoring field parameters continuously until stabilisation criteria are met (typically ±0.1 pH units, ±3% electrical conductivity, ±10% dissolved oxygen across three consecutive measurements). Samples are collected directly from pump discharge into clean bottles with appropriate preservation, with purge water volumes typically 1-3 litres substantially less than traditional three-casing-volume purging employed where low-flow equipment is unavailable.

Surface water sampling uses grab samples from well-mixed mid-depth water column for routine characterisation, automated samplers programmed for time-based intervals during events (typically 15-minute frequency during first hour, hourly thereafter), and composite samples for average quality assessment. Sample handling follows standardised preservation and holding time protocols with most parameters cooled to 4°C immediately and maintained refrigerated until analysis, dissolved metals filtered (0.45 µm) in field and acidified to pH <2, nutrients preserved with H_2SO_4 for some parameters and analysed within 48 hours, microbiology samples cooled without freezing and analysed within 6-8 hours. Chain of custody documentation accompanies all samples with continuous documented possession from collection through analysis, whilst laboratory selection emphasises ISO/IEC 17025 accreditation for regulatory compliance parameters with method detection limits adequate for expected concentration ranges.

Quality control samples constitute 10% of total samples as field blanks prepared using contaminant-free water processed through sampling equipment quantifying contamination, 10% as replicate samples collected from same location and time quantifying sampling and analytical variability, and equipment blanks from cleaned sampling equipment verifying decontamination procedures. Demonstrator-specific protocols reflect varying contexts, with Gran Canaria employing particularly rigorous chain of custody and laboratory quality assurance given public concerns about reclaimed water injection, Faial implementing efficient low-flow procedures minimising purge water disposal in remote locations, El Hierro sampling from dedicated taps at each compartment avoiding well sampling equipment, Madeira benefiting from rapid transport to university laboratories supporting shorter holding times, and Cape Verde using portable test kits for immediate field measurements with preserved samples for comprehensive laboratory analysis during longer field campaigns.

4.2.4 Quality assurance and quality control

Systematic quality assurance and quality control procedures ensure monitoring data meet accuracy, precision, representativeness, comparability, and completeness standards through automated real-time screening, routine manual review, and periodic comprehensive audits. Automated data quality control employs range checks flagging values exceeding physically plausible ranges, rate-of-change limits detecting sudden changes exceeding realistic rates, redundant sensor comparisons identifying divergence beyond expected precision indicating sensor drift or failure, and spike detection algorithms distinguishing isolated anomalous values from real phenomena. Automated quality control assigns flag codes with A (approved) indicating data passing all checks, E (estimated) indicating missing data filled by documented interpolation, S (suspect) indicating automated flags requiring manual review, and R (rejected) indicating data confirmed invalid through manual review.

Manual review processes operate at weekly, monthly, and quarterly frequencies with operational personnel examining data plots for sensor issues requiring maintenance, technical specialists conducting comprehensive review examining temporal patterns and spatial consistency, and cross-demonstrator assessment validating standardised protocols maintain comparability. Laboratory quality assurance maintains ISO/IEC 17025 accreditation with documented quality manuals and standard operating procedures, internal quality control including method blanks, laboratory control samples, matrix spikes, and duplicate analyses tracking performance across batches, and external quality control through quarterly inter-laboratory comparison programmes and split samples verifying consistency.

Sensor calibration schedules require annual verification for water level sensors against manual measurements with recalibration if drift exceeds 1 cm, monthly field verification and quarterly comprehensive recalibration for water quality sondes (more frequent in fouling-prone conditions), annual verification for flow meters against volumetric methods or reference meters with recalibration if drift exceeds 5%, and annual verification for meteorological sensors against certified reference instruments. Corrective action protocols respond to identified data quality issues with minor issues (single sensor drift, isolated missing data) triggering field maintenance within 2-4 weeks and interim data flagging, moderate issues (multiple sensor problems, systematic gaps) prompting emergency site visits within one week, and severe issues (complete monitoring outage, suspected data integrity compromise) requiring immediate response within 24-48 hours with comprehensive system evaluation.

4.3 Data management

The GENESIS data management framework implements FAIR principles ensuring monitoring data serve immediate project needs whilst creating lasting value beyond project timescales.

4.3.1 Data architecture and standards

Data and metadata are assigned persistent identifiers (DOIs) enabling unambiguous citation and retrieval, with comprehensive metadata following international standards (ISO 19115 for geospatial, DataCite for datasets) ensuring datasets are discoverable through academic and government data catalogues. GENESIS datasets are registered in relevant repositories (European Geological Data Infrastructure, national geological surveys) maximising visibility whilst stored in repositories with guaranteed long-term access beyond project completion. Time-series data employ CF-compliant NetCDF or CSV formats with ISO 8601 date-times and documented units, spatial data use GeoPackage or standard GIS formats with defined coordinate reference systems, and controlled vocabularies from relevant ontologies (ENVO for environmental parameters, SWEET for Earth science) annotate measurements enabling semantic search and integration.

Comprehensive metadata document data collection methods, quality control procedures, known limitations, and appropriate uses with data dictionaries defining all variables, units, precision, and codes. Version control tracks dataset evolution with change logs documenting additions or corrections, clear licensing (Creative Commons or similar) specifies permissible reuse whilst ensuring proper attribution, and provenance metadata link processed datasets to source measurements and processing code enabling reproducibility [44, 45].

4.3.2 Data collection, storage and quality control

Data flow proceeds from field sensors through telemetry to cloud infrastructure where incoming streams are parsed by API endpoints validating format and assigning preliminary quality flags based on range checks and rate limits. All incoming data are stored in raw form preserving original timestamps and values providing permanent audit trail, then processed through quality control algorithms assigning flags and generating alerts for operator attention. Operators review flagged data consulting field logs and contextual information to approve or reject suspect values, with validated data released to production database accessible through standard interfaces. Validated data are processed to compute derived parameters (water level changes, recharge rates), temporal aggregations (hourly to daily to monthly means), and spatial interpolations (kriged surfaces), with annual snapshots archived to long-term preservation systems ensuring data survive beyond project timescales.

