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Research paper

Effects of the 2021 La Palma volcanic eruption on groundwater resources (part I): Hydraulic impacts

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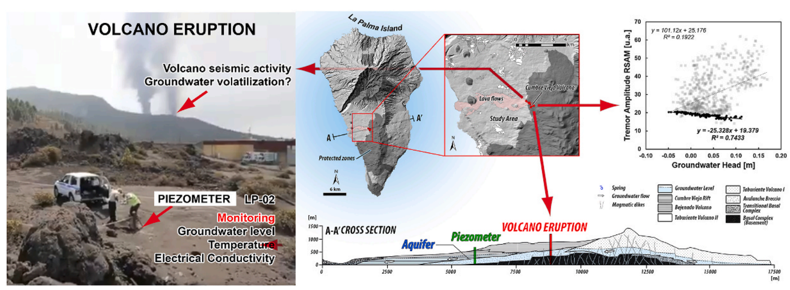
HIGHLIGHTS

- A correlation between groundwater levels and seismic signals was identified.
- Opposite responses in highland recharge vs. discharge areas.
- Groundwater flow model shows complex behavior during eruption.
- Magma pumping effect; uncertainty up to 2000 $m^3 \cdot day^{-1}$.
- Study urges regular monitoring of resources during eruptions.

GRAPHICAL ABSTRACT



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ABSTRACT

The 2021 volcanic eruption in the Cumbre Vieja mountain range on La Palma Island (Canary Islands, Spain) raised concerns regarding the potential impact on groundwater resources. This study is the first part of a series of papers investigating those impacts, and focuses on the hydraulic impacts of the eruption, while subsequent papers will explore the geochemical consequences. Three boreholes equipped with sensors to measure hydraulic head, temperature, and electrical conductivity of groundwater were installed near the volcano. Monitoring started during the eruption and continued a year after it. Statistical analysis were performed to assess the relationship between the measured variables and real-time seismic-amplitude measurements (RSAM). In addition, the possibility of groundwater vaporization due to magma emergence was assessed with a groundwater flow numerical modelling of the island. Correlation coefficients were computed to assess the linear relationship between groundwater parameters and seismic signals, observing a statistically significant association, and suggesting near-instantaneous variations in parameters such as groundwater levels and EC. Different response patterns of groundwater levels were observed in recharging areas in highlands compared to discharge areas, showing an opposite correlation direction. Deduction of natural trends from the linear regression models of head and RSAM two months after the eruption revealed a more predictable impact on the groundwater system, as the hydrogeological system adjusts to the volcanic activity and its effects on the aquifer. The hydrogeological

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simulation of the "magma pumping effect" suggested that groundwater extraction was possible, but the absence of an appropriate groundwater monitoring network made it impossible to determine the amount of water extracted from the aquifer. The uncertainty analysis showed values up to 2000 $m^3 \cdot day^{-1}$. These findings have important implications for understanding the negative impacts of volcanic eruptions on groundwater resources, highlighting the need for regular monitoring and assessment by hydrogeologists and water management professionals.

1. Introduction

Water is a critical resource for human life and the functioning of ecosystems, and groundwater is often a vital water source where surface water is scarce or unreliable (Amanambu et al., 2020; Eamus et al., 2016). This groundwater dependence is particularly relevant in volcanic archipelagos presenting semiarid or semidesertic climate conditions, where rainfall is limited and groundwater is a key source of water for human consumption and agriculture (Carreira et al., 2010; Custodio, 2020; Sharan et al., 2021). Besides water scarcity and saltwater intrusion in volcanic environments (Choi et al., 1991; Comte et al., 2017), groundwater resources can be vulnerable to contamination and depletion due a variety of reasons, including natural disasters such as volcanic eruptions (Cronin et al., 2003).

Volcanic eruptions can have significant impacts on groundwater resources, including changes in water quality and quantity, changes in the permeability of the subsurface, and contamination of water supplies (Taran and Kalacheva, 2020). Hydrology around active volcanoes is strongly controlled by the interaction between groundwater and the hydrothermal fluids, dissolved elements, and heat associated with magmatic intrusion (Jasim et al., 2019). The interplay between hydrological and volcanic systems plays a crucial role in volcanic disturbances (Albano et al., 2002). Variations in hydrological patterns, including water table levels, spring discharge, temperature, and composition at an active volcano may offer early signs of shifts in volcanic behaviour. Variations in groundwater levels in volcanic regions can be influenced by several factors, such as magmatic intrusions, seasonal loading, and rainfall. In Iceland, a study found a correlation between seismic velocity changes, which are sensitive to magmatic processes, and volumetric strain and groundwater level fluctuations caused by seasonal factors like snow thickness and atmospheric pressure (Donaldson et al., 2019). Similarly, a study on Kilauea Volcano in Hawai'i observed a sudden increase in compressional strain due to abrupt inflation of the volcano's summit, leading to a drop in water level in a deep well due to fractures or interflows opening up (Hurwitz and Johnston, 2003). In southwestern Japan, changes in crustal pore pressure in response to rainfall were observed to impact seismic velocity and groundwater level changes (Andajani et al., 2020). A study on Izu-Oshima in Japan noted that tidal fluctuations in groundwater level were associated with changes in volcanic gas concentration and aquifer permeability (Koizumi et al., 1998).

It is widely recognised that the variation of groundwater levels combined with more precise deformation data can provide valuable insights for eruption forecasting (Ingebritsen et al., 2021; Jasim et al., 2019; Nur et al., 2021; Poland and Anderson, 2020). The specific mechanisms causing these changes include strain, ground surface uplift or subsidence, recharge boiling, and alterations in aquifer permeability (Albano et al., 2002). The monitoring of groundwater levels is a crucial tool for constraining the depth of intrusion in volcanic systems, thereby providing essential data for understanding volcanic processes. By tracking changes in the chemistry and temperature of groundwater, surface water, and steam at a volcano over time, valuable information can be obtained regarding changes in volcanic activity, especially when related to phreatic eruptions (Barberi et al., 1992).

Volcanic eruptions can cause significant changes in aquifer systems within the volcanic provinces, impacting water tables, wells, and springs. Fluctuations in the water table level and spring discharge rates have been observed before the onset of magmatic activity and are often interpreted as the effect of opening and closing of fractures during the intrusion of fresh magma (Newhall et al., 2001; Shibata and Akita, 2001; Tanguy, 1994). Additionally, the effect of the water phase transition from liquid to gas at relatively shallow depths (<2 km) may also cause an uplift of the water table (Jasim et al., 2015). The interaction between groundwater and volcanic systems can lead to complex trends in groundwater levels, even showing opposite behaviours under the same eruption event. This happened in the eruption of *Usu* volcano on March 31, 2000, where two wells near the volcano showed two trends before its eruption: one well's water level decreased, while the other well's water level initially increased by 0.05 m and then gradually decreased (Shibata and Akita, 2001). These groundwater level changes are generally attributed to groundwater flow into widening cracks due to intruding magma and volumetric expansion of magma inside the chamber. In a study by Hurwitz and Johnston (2003), the researchers examined the groundwater pressure response in a deep well at the summit of Kilauea Volcano during an intrusion event. Their findings showed that, contrary to poroelastic theory predictions, the stress induced by the intrusion led to the development of fractures or interflows, resulting in water drainage from the well. This proposed model has important implications for understanding ground surface deformation and identifying the factors responsible for initiating phreatomagmatic eruptions.

On the other hand, fluctuations in spring discharge are less thoroughly documented compared to groundwater levels, primarily due to the frequent absence of continuous discharge rate measurements. A documented decline in non-thermal spring discharge occurred on the volcanic island of Montserrat before the onset of volcanic activity at the adjacent *Soufrière* Hills Volcano in 1995 (Hemmings et al., 2015). This decrease was succeeded by an increase following the termination of the second eruptive phase in 2004. Although the mechanism underlying spring discharge fluctuations remains ambiguous, the authors hypothesize that discharge rates may correlate with fracture dynamics associated with magmatic pressurization and depressurization.

Characterizing and modelling the interaction between hydrogeological systems (regional groundwater flow) and hydrothermal systems becomes increasingly complex, thus requiring coupling multiphase flow systems in evolving lithologies, and resulting in intricate groundwater-volcano interactions (Moeck, 2014). The high temperatures generated during the eruption can cause the groundwater to boil and create steam vents and geysers. These modifications can have long-lasting impacts on groundwater resources, creating challenges for their utilization for drinking, irrigation, and other purposes. Therefore, it is imperative to conduct monitoring of groundwater resources before, during, and after volcanic eruptions to assess the impacts and implement appropriate measures to protect these vital resources (Yoshida et al., 2013). Therefore, it is important to consider the impacts of volcanic eruptions on groundwater resources to better understand and mitigate the hazards associated with volcanic activity.

The understanding of groundwater pressure response to volcanic activity remains limited. A scarcity of deep wells either on or in the vicinity of volcano summits results in the limited accessibility to continuous groundwater level records. The primary objective of this study is to present water-level observations during the eruption of *Cumbre Vieja* and analyze the response of the aquifer to the volcanic activity. We aim to determine the extent to which water levels remains secured for water production from the volcanic aquifer, given that a significant portion (90%) of the island's population relies on groundwater resources for human consumption and agriculture (Santamarta, 2013). Furthermore, this research seeks to investigate the effects of volcanic vaporization on the groundwater system and introduce the concept of "magma pumping". This magma pumping effect refers to a phenomenon that would occur during a volcanic eruption, where the movement of magma within the volcanic system interacts with the groundwater in the aquifer. This interaction leads to the formation of hydraulic breccia, which increases permeability within the aquifer. As a result, groundwater is introduced into the volatilization zone through preferential flow paths such as fractures, old lava conduits, and discontinuities. The effect of this interaction is similar to that of a pumping cone, where the movement of magma acts as a hydraulic pump, influencing the behavior and flow of the groundwater. This can result in changes to groundwater levels, modifications in flow directions, and the potential release of volatile substances into the aquifer. By achieving these objectives, we hope to contribute valuable insights into the relationship between volcanic activity and groundwater dynamics, thereby informing future resource management strategies in regions affected by volcanic eruptions.

2. Study area

The active volcanic island of La Palma, with a length of 47 km from north to south and 29 km from east to west, is located at the northwest end of the 500-km-long volcanic chain of the Canary Islands, situated off the northwest coast of Africa (Fig. 1). It comprises a ~6500 m above seafloor stratovolcano built on oceanic crust of Jurassic age (Hayes and Rabinowitz, 1975). *La Palma* Island is noteworthy for its volcanic strata structures (De la Nuez et al., 2008) with two distinguishable units (Hiltona et al., 2000): the Seamount Series (4–2.9 Ma) and a subaerial complex known as the *Coberta* Series (2.0–0.0 Ma). Except for the gabbroic outcrops of the Seamount Series at the bottom of the *Caldera de Taburiente* eroded remnants of the depression in the northern shield, the *Coberta Series* covers the whole island. The latter series include two different subunits; one forming the major shield volcano at the north of the island (2.0–0.6 Ma), and a recent (0.6–0.0 Ma) subunit of lavas forming the southern *Cumbre Vieja* ridge (Ancochea et al., 1994; Guillou et al., 1996). Additionally, the island features a locally erosive and intermittent structure known as the *COEBRA* structure (Navarro Latorre, 1993). This structure is located inside the northern shield volcano of the island and harbours numerous springs, some of which display significant flow rates (APHP, 1992).