Production database employs PostgreSQL with PostGIS extension providing operational storage with partitioned tables by time and demonstrator optimising query performance, whilst object storage holds non-tabular data including photographs, reports, processing scripts, and configuration files. Daily differential backups replicate to geographically separated locations with 30-day retention, monthly full backups are retained for project duration, and annual archival snapshots are preserved permanently, ensuring recovery point objective below 24 hours and recovery time objective below 72 hours.

4.3.3 Data accessibility and sharing protocols

Access tiers implement role-based permissions with public access to aggregated data (monthly means) and metadata immediately available through GENESIS website and registered repositories, consortium access to complete validated datasets including high-frequency time series through authenticated portal, collaborators and regulators granted access to specific datasets through formal data sharing agreements, and administrators maintaining unrestricted access including raw data and provisional datasets. Embargo policies maintain detailed operational data (hourly time series, comprehensive water quality) within consortium during active project period through 2029 enabling priority publication rights, with datasets underlying published research becoming fully public upon article publication and complete validated datasets for all demonstrators released to public archives no later than six months following project completion (mid-2030).

4.3.4 Integration with GENESIS data platform

The GENESIS data platform serves as central hub integrating monitoring data across five demonstrators, analytical tools from multiple work packages, and knowledge products serving diverse audiences. Platform architecture employs centralised PostgreSQL/PostGIS database hosting monitoring data from all demonstrators, browser-based web portal providing interactive data exploration and download without specialised software, RESTful API enabling programmatic access for analytical tools (R, Python, MATLAB, GIS software), and mobile applications supporting field data collection in offline mode with synchronisation upon network reconnection.

Integration across work packages connects WP1 regional climate data and projections providing context for demonstrator performance, WP2 social survey data enabling spatial analysis of acceptability patterns, WP3 and WP4 demonstrators data for calibration and scenario comparison, WP5 modelling and uncertainty analysis, and WP6 information supporting outreach activities.

Platform development proceeds through four phases with Phase 1 (Q4 2025 - Q1 2026) establishing core infrastructure and El Hierro integration demonstrating real-time capabilities, Phase 2 (Q2-Q3 2026) expanding to Gran Canaria and Faial with enhanced quality control for reclaimed water complexity, Phase 3 (Q4 2026 - Q3 2027) adding Madeira's urban demonstrator with distinct parameters and deploying Cape Verde mobile application, and Phase 4 (Q4 2027 onwards) operating full five-demonstrator platform and La Palma Deep demonstrator data with focus shifting to performance assessment and legacy planning ensuring platform persistence beyond project completion

4.4 NbS implementation protocols

Implementation protocols provide standardised approaches for design finalisation, construction management, commissioning, and operational management ensuring demonstrators deliver intended performance whilst generating lessons informing future implementations.

4.4.1 Design requirements

Comprehensive design documentation serves multiple purposes including obtaining permits, guiding contractors, training operational personnel, and creating permanent records. Conceptual design reports prepared during planning document site characterisation synthesising geophysical surveys and baseline monitoring, water balance analyses quantifying available water and storage capacity, NbS selection rationale explaining why chosen typology suits site conditions, preliminary layouts showing major components with positioning justification, stakeholder engagement summaries, permitting requirements analysis, preliminary cost estimates (±30% accuracy), and implementation timelines. Detailed design packages suitable for construction procurement include engineering drawings with dimensions and specifications, structural calculations and hydraulic analyses, technical specifications for materials and methods, integrated monitoring network design, operation and maintenance manuals, health and safety plans, environmental management plans, and final cost estimates (±10% accuracy).

Following construction completion, as-built documentation records updated drawings showing final conditions including deviations, photographic records documenting construction sequence and buried infrastructure, geotechnical data from construction, materials certifications, deviation reports explaining design changes and approval processes, commissioning test results demonstrating system functionality, and final cost accounting comparing estimated to actual expenditures. Demonstrator-specific design status varies with El Hierro's design complete focusing on telecontrol system development (Q4 2025 - Q1 2026), Gran Canaria's detailed design substantially complete with on-site staking-out finished and construction anticipated Q2-Q3 2026, Madeira's design consultancy tender launched Q4 2025 with detailed design expected Q1-Q2 2026, Faial's design requiring only final well positioning refinement following January 2026 geophysical survey with construction Q2-Q3 2026, and Cape Verde's conceptual design under refinement following November 2024 floods with detailed design expected Q2-Q3 2027.

4.4.2 Construction and commissioning standards

Pre-construction activities include contractor selection through competitive procurement balancing cost with demonstrated competence, pre-construction meetings reviewing design intent and expectations, site mobilisation establishing facilities and safety measures, baseline surveys documenting conditions, and stakeholder communication providing advance notice of construction activities. Construction quality control employs qualified engineer inspections verifying compliance with plans and specifications (typically daily during critical activities, weekly during routine work), systematic materials testing (concrete strength, compaction, aggregate quality), dimensional verification through surveying, comprehensive documentation (daily logs, inspection reports, test results, photographs), and adaptive problem-solving addressing unexpected conditions through engineering review and formal change orders.

Commissioning includes functional testing systematically verifying components and systems operate as designed (infiltration testing confirming design rates, flow monitoring verifying delivery systems, instrumentation testing validating sensor performance), pre-operational baseline monitoring immediately before system activation establishing reference for assessing operational impacts, operator training providing hands-on instruction covering routine procedures and emergency response with documented competency assessments, and provisional acceptance following successful testing with warranty period during which contractor remains responsible for defects correction.