The island of La Palma has a complex volcanic aquifer system that is predominantly composed of basaltic lavas with pyroclastic layers in between. The system is divided into blocks, creating a rift system that is crossed by an intricate network of dykes that compartmentalize the hydrogeological system and determine the direction of groundwater flow (Poncela et al., 2022). The proximity of the dykes to the areas of rift to the structural axes of La Palma determines their density and creates a variety of sealing cells, which act as hydrological barriers and cause high local piezometric gradients. The presence of debris avalanche deposits, a result of gravitational landslides, can also influence the confinement or semi-confinement of the island's aquifers (Poncela, 2009, 2015). Groundwater flow follows winding pathways from the summits towards the sea, but dykes hamper its path, causing it to reach regional groundwater levels at around 1800 m inland and sea level in the coastal zone (Custodio, 2020).

According to the WFD 2000/60/EC directive, the LP001

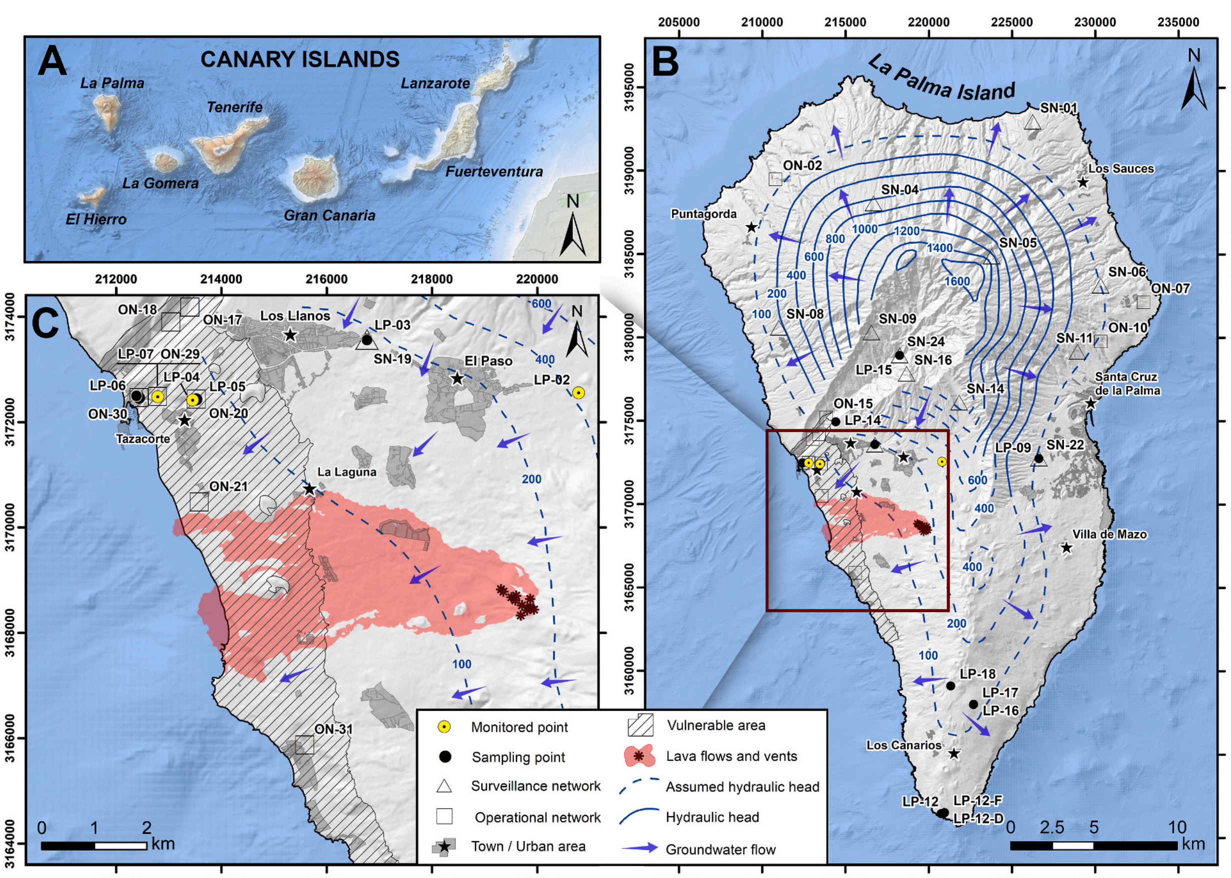

Fig. 1. Studied area. Location of (A) *La Palma* Island in the Canary Islands archipelago; (B) *La Palma* Island groundwater head contour map from Poncela (2015; and (C) The *Aridane* - *Tazacorte* Valley and Cumbre Vieja Volcano (2021). Projection: REGCAN95/UTM zone 28N. Bathymetric map backgrounds obtained from the European Marine Observation and Data Network (EMODnet) in A and the *IHM - Instituto Hidrográfico de la Marina – Armada* in B and C.

groundwater body was defined as the primary water reservoir, encompassing the main insular aquifer system, the *Taburiente* volcano cone materials, and the *COEBRA* structure (APHP, 1992; APPHLP, 2012; EGDHLP, 2009). It stretches from the north cone halfway to the south cone and down to the coastal fringe, reaching a 600 m.a.s.l. benchmark. The stacked lava and scoria layers from the Upper *Taburiente* volcano favor infiltration and natural recharge to the main aquifer, but permeability shows noticeable contrast due to lithological heterogeneity, such as the overlaid series constituting the hydrogeological base, which can either cut across or be in contact with the structure of *COEBRA* or the Basal Complex structure, acting as a low permeability basement. La Palma has two main flow regimes: a regional flow regime that includes recharged waters from decades or centuries ago, and a local flow regime at elevations above 1000 m.a.s.l. characterized by low groundwater residence times, low mineralization, and recent recharge indicators such as high Tritium contents. Water stratification processes can be found at upper levels of the aquifer. The debris avalanche scars have formed genuine erosive landforms of asymmetric caldera basins that were precursors to La Palma's main island groundwater reservoirs (Poncela and Skupien, 2013).

3. Methodology

3.1. Data collection

The Insular Water Authority of *La Palma* (*Consejo Insular de Aguas de La Palma*, CIALP) has established two networks for monitoring the chemical state of groundwater resources on the island - an operational and a surveillance network (Fig. 1). The surveillance network comprises 12 representative water galleries and one piezometer, and is employed to monitor the general trends of the chemical status of the groundwater bodies. On the other hand, the operational network comprises 11 representative wells located in specific areas where potential contamination risks exist. Additionally, a piezometer network consisting of 12 monitoring points has been established to monitor the quantitative state in the most intensively exploited and vulnerable area of the *Aridane-Tazacorte* Valley (Fig. 1C). In response to the eruption of *Cumbre Vieja* on September 19, 2021, the monitoring network was equipped with hydraulic and barometric pressure transducers, temperature sensors, and electric conductivity sensors at three monitoring points. (Fig. 1). The first monitoring point was a 400 m deep piezometer (LP-02 *Matadero*) from the CIALP's quantitative network, while the second was a 100 m deep piezometer (LP-04 *Tenisca*) located 73 m from a representative well known as *El Salto*. The third monitoring point was a well (LP-07 *San Miguel*) within the operative network. The distances of these monitoring points from the eruptive vents of *Cumbre Vieja* were 4,049, 7,200, and 7800 m, respectively. A DI271 DIVER Schlumberger datalogger was installed in the LP-02 *Matadero* piezometer for high-resolution pressure, temperature, and electrical conductivity measurements. The sensor has a pressure range of 10 mH_2O, a resolution of 0.2 cmH_2O, and an accuracy of ±0.5 cmH_2O for pressure. The temperature measuring range of the sensor is −20 °C–80 °C, with a resolution of 0.01 °C and an accuracy of ±0.1 °C. It has a conductivity range of 0 mS cm^{-1} to 30 mS cm^{-1}, with a reading accuracy of ±1% and a reading resolution of 0.1%. For high-resolution pressure and temperature measurements at LP-04 and LP-07 monitoring points, Seametrics/Van Walt LevelSCOUT sensors were installed. These sensors have a pressure range of 10 mH_2O, a resolution of 0.034 cmH_2O, and an accuracy of ±0.5 cmH_2O for pressure. The temperature measuring range of the thermistor is −20 °C–60 °C, with a resolution of 0.01 °C and an accuracy of ±0.1 °C.

The instrumentation was installed 29 days after the eruption began, to observe alterations in the groundwater level and quality that occurred as a result of the volcanic activity. These potential changes were monitored for 56 days during the eruption, and this monitoring continued for a period of 1 year after the end of the eruption, this is, until December 13th, 2022. The monitoring campaign conducted in this study involved the sensors being programmed to collect data at 2-h intervals for each pressure, temperature, and electrical conductivity reading. This comprehensive approach resulted in a dataset comprising a total of 78,840 measurements.

To study the relationship between groundwater levels and the eruption event, Real-time Seismic Amplitude Measurement (RSAM) data was provided by the National Geographic Institute of Spain (IGN), as well as precipitation data from meteoroidal stations in La Palma.

3.2. Statistical analysis

Statistical analysis was conducted to test the potential association between groundwater level and RSAM data. We computed Pearson's correlation coefficients to examine the intensity and direction of the relationship between the two variables. A significance level of 0.05 ($p < 0.05$) was adopted as the threshold for statistical significance. The data analysis was performed using SPSS statistical software version 19 (IBM, 2010). In order to evaluate the effects of the eruption in groundwater levels, time series of such variable in each monitoring point was filtered removing the natural groundwater trend. Hydrograph from monitoring point LP-07 San Miguel, since the sensor was introduced in the well, pumping drawdown and recovery oscillations were also removed from the dataset.