4.4.3 Operational management

Routine operational procedures vary by demonstrator typology with infiltration basin management (Madeira, Cape Verde) requiring pre-storm inspection ensuring outlets are clear, post-storm inspection documenting performance and sediment accumulation, dry season maintenance including sediment removal and vegetation management, and seasonal preparation activities. Injection well and trench operations (Faial, Gran Canaria) involve daily operational checks of flow rates and pressures, weekly water quality verification sampling at injection points, monthly performance reviews of cumulative volumes and aquifer response patterns, and seasonal adjustments optimising injection timing with natural recharge patterns. Multi-compartment well operation (El Hierro) employs continuous compartment-specific monitoring, weekly operational data review identifying optimal abstraction distribution, monthly performance assessment comparing actual to planned abstractions, and quarterly comprehensive review integrating regional monitoring and user feedback.

Operational decision-making follows established frameworks with flow diversion and injection rate control based on trigger criteria considering source water availability and aquifer conditions, basin drawdown and recovery cycles targeting intervals enabling sediment drying and infiltration rate maintenance, load management matching injection to aquifer acceptance capacity, and seasonal operational variations maximising capture during high water availability periods. Stakeholder engagement includes community participation in monitoring activities building ownership, transparent operational communication through regular updates and web portal dashboards, educational programming leveraging demonstrators as learning platforms, and feedback mechanisms enabling rapid response to concerns.

4.4.4 Adaptive management procedures

Adaptive management embraces uncertainty through structured cycles of implementation, monitoring, evaluation, and adjustment rather than treating design predictions as fixed truth. The cycle proceeds through establishing measurable objectives, implementing NbS whilst monitoring, evaluating performance against objectives, diagnosing causes when performance differs from expectations, identifying modifications, implementing adjustments, and continuing the cycle incorporating learning.

Adaptive management triggers include performance-based concerns (consistent performance exceeding 20% below targets, unexpected responses, ecological concerns), regulatory compliance issues (parameter exceedances, permit violations), stakeholder feedback (sustained community concerns, identified opportunities), and external conditions (extreme events, land use changes, climate manifestations). Adaptive management logs maintain permanent records tracking triggers through resolution, with regular lessons learned synthesis and knowledge sharing across demonstrators through quarterly meetings and annual workshops.

Governance for adaptive decisions follows WP2 frameworks with minor operational adjustments (injection timing, monitoring frequency) under site manager authority, moderate modifications (infrastructure repairs, network expansion) requiring stakeholder consultation and WP3 coordination with formal approval, and major changes (fundamental design modifications, target revisions) engaging full governance processes with broader stakeholder groups.

5 Implementation roadmap

5.1 Implementation strategy

The GENESIS demonstration programme unfolds across a carefully sequenced timeline designed to maximise learning transfer between sites whilst accommodating the diverse stages of development characterising each intervention. This phased approach recognises that the five demonstrators entered the project at different maturity levels—from advanced permitting stages in Azores and Canaries to conceptual planning in Cape Verde—creating both challenges for synchronised implementation and opportunities for iterative refinement of methodologies.

Rather than viewing this temporal distribution as merely a project management constraint, the implementation strategy deliberately leverages sequential development to strengthen the overall programme. Early learnings from more advanced sites inform design optimisation, monitoring protocol refinement, and stakeholder engagement approaches at later-stage demonstrations. This adaptive implementation model transforms potential coordination difficulties into strategic advantages, creating a portfolio of demonstrations that collectively advance beyond what simultaneous identical implementations could achieve.

The roadmap distinguishes four distinct implementation phases spanning the project duration: preparation and baseline establishment, construction and commissioning, operational monitoring and adaptive management, and synthesis and knowledge transfer. Whilst all sites progress through these phases, their temporal positioning differs according to site-specific circumstances and the deliberate sequencing strategy that enables knowledge flow across the demonstration portfolio.

5.1.1 Phase 1: Preparation and baseline establishment (months 1-16)

This phase corresponds to the work made since the project start (September 2024) until December 2025. This phase comprised all activities necessary for establishing the technical, institutional, and social infrastructure necessary for successful implementation. Site characterisation surveys generated the hydrogeological understanding upon which design decisions rest, permitting processes secure necessary regulatory approvals, and stakeholder engagement builds community support essential for long-term success. Simultaneously, baseline monitoring programmes commenced data collection establishing reference conditions against which intervention impacts will be assessed.

The speed of this process varies across demonstrators: El Hierro, Madeira and Gran Canaria have a clear design defined, marking baseline monitoring augmentation and integration with the standardised GENESIS framework. These sites can proceed rapidly toward construction after the completion of the ongoing permitting stage, whilst ensuring monitoring programmes align with the protocols established in Chapter 4 and capture parameters required for the assessment framework detailed in Chapter 3.

Sites requiring more extensive preparation—particularly Faial where geophysical surveys inform well positioning, and Cape Verde where conceptual designs were delayed by catastrophic flood events—are now heavily investing in characterisation activities. Nevertheless, this extended preparation enables incorporation of lessons learned from more advanced sites, potentially avoiding design limitations or monitoring gaps that early implementations might subsequently identify. The preparation phase served not merely as prerequisite activity but as opportunity for continuous improvement across the demonstration portfolio.

5.1.2 Phase 2: Construction and commissioning (months 17-28)

Physical implementation of nature-based solutions occurs during the construction phase, transforming designs into operational installations through carefully managed civil works. The phase encompasses procurement of construction services, mobilisation and site preparation, earthworks and structural construction, installation of monitoring instrumentation, system commissioning, and as-built documentation. Throughout construction, quality assurance procedures verify compliance with design specifications whilst adaptive problem-solving addresses unforeseen conditions that detailed investigations inevitably fail to detect.

Construction sequencing reflects both site readiness and strategic learning objectives. Gran Canaria's infiltration trench system, benefiting from advanced permitting and detailed design, constitutes the earliest physical implementation, with construction anticipated during months 12-18. This early completion enables operational monitoring data collection spanning the maximum possible duration within project timescales, generating the richest dataset for performance assessment and providing early insights informing subsequent implementations.