3.3. Modelling possible groundwater volatilization during the eruption

To evaluate the possible effects of the eruption on groundwater levels due to groundwater volatilization and introduce the concept of "magma pumping effect" the groundwater flow regime of the island was reproduced by means of a numerical model. To this end, a finite element code FEFLOW (Diersch, 2013) was used solve the standard (saturated) groundwater-flow equation for a 2D mesh under horizontal projection. The domain of the model coinciding with the island area (706 km^2) is 27.5 × 45.5 km (as shown in Fig. 2A), and the resulting mesh was composed of 37,165 triangle elements and 18,905 nodes. To include the draining effect of water galleries, its traces were included in the model as 1975 high transmissivity 1D elements (10^7 $m^2 \cdot day^{-1}$). The model was calibrated with fixed head (Dirichlet) boundary conditions applied to the nodes representing the coast line (as shown in Fig. 2A), and a constant Cauchy boundary condition was imposed to nodes representing water galleries entrance, major springs and major representative wells of the island (APPHLP, 2012), thus accounting for the water extractions and spring discharges. The calibration process also considered the topographic elevation of the major islands to increase the simulation accuracy. An averaged-constant recharge rate was considered spatially distributed according to La Palma hydrological plans (APPHLP, 2012) generated to comply with the Water Framework Directive (EU-WFD, 2000). Steady-state conditions were assumed due to the lack of recorded data on groundwater level variation, which prevented conducting a transient analysis of the aquifer system storativity. Nevertheless, transmissivity and storativity distribution maps were obtained from recession coefficients obtained from deep water gallery discharge study (Poncela et al., 2022). Although these estimations are only valid for the northern part of the island, interpolation results to the south were used only as reference values. Nevertheless, together with model simulations of the "magma pumping effect", an uncertainty analysis was carried out using FePEST and PEST++ (White et al., 2020) software. This software also enabled the resolution of the inverse problem by employing 300 pilot points to generate a geostatistical transmissivity field capable of replicating the observed groundwater levels on the island. Various transient simulations were conducted to assess potential volatilization of groundwater during an 85-day eruption period. This groundwater volatilization was incorporated into the model as pumping at rates of 1.16E-03, 1.16E-02, 3.82, 7.64, 11.57, 38.19, 76.38, and 115.74 $m^3 \cdot s^{-1}$. Recovery from this equivalent pumping was simulated using a modulation function that represented the given pumping rate for 85 days, and

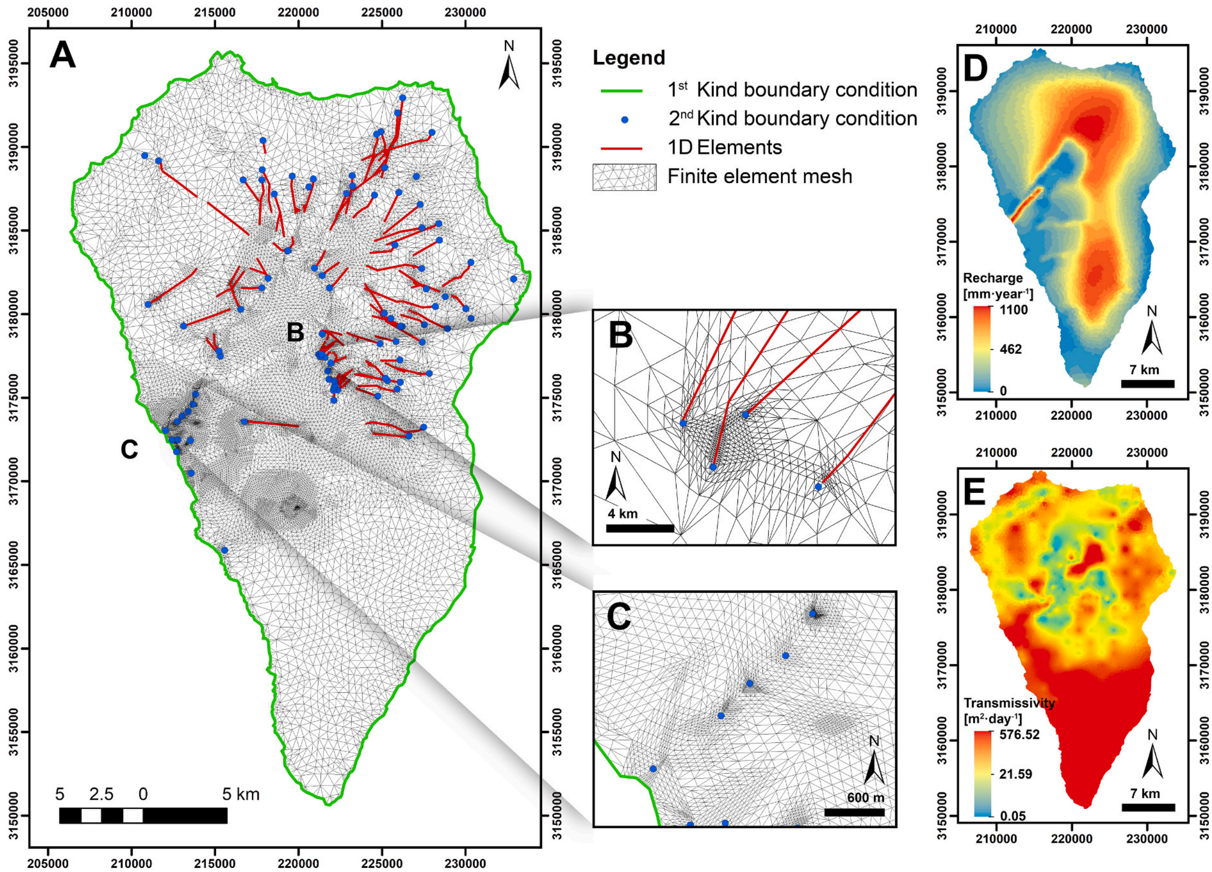

Fig. 2. (A) Two-dimensional finite element mesh encompassing the insular volcanic aquifer on La Palma Island. Mesh refinement for water galleries (B) and wells (C) is shown. Spatial discretization of recharge rates (APPHLP, 2012) (D) is presented. Hydraulic transmissivity (E) is depicted, obtained from the calibration procedure of the numerical groundwater flow model.

once the eruption ceased, the modulation function was set to zero to evaluate recovery throughout two years after the volcanic activity subsided. As mentioned, the spatial distribution of storativity was extracted from Poncela et al. (2022). Since the volcano eruption occurred at the South of the Island, and spatial correlation was made with no data in that area, a rigorous uncertainty analysis using PEST++ software was used for the purpose of quantifying model uncertainty. This advanced software package facilitated the evaluation of parameter and predictive uncertainty, enabling a comprehensive understanding of the model's reliability and potential limitations in the context of groundwater flow simulation.

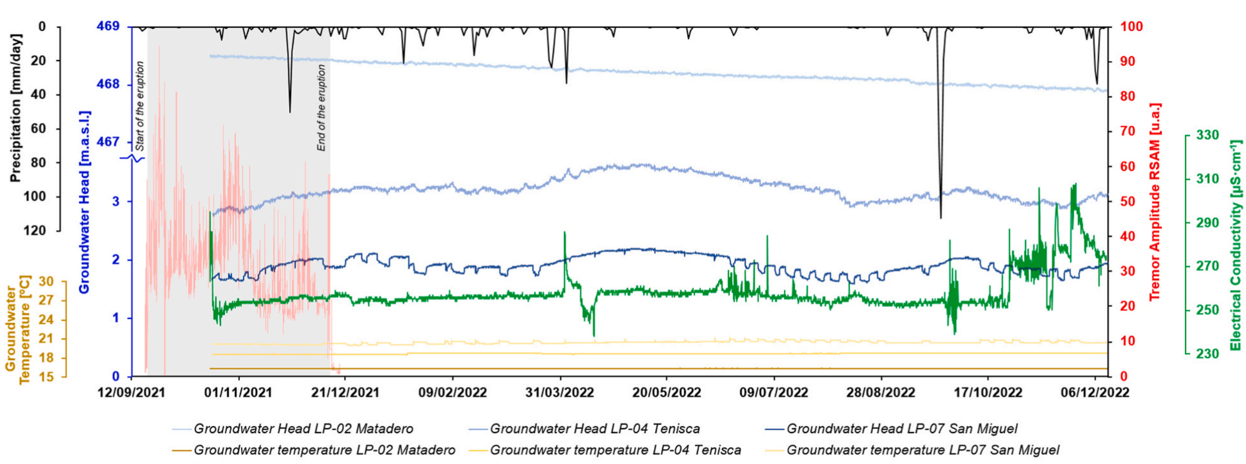

Fig. 3. Time evolution of groundwater head, temperature and electrical conductivity throughout and one year after the 2021 *La Palma* volcanic eruption measured at LP-02, LP-04 and LP-07 monitoring points. Location of monitored points is shown in Fig. 1. Precipitation and RSAM signal was obtained from the Spanish National Geographic Institute (IGN).

4. Results and discussion

4.1. Monitoring results

Variables obtained for each monitored points are shown in Fig. 3. The figure clearly shows how LP-04 and LP-07 present same trends with parallel variations with a 1.23 m difference. In contrast, LP-02 present a continuous decay of groundwater level throughout the monitored period. While the first monitoring points are located near the coast line in an area intensively exploited by numerous wells, LP-02 is an elevated point in the midlands close to the summit crest and groundwater divide (Fig. 1), thus representing each group a discharge/extraction area and a recharge area, respectively. As contrary as expected from a recharge area presenting higher variation due to recharge events mitigated towards the discharge areas, LP-02 does not showed any oscillation, only changed 0.63 m in the 425 days monitored. The other two points, LP-04 and LP-07 oscillated within a range of 0.43 and 0.69 m, respectively. Within these range of variation no major changes were observed when the eruption ceased on 19/09/21. Continuous lowering of groundwater trend in LP-02 can be attributed to a low drawdown caused by a near water gallery (*de Trasvase* water gallery) 1.1 km away from its advancing front. Groundwater temperatures were also found to be very stable, not showing any heating. Nevertheless, it should be noted the >4 km distance from the volcano vents. On the other hand, electrical conductivity