Faial's infiltration well construction follows completion of geophysical surveys and well position optimisation, targeted for months 19-21. This slight delay enables incorporation of any lessons learned from Gran Canaria construction, particularly regarding quality assurance procedures, stakeholder communication during disruptive works, and commissioning protocols. The temporal offset, whilst modest, provides valuable opportunity for adaptive improvement without substantially compromising monitoring duration.

Madeira's infiltration basin construction, dependent upon design consultancy completion and construction tender processes, is anticipated during months 18-24. This timeline reflects municipal procurement procedures and the deliberate decision to invest in thorough design before construction, reducing risks of costly modifications during implementation. The later start date also enables the Madeira team to observe operational experiences from both Gran Canaria and Faial, informing operational procedures and adaptive management approaches from project inception.

El Hierro represents a unique case where physical infrastructure already exists and ”construction” comprises solely monitoring system installation. This lighter intervention proceeds during months 18-24, enabling early operational data collection. The rapid implementation pathway demonstrates that enhancing existing infrastructure through improved monitoring and adaptive management can deliver benefits comparable to new construction whilst requiring substantially less time and investment.

Cape Verde's infiltration lagoon construction represents the programme's latest implementation, scheduled for months 20-28 following resolution of post-flood infrastructure recovery and completion of detailed design incorporating lessons from all other demonstrations. This final implementation benefits from the most comprehensive learning transfer, applying refined approaches across design, construction management, monitoring configuration, and stakeholder engagement. The late timing, whilst constraining operational monitoring duration, positions Cape Verde as the demonstration most likely to achieve optimal performance from project inception. A deliverable (D3.2) will detail the commissioning and implementation of NbS.

5.1.3 Phase 3: Operational monitoring (months 29-46)

The operational phase generates the empirical evidence quantifying nature-based solution performance across the diverse contexts represented by GENESIS demonstrators. Continuous automated monitoring accumulates high-frequency datasets characterising system response to varying hydrological conditions, periodic sampling campaigns assess water quality and ecological parameters, and adaptive management procedures adjust operational practices in response to observed performance and emerging understanding.

Operational monitoring commences upon system commissioning, establishing post-implementation baselines revealing initial system behaviour before steady-state conditions develop. This transition period often exhibits transient responses—such as initial water quality perturbations as infiltrating water contacts aquifer materials, or establishment lags before ecological communities colonise new habitat—that differ from long-term performance. Distinguishing commissioning transients from sustained operational behaviour requires sufficiently long monitoring duration, reinforcing the strategic value of early implementation enabling extended operational observation.

The monitoring frequency and parameter suite during operations reflect the standardised protocols established in Chapter 4, adapted where necessary to site-specific priorities or resource constraints. Continuous automated monitoring emphasises hydrological parameters—water levels, flow rates, and basic quality indicators—providing high temporal resolution datasets characterising system dynamics. Periodic sampling campaigns at monthly to quarterly intervals address parameters requiring laboratory analysis, including comprehensive water quality suites, contaminants of emerging concern, and ecological indicators. This hierarchical monitoring strategy balances comprehensive characterisation with sustainable resource requirements, focusing intensive effort where it delivers greatest insight.

Adaptive management procedures respond to monitoring evidence, operational experience, and stakeholder feedback through systematic evaluation cycles. Monthly operational reviews assess routine performance metrics, identifying any parameter exceedances or equipment malfunctions requiring immediate attention. Quarterly assessment meetings synthesise accumulated data, evaluating performance against objectives established in Chapter 3 and considering whether operational adjustments could improve outcomes. Annual comprehensive evaluations engage broader stakeholder groups in reviewing overall performance, assessing co-benefit delivery, and identifying opportunities for enhancement.

This adaptive approach recognises that nature-based solutions perform differently than engineering predictions anticipate, responding to site-specific conditions, unexpected interactions, and evolving external factors that models cannot fully capture. Rather than viewing deviations from predictions as failures, adaptive management treats them as learning opportunities, systematically investigating causes and implementing refinements. The monitoring programmes provide the empirical foundation enabling evidence-based adaptation rather than intuitive responses to perceived problems.

5.1.4 Phase 4: Synthesis and knowledge transfer (months 36-48)

The final phase synthesises learnings across the demonstration portfolio, evaluating comparative performance, identifying transferable principles, and disseminating results to water management communities throughout Atlantic Island territories and beyond. This synthesis extends beyond simple aggregation of site-specific findings to examine cross-cutting patterns, contextual factors influencing performance variability, and barriers or enablers affecting implementation success.

Comparative analysis examines performance across the demonstration portfolio, revealing how different nature-based solution typologies, hydrogeological contexts, and institutional arrangements influence outcomes. Statistical analyses quantify relationships between site characteristics and performance metrics, identifying which factors most strongly determine success and where careful attention during design or operation proves most critical. These quantitative assessments complement qualitative synthesis of implementation experiences, capturing tacit knowledge about stakeholder engagement, adaptive management, and operational problem-solving that numbers alone cannot convey.

Knowledge transfer activities translate technical findings into accessible guidance for water managers, policy makers, and implementing agencies. Site visits provide immersive learning experiences where practitioners observe functioning systems, discuss operational challenges directly with site managers, and envision adaptations to their own contexts. Workshops and training programmes synthesise learnings into structured curricula, building capacity for nature-based solution implementation across Atlantic Island territories. Technical publications document methodologies and results for scientific audiences, whilst policy briefs and practice guides distil insights for decision-making audiences requiring concise, actionable information.

The GENESIS data platform, described in Section 4.3.4, serves as the enduring legacy infrastructure enabling continued learning beyond project completion. By archiving monitoring data, technical documentation, and operational records in accessible standardised formats, the platform supports future research, enables performance benchmarking for new installations, and provides empirical foundation for refining design guidance as longer-term operational experience accumulates. This commitment to open data and knowledge sharing reflects recognition that nature-based solutions advance most rapidly when learning flows freely across implementations rather than remaining isolated within individual projects.