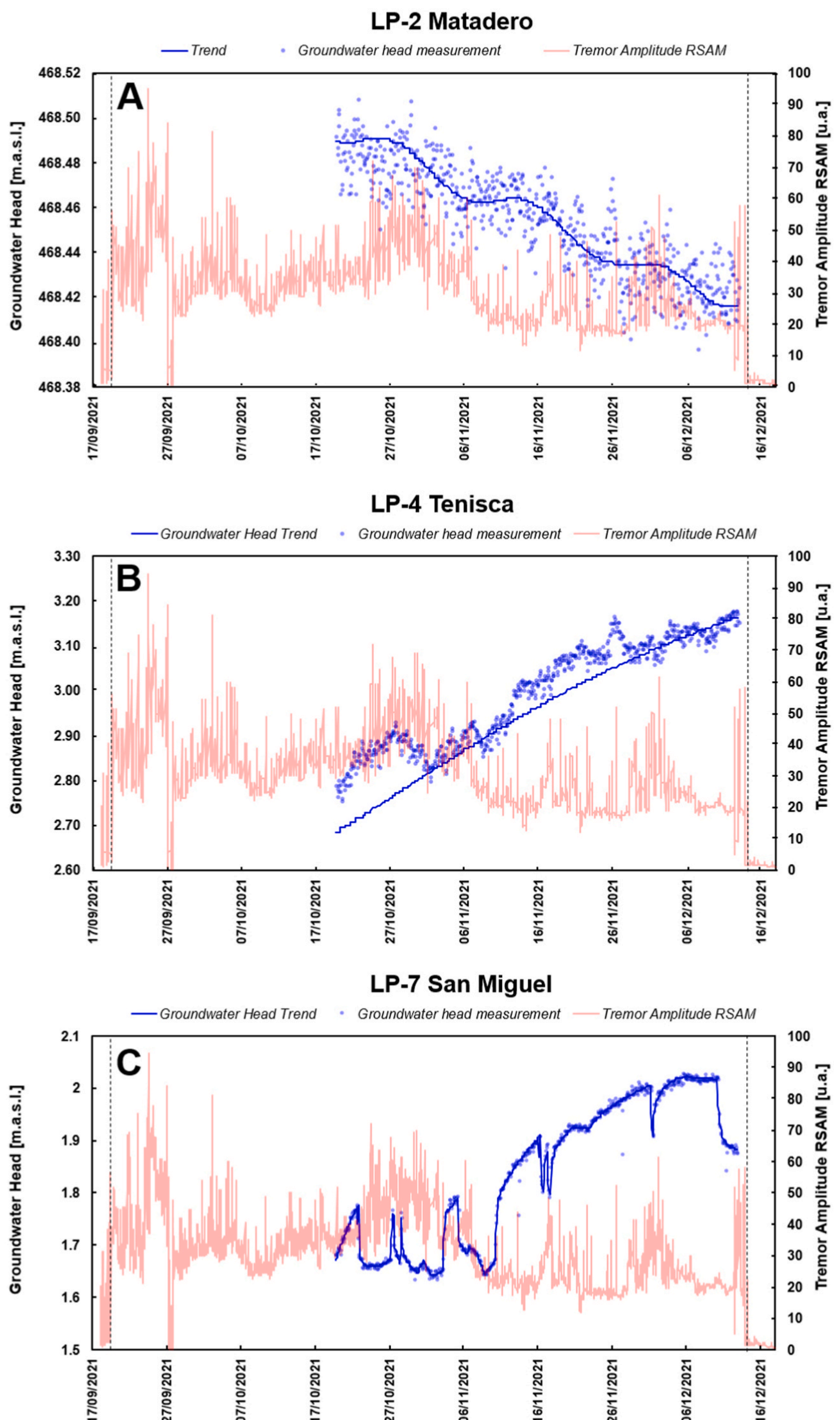

Fig. 4. The groundwater level trends identified at (A) LP-02 *Matadero*, (B) LP-04 *Tenisca* and (C) LP-07 *San Miguel* monitored points located in Fig. 1.

monitoring of LP-02 in the recharge area shows a respond to precipitation (Fig. 3). During the eruption event caused a major increase of 52 $\mu S\ cm^{-1}$ due to a very low precipitation event (7.5 mm) with a small downward bounce of 9 $\mu S\ cm^{-1}$. This could be interpreted that the fresh ashes from the volcanic eruption with acid salts adsorbed to the ash particles could be washout increasing largely recharge water electrical conductivity with the entrance of ash-leachates to the aquifer (Witham et al., 2005) and also explaining the low downward bounce. Small amount of water would be producing a large effect due to ash first washout since the beginning of the eruption. This hypothesis would explain why a major precipitation event (51.33 mm) close to the end of the eruption did not produced an increase in electrical conductivity, the ashes would be cleaned after the first precipitation event, despite its low intensity. In March 2022 similar increase and downward bounce in electrical conductivity of groundwater was produced indicating this possible salt wash effect is not only produced due to ash leachates, but also indicated that with acid leachates the amount of water required to produce this effect is lower. This can be interpreted as higher efficiency in the salt wash due to acidity of infiltrated water during eruptive events with accumulated ash (Tashima et al., 2023). However, the possible ash-leachates infiltration to the aquifer and its effects on the hydrochemical parameters of the groundwater is further investigated and modelled in the subsequent papers of this series of papers on the effects of the 2021 La Palma volcanic eruption on the groundwater resources.

The groundwater level trends (Fig. 4) not presumably attributable to the eruption were removed to evaluate the effects of the seismic activity considering RSAM signal as an independent variable. The groundwater trend in LP-02 (Fig. 4A) showed an oscillatory trend with a 14-day period, possibly corresponding to the variations for each lunar cycle between a full moon and a new moon equal to the 14.77 days lunar fortnightly tidal constituent (long-period tides). Groundwater level trend in LP-04 (Fig. 4B) and LP-07 (Fig. 4C) show similar trends since they are in the same discharge area close to the coast. The major difference is the pumping dynamic regime. Therefore, to evaluate the effects of volcano eruption the pumping drawdown and recovery trends were identified to be filtered in order to perform statistical analysis. The absence of continuous monitoring of the quantitative control network of the island by local Water Authority did not allow to evaluate if the observations made coincide with natural trend of the hydrograph. However, measurements made after the eruption (shown in Fig. 3) allow to identify the recharge patterns coinciding with the trends shown in Fig. 4B and C.

4.2. Statistical analysis results

The correlation between groundwater head and real-time seismic amplitude measurement (RSAM) was examined at three boreholes: LP-02, LP-04, and LP-07. Table 1 presents the results of the Pearson correlation tests for both the original dataset and the filtered dataset (with the removal of any trends).

For the original dataset, significant correlations were observed between groundwater head and RSAM at all three boreholes. A strong positive correlation ($r = 0.621$, $p < 0.01$, $n = 638$) was found at LP-02 Matadero, while strong negative correlations ($r = -0.693$, $p < 0.01$, $n = 638$) and ($r = -0.694$, $p < 0.01$, $n = 638$) were observed at LP-04 *Tenisca* and LP-07 *San Miguel*, respectively.

Upon removing the trends from the data, the correlation coefficients for the filtered dataset changed considerably. The correlation between groundwater head and RSAM at LP-02 became negative ($r = -0.187$, $p < 0.01$, $n = 638$), while the correlations at LP-04 and LP-07 became positive ($r = 0.438$, $p < 0.01$, $n = 638$) and not statistically significant ($r = 0.028$, $p = 0.485$, $n = 616$), respectively.

These results highlight the importance of considering both the natural trends in hydrographs and the influence of seismic activity on groundwater head. The significant correlations observed in the original dataset suggest that groundwater head is affected by seismic activity in the study area. However, the changes in the correlation coefficients after removing the trends indicate that the natural trends in hydrographs may also play a critical role in determining the observed relationship between groundwater head and RSAM.

Furthermore, the change in the sign of the correlation coefficients after removing the trends from the dataset suggests that the underlying factors driving the groundwater head fluctuations may be more complex than initially anticipated. The original dataset, which included both the natural trends in hydrographs and the influence of seismic activity, demonstrated a certain relationship between groundwater head and RSAM. However, when the natural trends were removed from the dataset, the sign of the correlation coefficients changed, indicating that the direction of the relationship between groundwater head and RSAM was not as straightforward as it initially appeared.

There could be several reasons for the change in the sign of the correlation coefficients. One possible explanation is that the natural trends in hydrographs may have masked the actual relationship between groundwater head and RSAM. By removing the trends, the filtered dataset revealed a more accurate representation of the relationship between these two variables, which was previously obscured by the presence of natural trends in the data.

Another possibility is that other factors, not considered in the analysis, could be influencing the relationship between groundwater head and RSAM. These factors could include temporal variations in recharge and discharge, changes in aquifer properties, or additional external influences such as meteorological events or human-induced disturbances.

To evaluate the change of sign between the different correlations, linear regression models were plotted in Fig. 5, Figs. 6 and 7 for each monitored point. Differences in linear regression between groundwater head and RSAM signal at LP-02 *Matadero*, with and without removing groundwater trends, allowed identifying a subgroup of the dataset in which the correlation sign did not change if the groundwater trend was removed (Fig. 5A and B). The slopes observed for each subgroup showed a similar order of magnitude even after removing the groundwater trend, suggesting that the relationship between groundwater levels and seismicity is consistent across the subgroups and is not influenced by the natural trends in groundwater. This finding implies that the two variables likely have a stable and uniform relationship in the dataset, and

Table 1
Pearson's correlation tests results between groundwater head and real-time seismic amplitude measurement (RSAM). Correlation is considered as statistically significant at the 0.05 level (2-tailed) ($p < 0.05$).

Original dataset		RSAM	Filtered dataset		RSAM
LP-02 *Matadero*	Pearson Correlation	0.621**	LP-02 *Matadero* (no trend)	Pearson Correlation	−0.187**
	Sig. (2-tailed)	0.000		Sig. (2-tailed)	0.000
	N	638		N	638
LP-04 *Tenisca*	Pearson Correlation	−0.693**	LP-04 *Tenisca* (no trend)	Pearson Correlation	0.438**
	Sig. (2-tailed)	0.000		Sig. (2-tailed)	0.000
	N	638		N	638
LP-07 *San Miguel*	Pearson Correlation	−0.694**	LP-07 *San Miguel* (no trend)	Pearson Correlation	0.028
	Sig. (2-tailed)	0.000		Sig. (2-tailed)	0.485
	N	638		N	616

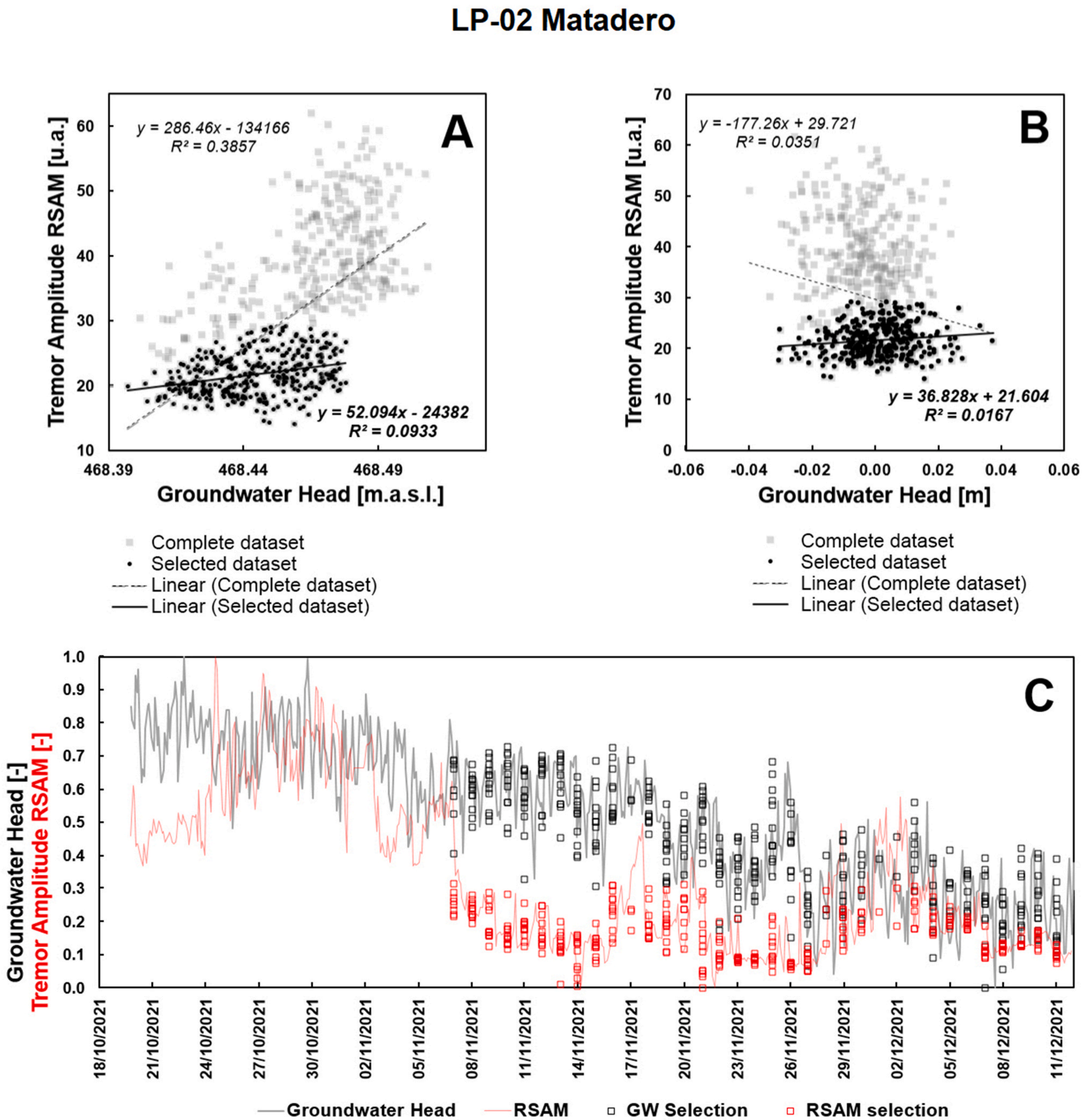

Fig. 5. Linear regression analysis of groundwater head measured (A) and groundwater levels with its natural trend removed (B) against real-time seismic amplitude measurement (RSAM) signal at LP-02 *Matadero* monitored point. Adimensional variation of the variables (C).

their association is not probably confounded by the natural groundwater fluctuations.

Interestingly, the data subgroup with a consistent slope identified in the regression models (highlighted with black bold dots, Fig. 5A and B) mostly was detected 2 months after the eruption began and up to the end of the eruption (Fig. 5C). This fact suggests that there may be a specific hydrogeological response to the volcanic activity during this time frame. This stable relationship between the two variables during the last part eruption period could be attributed to the direct influence of volcanic activity on the groundwater system, which is not confounded by natural groundwater fluctuations or other external factors. During the eruption, various factors such as magma intrusion, seismic activity, and changes in geothermal gradients can have significant impacts on the groundwater system. The consistent slope in the data subgroup during this period may indicate that these volcanic processes have a uniform and predictable effect on the groundwater system. The positive slope indicates that, as the tremor amplitude increases, the groundwater head also tends to increase, and vice versa. This direct relationship could be attributed to various mechanisms. One possible explanation is that increased volcanic activity, as indicated by higher tremor amplitudes, may lead to changes in the subsurface pressure, thus causing an increase in groundwater head. For example, the volcanic activity might cause the release of gases, which could raise the groundwater level. Increased tremor amplitudes could also be associated with ground deformation or fracturing, which could in turn enhance the connectivity or permeability of the aquifer system. These changes might facilitate the movement of groundwater or increase the recharge rate, leading to a rise in groundwater head.

Furthermore, these effects of enhanced connectivity or permeability

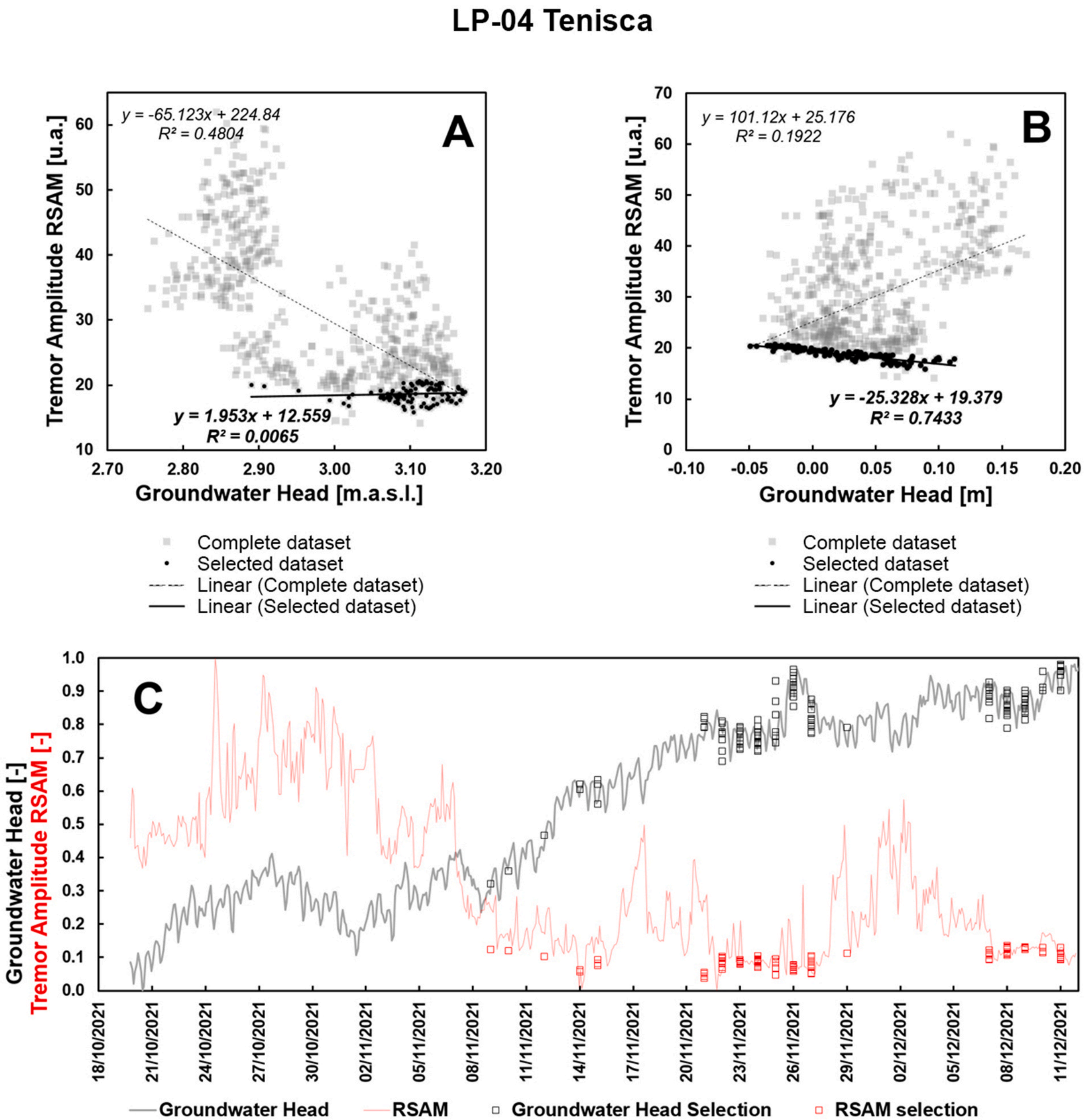

Fig. 6. Linear regression of groundwater head measured (A), groundwater levels with its natural trend removed (B) against real-time seismic amplitude measurement (RSAM) signal at LP-04 *Tenisca* monitored point. Adimensional variation of the variables (C).

of the aquifer as a response to the increased tremor amplitudes may also explain that, for specific locations and time periods, the groundwater from an upper aquifer could infiltrate to a lower aquifer level, thus simultaneously entailing a long-term increase in the groundwater level of the lower aquifer and a drawdown in the upper aquifer. This is consistent with the observed general long-term groundwater level trends (see Fig. 4) of LP-02 (Matadero), LP-04 (Tenisca) and LP-07 (San Miguel), where the upper groundwater level in m.a.s.l. corresponding to LP-02 shows a general trend of groundwater head decrease. This might be attributed to groundwater infiltrating into lower aquifers, together with the potential effect of groundwater volatilization during the eruption. Thus, it is also consistent with the fact that the lower groundwater levels corresponding to LP-04 and LP-07 show a general trend of groundwater head increase possibly resulting from enhanced recharge from upper aquifers or rainwater. However, they show several shorter-term drawdown responses to the near-instant events of increased RSAM, possibly due to different and more complex processes and interactions, such as interaction with near wells, short changes in aquifer pressure, among others.

The linear regression models for LP-04 (Fig. 6) show a change in the slope sign when the groundwater level trend is removed, indicating that the relationship between the variables is affected by the presence of groundwater fluctuations. However, when analyzing the selected data subset, a high R^2 value of 0.74 is observed, suggesting that the model explains a very significant portion of the variance in the data. Considering that the piezometer (LP-04 Tenisca) is located just 73 m away from a representative well known as El Salto, the change in the slope sign after removing the groundwater level trend could be related to the hydraulic interactions between the piezometer and the well, which might be affected by volcanic activity.