5.2 Roles and responsibilities

5.2.1 Support and coordination

EFG, as WP3 lead, bears overall responsibility for coordinating the demonstration programme, ensuring consistency across demonstrators, and delivering technical outputs including this framework document. This coordination role encompasses scheduling regular progress reviews, facilitating knowledge exchange between demonstrators, maintaining the shared data platform, and synthesising cross-site learnings. EFG provides technical support on monitoring protocols, data management procedures, and quality assurance, whilst respecting site managers' authority over operational decisions affecting local stakeholders and site-specific conditions.

The WP3 leadership also maintains critical interfaces with other work packages, particularly WP2 (social engagement), WP4 (La Palma deep demonstrator), WP5 (modelling and optimisation), and WP6 (clustering and exploitation). These interfaces ensure that demonstrators generate the data required for broader project objectives whilst benefiting from analytical capabilities and strategic insights developed elsewhere within the consortium. Regular coordination meetings spanning work package leads maintain alignment and identify opportunities for synergistic activities delivering value across multiple work packages simultaneously.

5.2.2 Site implementation partners

Each demonstrator operates under the leadership of a designated implementing partner bearing primary responsibility for local execution. These partners—CMH (Faial), ITC (Gran Canaria), ULL (El Hierro), UMA (Madeira), and UCV (Cape Verde)—manage design finalisation, permitting, procurement, construction supervision, operational management, and local stakeholder engagement. Site implementation partners possess intimate understanding of local contexts, institutional landscapes, and stakeholder priorities that external coordination cannot replicate, making their leadership essential for navigating site-specific complexities.

Site implementation partners serve as primary points of contact for local stakeholders, translating technical concepts into locally meaningful terms, addressing community concerns, and fostering collaborative relationships essential for long-term success. This stakeholder engagement role extends beyond consultation to genuine participation, incorporating local knowledge into design refinement and operational management whilst building local capacity for sustained management beyond project completion. The relationships site implementation partners cultivate often prove as valuable as physical infrastructure, creating social capital enabling adaptive responses to future challenges.

Technical responsibilities of site implementation partners include oversight of construction quality assurance, calibration and maintenance of monitoring equipment, data quality review, and operational performance assessment. These partners employ or contract technical specialists possessing expertise in hydrogeology, water quality analysis, construction management, and environmental monitoring, ensuring that implementation meets professional standards. Where specialist expertise proves unavailable locally, site implementation partners coordinate with WP3 leadership to identify consortium resources or external expertise addressing knowledge gaps.

5.2.3 External entities

Several demonstrators involve collaboration with entities beyond the core GENESIS consortium, including municipal authorities, water utilities, irrigation communities, and environmental agencies. These external partners contribute resources, expertise, or institutional authority essential for implementation but operate under distinct administrative and accountability frameworks. Managing these partnerships requires clear agreements defining respective responsibilities, resource contributions, intellectual property arrangements, and dispute resolution mechanisms.

5.3 Coordination mechanisms

Effective coordination across geographically dispersed sites operating under different institutional frameworks requires structured communication mechanisms preventing information silos whilst avoiding coordination overhead that impedes actual implementation. The GENESIS programme employs a tiered coordination strategy combining regular scheduled interactions with responsive ad hoc communication, supported by digital collaboration infrastructure enabling asynchronous knowledge exchange.

5.3.1 Coordination meetings

Quarterly coordination meetings bring together GENESIS WP leaders do discuss progress reporting, technical problem-solving, adaptive planning, and knowledge exchange across project activities. Structured agendas balance reporting requirements with interactive discussion, ensuring meetings serve learning and coordination rather than merely status updating.

Meeting formats alternate between virtual sessions enabling efficient participation across Atlantic Island locations and in-person gatherings coinciding with site visits or consortium-wide project meetings. In-person meetings incorporate site tours, enabling partners to observe diverse implementation approaches firsthand and envision adaptations to their own contexts. These immersive experiences generate insights difficult to convey through remote presentations, strengthening cross-site learning and building interpersonal relationships that facilitate ongoing collaboration.

Quarterly meetings are booked by the Project Coordinator and employ systematic reporting templates ensuring consistent information flow whilst enabling site-specific emphasis on current priorities or challenges. Template sections address implementation progress against milestones, monitoring data summary and preliminary interpretation, operational challenges and adaptive responses, stakeholder engagement activities and feedback, and upcoming decisions requiring coordination or advisory input. Standardised reporting reduces preparation burden whilst ensuring all sites provide information necessary for portfolio-level assessment and coordination.

5.3.2 Technical coordination

Monthly calls rotate thematic focus across critical technical domains including hydrogeological monitoring, water quality assessment, ecological monitoring, data management, and adaptive management implementation. This rotation ensures adequate attention to diverse technical aspects whilst preventing meetings from becoming unwieldy attempts to cover all topics simultaneously. Sites facing particular challenges in the month's focus area receive concentrated attention from collective expertise, whilst others benefit from learning about potential issues before encountering them.

Participation in monthly calls scales according to topic relevance, with core attendance from site implementation partners and WP3 coordination but flexible participation from technical specialists whose expertise addresses specific discussion topics. This variable attendance model respects participants' time constraints whilst ensuring relevant expertise informs discussions. Call summaries distributed to all consortium members maintain transparency and enable indirect participation from those unable to attend synchronously.

5.3.3 Site visits

Structured site visits enable consortium members to observe implementation progress, assess monitoring installations, and engage with local stakeholders across diverse demonstration contexts. The visit programme balances learning objectives with logistical constraints, prioritising visits timed to coincide with critical implementation phases—such as commissioning new monitoring installations or evaluating operational performance—when external perspective proves most valuable.

Each site hosts at least two consortium visits during the demonstration programme: during initial implementation to observe site conditions and baseline monitoring, during system commissioning to evaluate installation quality and operational procedures, or during the synthesis phase to assess mature operational performance and facilitate knowledge transfer. Additional visits occur as needed to address specific technical challenges or support collaborative research activities spanning multiple work packages.

Site visit protocols establish clear expectations regarding schedule, participants, objectives, and deliverables, ensuring visits serve structured purposes. Pre-visit briefing materials provide participants background on site context, implementation status, and specific questions or issues warranting attention. Post-visit reports synthesise observations and recommendations, creating documented record informing subsequent implementation decisions and contributing to cross-site comparative analysis.

5.4 Milestones

NbS operate in complex, incompletely understood systems where rigid adherence to predetermined plans often proves counterproductive. For this reason, it’s important to recognise when to persist with established approaches and when adaptation serves project objectives better—a judgement informed by the monitoring evidence, assessment frameworks, and coordination mechanisms this document establishes.

Milestones are crucial for the monitoring process. Milestones demarcate progress through successive phases and decision points, and provide structure for programme management, enabling assessment of whether implementation proceeds according to plan, and adaptive responses to emerging information or changing circumstances.

5.4.1 Preparation phase

Completion of baseline characterisation reports for each site represents the first major milestone, establishing that sufficient understanding exists to proceed toward detailed design and construction. These reports synthesise geophysical surveys, aquifer testing, water quality assessments, ecological inventories, and stakeholder analyses, demonstrating that key uncertainties have been addressed and residual unknowns fall within acceptable bounds. Milestone achievement triggers progression to design finalisation and construction procurement. Within the GENESIS demonstration portfolio, El Hierro, Gran Canaria, and Madeira have already achieved this milestone, whilst Faial approaches completion following geophysical survey execution and Cape Verde continues baseline characterisation alongside post-flood infrastructure recovery.

Securing necessary permits and regulatory approvals constitutes another critical preparation milestone, verifying that legal and institutional prerequisites for implementation are satisfied. This milestone encompasses diverse approvals depending on site context—including construction permits, water rights modifications, and occupancy authorisations for public domain. Achieving this milestone demonstrates that proposed interventions align with regulatory frameworks and broader policy objectives, reducing implementation risks and enabling confident resource commitment. El Hierro is the only demonstrator that has successfully achieved this milestone, having secured the required permits under Spanish Law. Madeira, Gran Canaria, and Faial have initiated permitting processes with varying degrees of progress, whilst Cape Verde is completing the baseline characterisation before commencing formal licensing procedures.

Stakeholder engagement milestones confirm that local communities, water users, and regulatory authorities understand proposed interventions and support implementation. These milestones are demonstrated through documented consultation processes, incorporation of stakeholder feedback into design refinement, and formal agreements with key partners. Achieving stakeholder milestones creates social licence for implementation, reducing risks of opposition or conflicts that could delay or derail activities. All demonstrators have run focus group sessions and surveys with the general public (in the context of Work Package 2 activities), successfully achieving this milestone and establishing the collaborative relationships essential for long-term operational success.

5.4.2 Construction phase

Commencement of construction following successful contractor procurement represents a major milestone, transitioning from planning to physical implementation. This milestone requires that detailed designs are completed, materials procurement is secured, and site access is arranged. The construction commencement date anchors subsequent scheduling for monitoring installation, commissioning activities, and operational planning.

Structural completion milestones mark achievement of major construction elements—such as excavation completion for infiltration basins, well drilling completion and screen installation for injection wells, or trench construction and conveyance system connection for infiltration trenches. These milestones enable assessment of construction progress against schedules, verification of as-built conditions against design specifications, and planning for subsequent activities dependent upon structural readiness. Photographic documentation and survey verification accompany structural completion milestones, creating permanent record of achieved conditions.

Monitoring network installation completion represents a critical milestone enabling transition from construction to operational monitoring. This milestone requires that all sensors are installed and calibrated, telemetry systems are operational and transmitting data reliably, data quality control algorithms are validated, and manual sampling procedures are established and tested. Achieving this milestone demonstrates readiness to capture system commissioning transients and operational performance from project initiation rather than losing valuable early data to delayed monitoring activation.

System commissioning and provisional acceptance marks transition from construction contractor responsibility to owner operational responsibility. This milestone requires successful functional testing demonstrating that installations perform according to design specifications, training of operational personnel, completion of as-built documentation, and formal acceptance by site owners. The commissioning process often reveals minor deficiencies requiring contractor rectification before final acceptance, making provisional acceptance an important decision point where performance verification occurs before releasing contractual obligations.

5.4.3 Operational phase

Twelve months of continuous operational monitoring represents an important operational milestone, demonstrating system performance across diverse hydrological conditions including both wet and dry seasons. This duration enables preliminary performance assessment addressing questions about recharge efficiency, water quality impacts, and ecological responses whilst acknowledging that longer-term trends may differ from initial observations. The twelve-month assessment informs adaptive management decisions and provides early insights potentially benefiting later-stage implementations within the demonstration portfolio and early-engaged replicator regions.

Performance threshold achievements mark delivery of specific objectives established during project design. These might include documented groundwater level increases exceeding target magnitudes, water quality maintenance within specified bounds, ecological colonisation meeting diversity targets, or stakeholder satisfaction levels surpassing baseline conditions. Achieving performance milestones demonstrates that interventions deliver anticipated benefits, validating design approaches and building confidence for transferability to other contexts. These validated outcomes provide the empirical foundation essential for encouraging replication beyond the immediate demonstrators.

5.4.4 Replication phase

The final phase synthesises learnings across the demonstration portfolio whilst actively engaging prospective replicators in knowledge transfer activities designed to accelerate nature-based solution adoption across Atlantic Island territories and comparable contexts globally. This phase transforms accumulated monitoring evidence and operational experience into accessible guidance whilst building implementation capacity within networks already established through consortium partnerships.