As volcanic activity increases, it can cause ground deformation, fracturing, or changes in the subsurface pressure and temperature. These changes may enhance the connectivity or permeability of the aquifer system, affecting the hydraulic interactions between the piezometer and

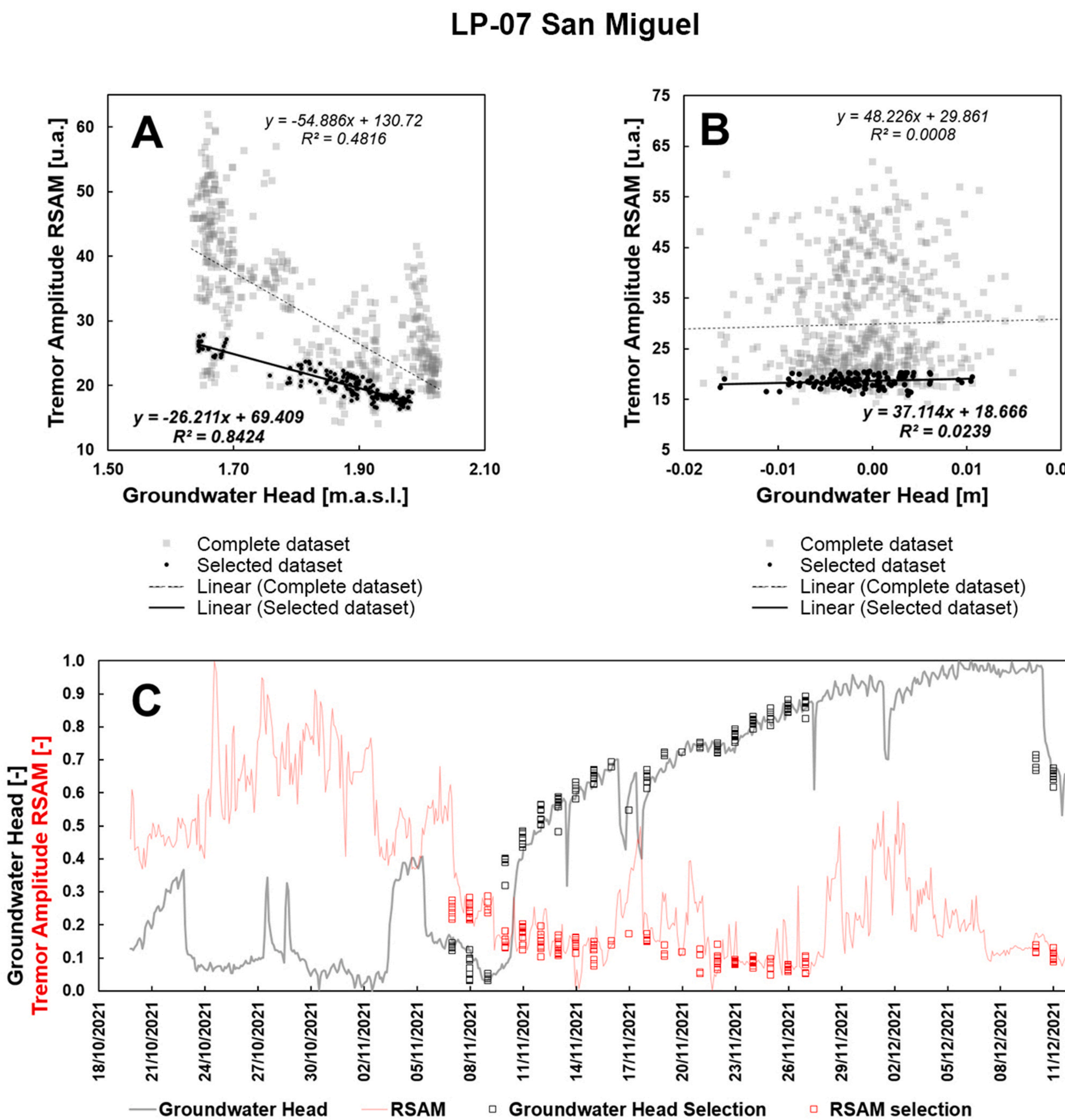

Fig. 7. Linear regression of groundwater head measured (A), groundwater levels with its natural trend removed (B) against real-time seismic amplitude measurement (RSAM) signal at LP-07 *San Miguel* monitored point. Adimensional variation of the variables (C).

the well. The observed change in the slope sign after removing the groundwater level trend could be a result of these interactions, which become more pronounced due to the volcanic processes. The close proximity of the piezometer to the well may also make the piezometer more sensitive to local changes in the aquifer system, such as well pumping, which could impact the observed relationship between the variables in the linear regression model.

In this case, when studying the data subgroup of interest (highlighted with black bold dots) only after the second month of the eruption and, concretely, in the time periods when RSAM is relatively mild (Fig. 6C), the change in correlation directions between the variables could be attributed to other factors or processes.

The milder RSAM changes during this time period may not have a strong enough impact on the aquifer system to cause significant variations in groundwater head. However, it is possible that the hydraulic interactions between the piezometer (LP-04) and the nearby well (*El Salto*) become more influential during this time due to changes in pumping rates, recharge rates, or other hydrogeological factors. Additionally, the time period after the second month of the eruption might correspond to a transition or recovery phase in the hydrogeological system, where the aquifer is adjusting to the changes induced by the volcanic activity. During this phase, the groundwater system may exhibit different response patterns compared to the initial stages of the eruption, leading to the observed change in the slope sign.

In the case of LP-07 (Fig. 7), a change in the slope of the regression models is observed when the groundwater level trends are removed. The selected data subset, which corresponds to measurements taken 2 months after the eruption began this avoiding abrupt changes in RSAM, may provide insights into the hydrogeological response during a specific period of the volcanic activity. The fact that the data subset of interest for LP-07 also starts after the second month of the eruption, like LP-04, suggests that there might be a common hydrogeological response or pattern during this time frame. The relatively mild RSAM changes during this period, as opposed to abrupt changes, might be associated with a more stable or predictable impact on the groundwater system. This could lead to the observed change in the slope when the groundwater level trends are removed, as the hydrogeological system adjusts to the volcanic activity and its effects on the aquifer.

4.3. Potential groundwater volatilization during the eruption

The groundwater flow numerical model was calibrated under steady-state conditions and considering major features of the insular system. The absolute error E, the root mean square (RMS), and the standard deviation (sigma) values are small.

Fig. 8 illustrates the correlation between the simulated and measured groundwater levels at 184 calibration targets. The residuals are assumed to follow a normal distribution around the 1:1 line. The simulation quality of the measured heads is expressed by a mean residual error (ϵ) of 42 m, which represents a 2.8% error of the variation for an abrupt volcanic island, with a significant hydrogeological heterogeneity. The root mean squared residual (RMS) and the standard deviation (σ) for the hydraulic heads are 71 m and 72 m, respectively.

The piezometric contour map shown in Fig. 9 displays the spatial distribution of the groundwater table across *La Palma* volcanic Island. The contours were generated as a result of the inverse method application under steady state conditions. The map clearly indicates the direction of groundwater flow, which runs from the summits towards the coastline. The flow network shown in Fig. 9 represents the direction of groundwater flow within the aquifers of La Palma Island. The network was generated from the results provided by the numerical model developed, which simulated the groundwater flow regime of the volcanic island. The flow network clearly indicates that the areas of groundwater recharge are close to the summits and discharge, both towards the coastline and water galleries. The hydraulic head contours and streamlines provide a visual representation of the complex behavior of the groundwater system, showing the areas where water is likely to flow into or out of wells or water galleries characteristic of the Canary Islands. The flow network for La Palma Island allowed to identify hydraulic gradients close to the area of the 2021 Cumbre Vieja eruption, where groundwater resources may be at risk. The results of the flow network analysis showed that the groundwater flow system on La Palma Island is complex and highly dynamic, with a significant amount of groundwater recharge occurring in the central part of the island and discharge along the coastal areas. The flow network also revealed the presence of several groundwater divides, which play an important role in controlling the movement of groundwater within the insular aquifer.

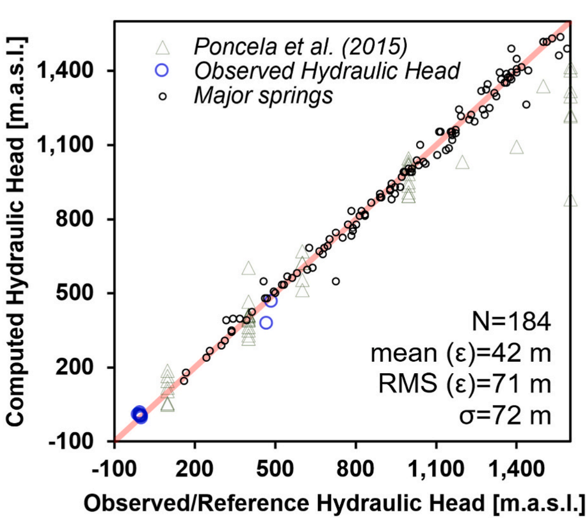

Fig. 8. Simulated vs. measured head at 184 calibration targets. Mean (ε) = average head residual, RMS(ε) = root mean squared residual, and σ = standard deviation.

Finally, Fig. 10A illustrates the long-term groundwater level trend at LP-02 El *matadero* monitoring point on La Palma Island indicating that the registered downward trend has ocurred with the same slope values since 2017 or earlier. The interpolation of this trend indicates the possible recovery of groundwater levels after the end of the volcanic eruption (Fig. 10B). A possible equivalent pumping rate of 40 L s^{-1} that initiated with the start of eruption and finished with its end would be possible according with the hydrograph registered (Fig. 10C). Therefore, this simulated potential volatization of groundwater during the 85-day eruption period within the island aquifer in the Cumbre Vieja area would be viable. However a storativity of $1.12 \cdot 10^{-4}$ would be necessary, indicating confined conditions. Furthermore, Fig. 10 presents the spatial distribution of the drawdown after 85 days of equivalent "groundwater magma pumping" effect. The possible drawdowns for different equivalent pumping flow rates are shown in Fig. 10F, assuming calibrated transmissivities and storativity values obtained from Poncela et al. (2022). Furthermore, uncertainty analysis taken with PEST++ indicated that a transmissivity of 64.12 $m^2 \cdot day^{-1}$ and a storativity of 0.3 or higher would be necessary to even pump 115 m^3 s^{-1} without suffering a drawdown in the monitored piezometers and a well. Thus, that would entail a considerable flow rate, in the same order of magnitude as a relevant river in Europe. The results presented in Fig. 10 are significant for understanding the behaviour of the groundwater system during and after the volcanic eruption. The recovery of groundwater levels after the end of the eruption suggests a positive trend towards the restoration of the aquifer. However, the simulation of possible volatization of groundwater during the eruption period raises concerns about potential groundwater contamination and the need for further monitoring and management.

5. Conclusions

This study examined the relationship between groundwater head and RSAM during the 2021 Cumbre Vieja volcanic eruption on La Palma Island, Canary Islands, and evaluated the potential impact of volcanic activity on the island's groundwater system. To assess these impacts, a statistical analysis was conducted to study the potential correlation between groundwater levels and RSAM data, by means of the Pearson's *r* correlation coefficients. Further, to evaluate the possible effect of groundwater volatilization due to the eruption and to introduce the concept of "magma pumping effect", the groundwater flow regime of the island was reproduced by means of a numerical model using the code FEFLOW. The main findings and conclusions drawn from this study are as follows:

- The eruption event did not produce a significant change in the groundwater temperatures but it caused major increases in the electrical conductivity, such as an increase of 52 μS·cm-1 at LP-02 after a very low precipitation event (7.5 mm). This could be related to the washed acid salts adsorbed to the ash particles and the subsequent ash-leachates infiltration to the aquifer. Also, this effect would be mainly restricted to the first precipitation event, since the following higher precipitation events did not lead to similar raises in the EC, probably due to the fact that the volcanic ash was already washed.
- A statistically significant and strong correlation was observed between groundwater head and RSAM at three boreholes (LP-02, LP-04, and LP-07) in the original dataset, suggesting that seismic activity influenced the groundwater system during the volcanic eruption. However, this correlation changed directions after removing

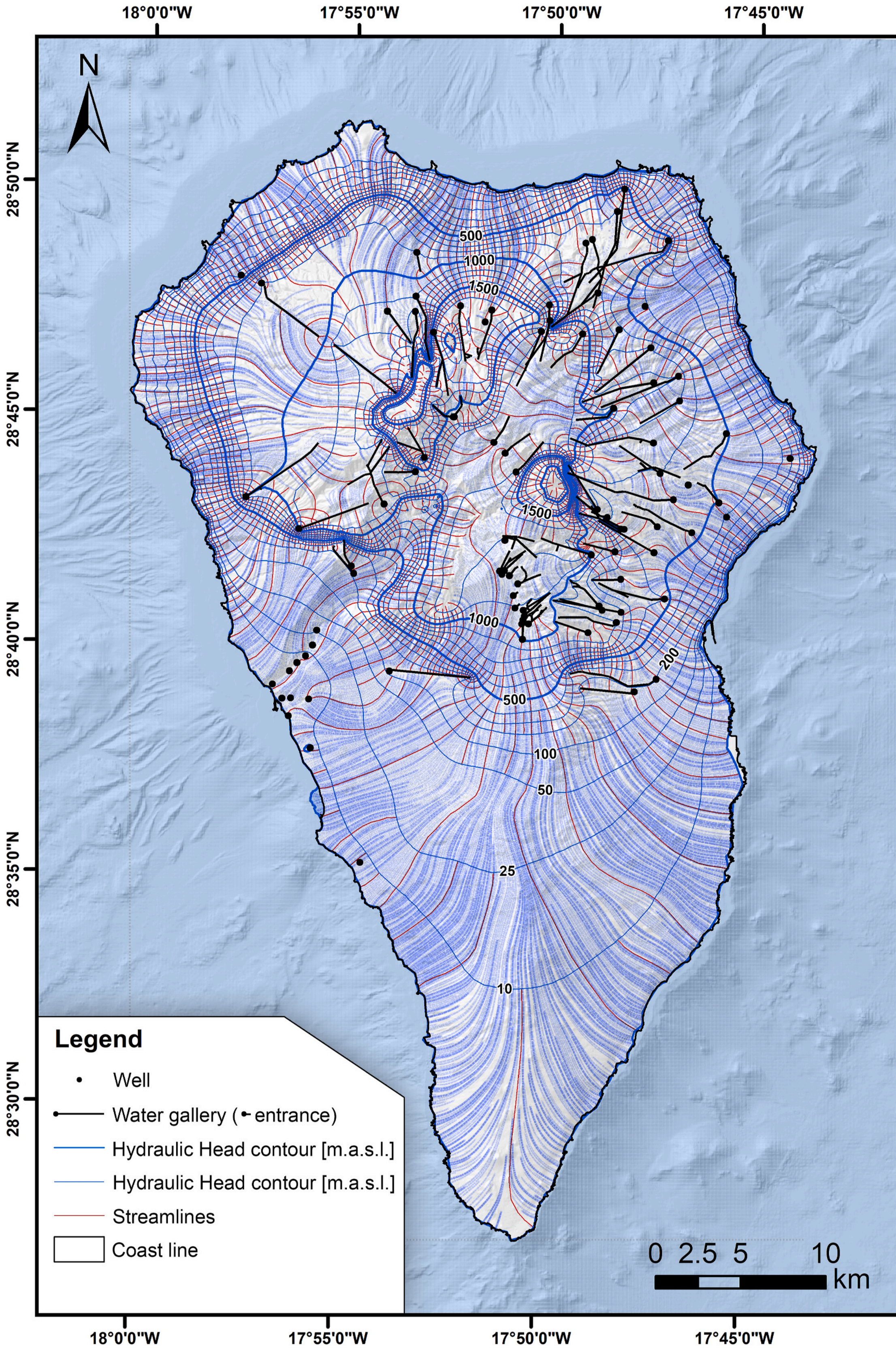

Fig. 9. Calculated hydraulic flow network for *La Palma* Island. Projection: REGCAN95/UTM zone 28N. Bathymetric map background obtained from the *IHM - Instituto Hidrográfico de la Marina – Armada*.

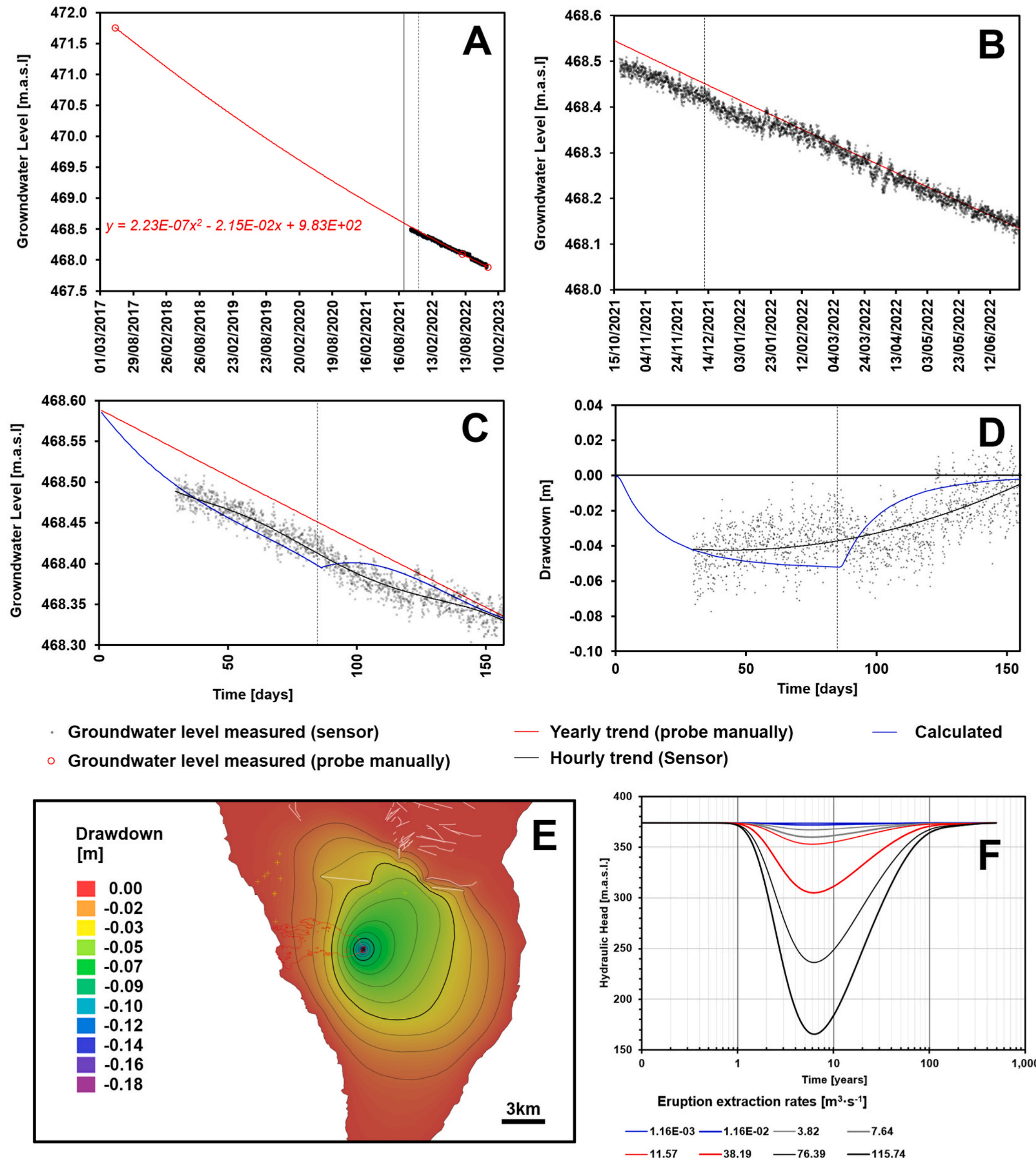

Fig. 10. Long-term groundwater level trend at LP-02 El *matadero* monitored point (A). Possible recovery of groundwater levels after the end of the eruption, represented by a vertical dashed line (B). Simulated possible volatization of groundwater by the 85-day period eruption within the island aquifer in the *Cumbre Vieja* area in terms of absolute groundwater levels (C) and relative to possible drawdown (D). Spatial distribution of the drawdown after 85 days of equivalent "groundwater magma pumping" effect. Possible drawdowns for different equivalent pumping flow rates assuming calibrated transmissivities and storativity obtained from Poncela et al. (2022 (F).

the natural trends from the dataset. This indicates that natural hydrograph trends may also play a critical role in determining the observed association between groundwater head and RSAM.

- The change in the sign of the correlation coefficients after removing the trends from the dataset suggests that the underlying factors driving the groundwater head fluctuations may be more complex than initially anticipated. These factors could include temporal variations in recharge and discharge, changes in aquifer properties such as connectivity and permeability, or additional external influences such as meteorological events or human-induced disturbances.
- The linear regression models of groundwater head and RSAM at each monitored point revealed that the relationship between these variables was consistent and not influenced by natural groundwater fluctuations in some cases. This finding implies that the two variables have a stable and uniform relationship, particularly during the eruption period, which could be attributed to the direct influence of the volcanic activity on the groundwater system.
- When the natural trends are removed in the linear regression models of groundwater head and RSAM, measurements taken two months after the eruption began mostly avoids abrupt changes in RSAM, providing insights into a common hydrogeological response or pattern during this time frame. The relatively mild RSAM changes during this period, as opposed to abrupt changes, might be associated with a more stable or predictable impact on the groundwater system, which could in turn lead to the observed slope change as the hydrogeological system adjusts to the volcanic activity and its effects on the aquifer.
- The numerical groundwater flow model developed for La Palma Island provided insights into the complex behavior of the groundwater system and the direction of groundwater flow within the insular aquifers. The flow network analysis identified hydraulic gradients

close to the area of the 2021 Cumbre Vieja eruption, where groundwater resources may be at risk.
- The long-term groundwater level trend at the LP-02 monitoring point indicated a possible recovery of groundwater levels after the end of the volcanic eruption. However, the simulated possible volatilization of groundwater during the eruption period raised concerns about potential groundwater contamination and highlighted the importance of further monitoring and management of the island's groundwater resources.
- The introduction of the novel concept of equivalent pumping simulations to represent the volatilization of groundwater during the eruption demonstrated that a considerable flow rate of 115 m^3 s^{-1} would be necessary to cause a significant drawdown in the monitored piezometers and wells. This finding has implications for understanding the behavior of the groundwater system during and after the volcanic eruption and highlights the need for further research on the potential effects of volatilization on groundwater resources in volcanic environments.