Comparative analysis completion across the five demonstrators identifies performance patterns, contextual factors influencing outcomes, and generalisable principles informing future implementations. This milestone requires sufficient operational data from all sites to support robust statistical comparison, making it dependent upon latest-implementing sites achieving adequate monitoring duration. The comparative analysis informs development of design guidance, operational recommendations, and transferability frameworks specifically tailored to support replication planning. The analysis examines how different nature-based solution typologies, hydrogeological contexts, institutional arrangements, and stakeholder engagement approaches influence outcomes, revealing which factors most strongly determine success and where careful attention during design or operation proves most critical. These insights enable prospective replicators to assess which demonstration experiences most closely match their own contexts, focusing learning efforts where relevance proves highest whilst understanding how contextual differences might require adaptation.

Knowledge transfer product completion encompasses diverse outputs including peer-reviewed publications, technical guidance documents, policy briefs, training materials, and data platform population. These products translate project learnings into formats appropriate for distinct audiences, maximising the reach and impact of demonstration programme insights. Knowledge transfer milestones mark the programme’s transition from generating knowledge to disseminating it, fulfilling the broader objective of advancing nature-based solution adoption across Atlantic Island territories and comparable contexts globally.

European and global replicators are being systematically identified and recruited through the extensive networks of the European Federation of Geologists (EFG) and the European Association for Local Democracy (ALDA). This strategic engagement leverages established relationships spanning local governments from eight EU regions, eighteen associations of local authorities, twenty-one municipalities, and eighteen geoscience organisations directly accessible through ALDA and EFG membership. Three replicator regions—the Azorean municipalities of Santa Maria and Graciosa, and the University of La Réunion—constitute formal consortium partners, ensuring replication perspectives inform project activities from inception whilst positioning these regions to rapidly implement validated approaches.

All replicator prospects receive encouragement to attend GENESIS meetings and workshops, visit demonstrators and the La Palma Living Lab, and participate in the training boot camp scheduled for the synthesis phase. These immersive learning experiences enable prospective replicators to observe functioning systems, discuss operational challenges directly with site managers, and envision adaptations to their own contexts. The physical site visits prove particularly valuable for conveying tacit knowledge about adaptive management and stakeholder engagement that technical documentation alone cannot fully communicate.

Beyond attendance at consortium activities, replicators are encouraged to prepare initial assessments of their own water security challenges and identify potential groundwater nature-based solutions applicable to their contexts. These preliminary assessments serve dual purposes: helping replicators develop concrete implementation plans whilst providing consortium members with insights into diverse contexts where GENESIS frameworks might be applied. The engagement strategy thus creates bidirectional knowledge flow, enriching both demonstrator understanding and replicator implementation capacity.

6 Conclusions

The GENESIS harmonised framework for demonstrator evaluation and management establishes the operational foundation enabling systematic, rigorous, and comparable assessment of nature-based solutions across five diverse Atlantic Island contexts. This concluding chapter synthesises the framework's contributions, reflects on implementation challenges and opportunities, and identifies priorities for maximising learning value as demonstrations progress from design through operational monitoring to knowledge synthesis and transfer.

The harmonised framework directly advances GENESIS Work Package 3 objectives through six interconnected contributions. By establishing standardised assessment methodologies, performance indicators, and data collection protocols whilst maintaining necessary flexibility for site-specific adaptation, the framework ensures meaningful comparison of findings across Faial, Gran Canaria, El Hierro, Madeira, and Cape Verde. Comprehensive quality assurance procedures spanning sensor calibration, automated data screening, manual review processes, and laboratory accreditation ensure technical soundness, generating evidence that water authorities, funding agencies, and policy-makers will consider credible when making investment decisions. The framework's explicit attention to data quality, uncertainty quantification, and transparent documentation converts demonstrations into rigorous scientific experiments generating publishable evidence rather than merely technical showcases.

The framework facilitates integration across GENESIS Work Packages by connecting directly to participatory governance models developed in WP2, providing standardised hydrological data for WP4 modelling, delivering cost and performance information for WP5 economic valuation, and generating empirical foundations for WP6 policy recommendations. Through systematic monitoring protocols and explicit performance evaluation criteria triggering adaptive management responses, the framework enables early detection of challenges and iterative refinement of designs and operational procedures. By providing practical guidance complemented by training workshops and comprehensive documentation, the framework builds institutional capacity and facilitates knowledge transfer extending beyond immediate GENESIS partners through engagement with replicator regions.

These contributions are enabled by the strategic design of the demonstrator portfolio. The five GENESIS demonstrators collectively span the typology spectrum characterising nature-based approaches to groundwater management. Managed aquifer recharge through infiltration wells (Faial) addresses contexts with high transmissivity fractured rock aquifers where surface infiltration proves inefficient. Infiltration trenches for coastal aquifer protection (Gran Canaria) specifically target seawater intrusion through sustained barrier recharge with reclaimed water. Surface infiltration basins (Madeira, Cape Verde) restore hydrological connectivity disrupted by urbanisation or capture episodic flows in ephemeral streams. Multi-compartment well monitoring (El Hierro) demonstrates that sophisticated management of natural hydrogeological features can deliver water security benefits comparable to physical infrastructure whilst avoiding construction impacts.

This typology diversity enables systematic evaluation of which approaches suit which contexts, advancing beyond anecdotal case studies toward evidence-based typology selection guidance. The demonstrators also span critical contextual gradients including climate (humid Azores to semi-arid Cape Verde), development level (sophisticated infrastructure to resource-constrained contexts), institutional capacity, and social context (urban to agricultural to remote settings). The temporal distribution of demonstrator implementation, whilst creating coordination challenges, enables iterative learning, with El Hierro and Gran Canaria commencing operations earliest and generating performance data informing design refinement for later-implementing Madeira and Cape Verde. However, the August 2028 project conclusion creates significant constraints. El Hierro and Gran Canaria achieve comprehensive monitoring coverage (27 and 24 months respectively), Faial and Madeira achieve adequate durations (20 and 18 months), whilst Cape Verde reaches only 11 months without achieving mature operational phase, limiting opportunities for multi-year assessment and making post-project monitoring continuation particularly important.