Despite the limitations of the study, the limited dataset and the need for further research to fully understand the impacts of volcanic activity on insular groundwater systems, significant efforts have been made to analyze these impacts as they could offer very valuable information. In particular, a novel interaction between the eruption and aquifers has been introduced, termed the "magma pumping effect." However, it is important to acknowledge the constraints imposed by the limited dataset available and the necessity for more extensive research to confirm or dismiss this phenomenon. Clarification of these evaporation phenomena could be achieved through stable isotopic studies of groundwater. In conclusion, this study provided valuable insights into the impacts of volcanic activity on insular groundwater systems and highlighted the importance of understanding the complex relationships between groundwater head, seismic activity, and other influencing factors, including the potential volatilization of groundwater during volcanic eruptions. The results obtained can contribute to the development of more effective groundwater management strategies and enhance our understanding of hydrogeological processes in volcanic environments. Thereby, the integration of these findings and strategies into larger civil protection and emergency response plans for volcanic risk management in volcanic islands is essential. The implications extend to improved groundwater management, facilitating the implementation of sustainable practices and protective measures to ensure the long-term availability and quality of groundwater resources in volcanic island environments. Overall, our research offers practical implications that can enhance resilience and safety in volcanic island regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Albano, S., Matsumoto, N., Newhall, C., Koizumi, N., Sato, T., 2002. Mechanisms of Groundwater Level Changes at Volcanoes, vol. 2002. AGU Fall Meeting Abstracts, pp. V21A–V1177.

Amanambu, A.C., Obarein, O.A., Mossa, J., Li, L., Ayeni, S.S., Balogun, O., et al., 2020. Groundwater system and climate change: present status and future considerations. J. Hydrol. 589, 125163.

Ancochea, E., Hernán, F., Cendrero, A., Cantagrel, J.M., Fúster, J., Ibarrola, E., et al., 1994. Constructive and destructive episodes in the building of a young oceanic island, La Palma, canary islands, and genesis of the caldera de Taburiente. J. Volcanol. Geoth. Res. 60, 243–262.

Andajani, R.D., Tsuji, T., Snieder, R.K., Ikeda, T., 2020. Spatial and Temporal Influence of Rainfall on Crustal Pore Pressure Changes Based on Seismic Velocity Monitoring.

APHP, 1992. Avance del Plan Hidrológico de La Palma. Cabildo Insular de La Palma, Santa Cruz de Tenerife, p. 245.

APPHLP, 2012. Avance o Proyecto del Plan Hidrológico de Palma. Memoria de Información. Consejo Insular de Aguas de La Palma, La Palma, p. 136.

Barberi, F., Bertagnini, A., Landi, P., Principe, C., 1992. A review on phreatic eruptions and their precursors. J. Volcanol. Geoth. Res. 52, 231–246.

Carreira, P.M., Marques, J.M., Pina, A., Mota Gomes, A., Galego Fernandes, P.A., Monteiro Santos, F., 2010. Groundwater assessment at santiago island (cabo verde): a multidisciplinary approach to a recurring source of water supply. Water Resour. Manag. 24, 1139–1159.

Choi, S.H., Kim, Y.K., Lee, D.Y., 1991. Sea water intrusion in the coastal area of Cheju volcanic island, Korea. Econ.Environ.Geol. 24, 319–327.

Comte, J.-C., Wilson, C., Ofterdinger, U., González-Quirós, A., 2017. Effect of volcanic dykes on coastal groundwater flow and saltwater intrusion: a field-scale multiphysics approach and parameter evaluation. Water Resour. Res. 53, 2171–2198.

Cronin, S.J., Neall, V., Lecointre, J., Hedley, M., Loganathan, P., 2003. Environmental hazards of fluoride in volcanic ash: a case study from Ruapehu volcano, New Zealand. J. Volcanol. Geoth. Res. 121, 271–291.

Custodio, E., 2020. Hydrogeology and Groundwater Resources in Volcanic Formations and Islands. Universidad Politécnica de Cataluña, Barcelona.

De la Nuez, J., Casillas, R., Martín, M.C., 2008. In: Cabrera, PTy (Ed.), Estructura interna y vulcanismo reciente de la Isla de La Palma, vol. 4. Geoguías, pp. 127–153.

Diersch, H.J., 2013. FEFLOW: Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media. Springer Berlin Heidelberg.

Donaldson, C., Winder, T., Caudron, C., White, R.S., 2019. Crustal seismic velocity responds to a magmatic intrusion and seasonal loading in Iceland's Northern Volcanic Zone. Sci. Adv. 5, eaax6642.

Eamus, D., Fu, B., Springer, A.E., Stevens, L.E., 2016. Groundwater dependent ecosystems: classification, identification techniques and threats. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.-D., Ross, A. (Eds.), Integrated Groundwater Management: Concepts, Approaches and Challenges. Springer International Publishing, Cham, pp. 313–346.

EGDHLP, 2009. Estudio General de la Demarcación Hidrográfica de La Palma. Plan Hidrológico. Consejo Insular de Aguas de La Palma, La Palma, p. 105.

EU-WFD, 2000. European Water Framework Directive 2000/60/EC. European Parliament.

Guillou, H., Carracedo, J.C., Torrado, F.P., Badiola, E.R., 1996. K-Ar ages and magnetic stratigraphy of a hotspot-induced, fast grown oceanic island: El Hierro, Canary Islands. J. Volcanol. Geoth. Res. 73, 141–155.

Hayes, D.E., Rabinowitz, P.D., 1975. Mesozoic magnetic lineations and the magnetic quiet zone off northwest Africa. Earth Planet Sci. Lett. 28, 105–115.

Hemmings, B., Whitaker, F., Gottsmann, J., Hughes, A., 2015. Hydrogeology of Montserrat review and new insights. J. Hydrol.: Reg. Stud. 3, 1–30.

Hiltona, D.R., Macphersona, C.G., Elliottb, T.R., 2000. Helium isotope ratios in mafic phenocrysts and geothermal fluids from La Palma, the Canary Islands (Spain): implications for HIMU mantle sources. Geochem. Cosmochim. Acta 64, 2119–2132.

Hurwitz, S., Johnston, M.J.S., 2003. Groundwater level changes in a deep well in response to a magma intrusion event on Kilauea Volcano, Hawai'i. Geophys. Res. Lett. 30.

Armonk (Ed.), 2010. IBM SPSS Statistics for Windows, Version 19.0. IBM Corp., NY.

Ingebritsen, S.E., Flinders, A.F., Kauahikaua, J.P., Hsieh, P.A., 2021. Modeling groundwater inflow to the new crater lake at kilauea volcano, Hawai'i. Groundwater 59, 7–15.

Jasim, A., Hemmings, B., Mayer, K., Scheu, B., 2019. Groundwater Flow and Volcanic Unrest. From Science to Society, Volcanic Unrest, pp. 83–99.

Jasim, A., Whitaker, F.F., Rust, A.C., 2015. Impact of channelized flow on temperature distribution and fluid flow in restless calderas: insight from Campi Flegrei caldera, Italy. J. Volcanol. Geoth. Res. 303, 157–174.

Koizumi, N., Kitagawa, Y., Kazahaya, K., Takahashi, M., 1998. Volcanic gas concentration and aquifer permeability estimated from tidal fluctuations in groundwater level: case of Koshimizu Well in Izu-Oshima, Japan. Geophys. Res. Lett. 25.

Moeck, I.S., 2014. Catalog of geothermal play types based on geologic controls. Renew. Sustain. Energy Rev. 37, 867–882.

Navarro Latorre, J.M., 1993. Mapa Geológico de La Palma. Ministerio de Agricultura, Pesca y Alimentación-ICONA, Madrid.

Newhall, C.G., Albano, S.E., Matsumoto, N., Sandoval, T., 2001. Roles of groundwater in volcanic unrest. J. Geol. Soc. Philipp. 56, 69–84.

Nur, A.S., Park, S., Lee, S., Lee, C.-W., 2021. Monitoring Volcanic Activity of Baekdu Mountain Based on Ice Area Changes during the Winters of 2015-2020.

Poland, M.P., Anderson, K.R., 2020. Partly cloudy with a chance of lava flows: forecasting volcanic eruptions in the twenty-first century. J. Geophys. Res. Solid Earth 125, e2018JB016974.
Poncela, R., 2009. Definición del modelo conceptual del flujo subterráneo de la Isla de La Palma. Gobierno de Canarias, Santa Cruz de Tenerife, p. 144.
Poncela, R., 2015. La Palma Volcanic Aquifer System Hydrogeology Civil Engineering Department. Alicante University, Islas Canarias, p. 227.
Poncela, R., Santamarta, J.C., García-Gil, A., Cruz-Pérez, N., Skupien, E., García-Barba, J., 2022. Hydrogeological characterization of heterogeneous volcanic aquifers in the Canary Islands using recession analysis of deep water gallery discharge. J. Hydrol. 610, 127975.
Poncela, R., Skupien, E., 2013. Estado de las masas de agua subterránea de La Palma. Consejo Insular de Aguas de La Palma, p. 131.
Santamarta, J., 2013. Hidrología y Recursos Hídricos en Islas y Terrenos Volcánicos. Tenerife. Colegio de Ingenieros de Montes.
Sharan, A., Lal, A., Datta, B., 2021. A review of groundwater sustainability crisis in the Pacific Island countries: challenges and solutions. J. Hydrol. 603, 127165.
Shibata, T., Akita, F., 2001. Precursory changes in well water level prior to the March, 2000 eruption of Usu volcano, Japan. Geophys. Res. Lett. 28, 1799–1802.
Tanguy, J.-C., 1994. The 1902–1905 eruptions of Montagne Pelée, Martinique: anatomy and retrospection. J. Volcanol. Geoth. Res. 60, 87–107.
Taran, Y., Kalacheva, E., 2020. Acid sulfate-chloride volcanic waters; Formation and potential for monitoring of volcanic activity. J. Volcanol. Geoth. Res. 405, 107036.
Tashima, M.M., Soriano, L., Borrachero, M.V., Monzó, J., Payá, J., 2023. Towards the valorization of Cumbre Vieja volcanic ash – production of alternative cements. Construct. Build. Mater. 370, 130635.
White, J.T., Hunt, R.J., Fienen, M.N., Doherty, J.E., 2020. Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis. US Geological Survey.
Witham, C.S., Oppenheimer, C., Horwell, C.J., 2005. Volcanic ash-leachates: a review and recommendations for sampling methods. J. Volcanol. Geoth. Res. 141, 299–326.
Yoshida, K., Tahara, K., Tsunemi, K., Kajihara, H., Wada, Y., Makino, R., et al., 2013. G-EVER Consortium: the New Earthquake and Volcanic Hazards Mitigation Activities.