Implementation inevitably encounters challenges requiring adaptive responses. Resource constraints varying across demonstrators create tensions between standardised protocols and practical limitations. Cape Verde exemplifies this challenge, where quarterly site access, limited infrastructure, and constrained analytical capacity preclude continuous telemetry and frequent laboratory analyses achievable elsewhere. The framework addresses this through tiered monitoring approaches maintaining essential comparability whilst accommodating site-appropriate methods. Technical capacity variations across implementing partners require differentiated support strategies provided through comprehensive documentation, training workshops, and sustained technical assistance, whilst temporal distribution enables early-implementing sites to develop expertise subsequently shared with later implementations. Stakeholder engagement complexity also varies, with Gran Canaria's reclaimed water injection facing public concerns requiring sustained transparent communication, whilst Faial's agricultural setting demands careful landowner coordination. The framework addresses this through explicit stakeholder engagement protocols informed by WP2 governance research, complemented by site-specific adaptation.

The framework itself remains subject to adaptive refinement as implementation experience accumulates. Initial monitoring networks may require adjustment once operational data reveal actual system behaviour differs from predictions. Performance targets may prove overly optimistic or unnecessarily conservative once empirical data accumulate. Quality control thresholds, data processing algorithms, and stakeholder engagement approaches evolve based on feedback and observed effectiveness. The framework's systematic documentation enables ongoing evaluation and improvement benefiting not only GENESIS demonstrators but future implementations adopting framework methodologies.

Looking forward to knowledge synthesis, operational monitoring accumulation across the five demonstrators will enable comparative performance analysis examining which NbS typologies deliver greatest recharge efficiency, best water quality maintenance, most valuable ecological co-benefits, highest stakeholder acceptance, and most favourable benefit-cost ratios. Statistical analyses will quantify relationships between site characteristics and performance outcomes, identifying which contextual factors most strongly influence success. Cost analysis synthesis will compare total lifecycle costs across typologies and contexts, revealing cost-effectiveness patterns. Co-benefit quantification will synthesise ecological monitoring, social surveys, and economic assessments to demonstrate the full value proposition for nature-based solutions. Institutional and governance analysis will identify enabling conditions and persistent barriers, informing policy recommendations addressing structural constraints rather than merely technical design guidance.

Transferability assessment will evaluate which demonstration lessons apply broadly across Atlantic Island contexts versus which prove specific to particular settings, developing decision frameworks guiding practitioners through typology selection, design choices, monitoring approaches, and operational strategies appropriate to their specific contexts. This assessment recognises that successful transferability depends on adapting approaches to local institutional capacities, stakeholder priorities, and resource constraints.

Beyond immediate GENESIS objectives, the harmonised framework contributes to broader advancement of nature-based solution practice through comprehensive documentation and open data publication enabling independent researchers to evaluate methodologies, verify results, and build upon findings. The framework's emphasis on multi-dimensional assessment spanning hydrological, ecological, social, and economic domains provides template for holistic NbS evaluation applicable beyond groundwater contexts. The explicit attention to comparability whilst accommodating contextual variation addresses persistent challenge in NbS research where case studies proliferate but systematic comparative assessment remains rare.

Several research priorities emerge for maximising learning value. Long-term monitoring extending beyond August 2028 proves essential for detecting outcomes requiring years to manifest—vegetation community succession, gradual quality changes, stakeholder perception evolution. Securing commitment and resources for sustained monitoring should remain priority, particularly for later-implementing demonstrators. Extreme event documentation offers critical opportunities for understanding nature-based solution resilience under stress conditions. Integration with climate projections enables assessment of how projected changes might affect long-term NbS performance and sustainability. Replication monitoring tracking how knowledge transfer recipients adapt GENESIS methodologies to their contexts would provide valuable insights about transferability barriers and enablers.

The harmonised framework represents substantial investment in systematic methodology and comparative assessment infrastructure, paying dividends through credible evidence generation, efficient integration across work packages, enabled adaptive management, built institutional capacity, and facilitated knowledge transfer—outcomes that ad hoc monitoring without deliberate standardisation could not achieve. By treating the five GENESIS demonstrators as carefully coordinated portfolio rather than isolated pilots, the framework maximises learning value whilst maintaining scientific rigour. The framework recognises that successful nature-based solutions require more than technical performance—they depend equally on stakeholder acceptance, institutional support, economic viability, and adaptive capacity. By addressing all these dimensions systematically and comparably across diverse contexts, GENESIS generates comprehensive understanding of factors determining whether nature-based approaches achieve sustained implementation and replication beyond demonstration projects.

The August 2028 project conclusion creates real constraints, particularly for later-implementing demonstrators. Post-project monitoring continuation and sustained stakeholder engagement prove essential for validating preliminary conclusions and demonstrating long-term sustainability. Institutional arrangements for continued monitoring should be established during project implementation to ensure continuity beyond formal project timescales.

As climate change intensifies water security challenges facing island communities globally, the need for evidence-based nature-based solutions becomes ever more urgent. The GENESIS harmonised framework ensures that when water managers, policy-makers, and funding agencies ask whether nature-based approaches can deliver reliable water security at acceptable costs whilst generating valuable co-benefits, GENESIS will provide credible answers grounded in rigorous standardised assessment across diverse real-world contexts. These answers—and the transparent methodologies enabling their independent verification and replication—constitute GENESIS's enduring contribution to advancing sustainable water futures for Atlantic Islands and comparable vulnerable communities worldwide.

7 References

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