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Research papers

# Hydrogeological characterization of heterogeneous volcanic aquifers in the Canary Islands using recession analysis of deep water gallery discharge

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ABSTRACT

Aquifers constitute the main freshwater supply of oceanic islands. Maintaining groundwater quantity and quality is of critical concern as demographic and climatic changes place additional pressures on already fragile water resources systems. Islands with heterogeneous volcanic aquifers pose additional difficulties in assessing their water resources. This work proposes an approach for improving the hydrogeological characterization of heterogeneous volcanic aquifer systems by making use of recession coefficients from deep water gallery discharge. To demonstrate the usefulness of this approach, hydrographs and recession curves from groundwater discharge of 30 water galleries on La Palma (Canary Islands) were evaluated. This analysis allowed us to obtain the main hydrogeological parameters of a volcanic aquifer system, in terms of hydraulic diffusivity. A Maillet-Boussinesq model with an exponential decay law was adopted, according to field observations of drainage discharge. The alpha coefficients of recession values ranged between $10^{-3}$ and $4{\cdot}10^{-4}$ day$^{-1}$ and showed significant spatial correlation with insular geology. Additionally, hydraulic diffusivity values of island hydrogeological domains were obtained from recession coefficients using the Rorabaugh-Singh method. Weighted storage coefficients for volcanic materials were in the range of 3% to 7%, with an average transmissivity in the range of 15 to 150 m$^2{\cdot}$day$^{-1}$. The methodology proposed has demonstrated its usefulness in coping with local uncertainty in hydraulic characterization of insular aquifers associated with volcanic heterogeneity. This is an improvement compared to standard pumping tests, thus providing hydraulic parameters prior to numerical analysis for water management planning.

## 1. Introduction

Fresh groundwater resources within oceanic islands are both limited and vulnerable (Urish, 2010; Werner et al., 2017). Oceanic islands have no significant surface water resources and rely on limited groundwater resources where rain-fed agriculture dominates and economies are particularly vulnerable to rainfall variability (drought) and climate change pressures (Duncan, 2012). The availability of fresh water on an oceanic island depends on the existent interactive relationship between size, topography, climate and island hydrogeology (Urish, 2010). The hydrogeology of oceanic islands is strongly related to volcanic activity within the oceanic crust and, when climate is adequate, formation of the fringing reef associated with volcanic islands, which, finally, end in atoll islands if continued subsidence leads to submersion of the volcanic core (Wheatcraft and Buddemeier, 1981). Oceanic islands composed of igneous rocks (juvenile) are classified as high islands, and those composed of limestone or more permeable unconsolidated coral or sand are classified as low islands (Kashef, 1983). The hydrogeology of each type of island is radically different. Volcanic island present as hard-rock hydrogeology, with fresh groundwater flow through fracture zones in relatively dense andesite volcanic islands and, additionally, through extrusive strata and lava flow materials in less dense basalt islands. Raised limestone islands of ancient coral, also containing primary dense rocks, show fresh groundwater flow presenting karstic behavior with solution cavities that act as a fresh groundwater drainage system. High islands (>600 m) create their own high altitude climate, which may present a wet side with running streams, even crater lakes, and a much drier side as a result of the “rain shadow” effect (Urish, 2010). Low

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islands composed of relatively permeable unconsolidated coral or sand do not commonly present free-flowing surface streams and fresh groundwater flow patterns are dominated by the generation of a freshwaterlens, driven by the Ghyben-Herzberg principle (Bailey et al., 2009).

Although efficient management of freshwater resources is critical to oceanic island authorities (Tribble, 2008; White and Falkland, 2010), heterogeneity and anisotropy found in volcanic islands represent a major challenge for resource assessment and planning (Santamarta et al., 2014). The range of values for porosity and hydraulic conductivity of volcanic rocks is almost nine orders of magnitude (Flint et al., 2002; Singhal and Gupta, 2010). Such a variation indicates the importance of characterization of hydraulic parameters for freshwater supply in oceanic islands. Currently, there are numerous and sophisticated technical and methodological instruments available for volcanic environments that include the use of remote sensors (El-Rayes et al., 2020), specific mathematical models (Herrera and Custodio, 2014), technical instruments (Flint and Selker, 2003), and simulation of processes. All these, combined with the fieldwork, are indispensable for the efficient exploitation of water resources in volcanic oceanic islands (Rotzoll and El-Kadi, 2008). In some cases, e.g. in the Canary islands (Custodio, 1978; Poncela, 2009; Poncela, 2015), hydrogeological characterization of heterogeneous volcanic aquifer systems leads to high costs, even though some of the field data can be obtained with conventional methods at far lower costs (though without excluding the other above-mentioned methods). Therefore, in areas or territories with difficult relief, or with significant environmental risks and potential impact on autochthonous or indigenous populations (social responsibility), there must be a thorough analysis and characterization of the regional hydrogeology. The use of relatively simple methods of providing estimations and calculations of key hydrogeological parameters in aquifer systems or indicating relationships amongst them are essential (Poncela, 2009; Poncela, 2015; Rutledge, 2006). A significate advance in this issue was shown by Rotzoll and El-Kadi (2008) for the volcanic rocks in Maui, Hawaii (USA), where hydraulic conductivity was estimated from 1,257 specific capacity values in Hawaii's well database. These authors also applied a geostatistical approach to Maui and Oahu islands in generating island-scale hydraulic conductivity maps to facilitate groundwater management efforts.

High volcanic islands of the Canary Islands present substantial groundwater flow (Custodio, 1978; Custodio and Llamas, 1983; MAC-21, 1980; SPA-15, 1975). In the case of Tenerife and La Palma islands, such groundwater flows have been evaluated to approximately 5,335 and 2,100 $l \cdot s^{-1}$, respectively. These values reflect the importance of increasing hydrogeological knowledge of volcanic systems, especially as human and agricultural consumption uses approximately 90% of these water flows, without considering non-conventional resources. The main aim of this investigation is to propose and demonstrate the effectiveness of using recession coefficients from deep water gallery discharge for hydrogeological characterization of volcanic heterogeneous aquifers in high volcanic islands. Although the study of recession curves of flood hydrographs is already a well-established technique in surface hydrology (Fiorillo, 2014; Pinder et al., 1969; Rutledge, 2006; Shi et al., 2018) and hydrogeology (Cuthbert, 2014; Gregor and Malík, 2012; Healy and Cook, 2002; Nurkholis et al., 2019), its application to water galleries in heterogeneous volcanic aquifers has not been reported to our knowledge. The proposed approach requires fewer economic resources compared with other more sophisticated methods (which are also necessary), since it can take advantage of existing, or easily obtained, information during the resource exploration phases. Finally, the study of recession coefficients for the discharge of drainage galleries reported in this work for La Palma island could be generalized to other volcanic aquifers in the Canary Islands, even to other volcanic islands in the Macaronesian zone, Pacific area, etc. The proposed water gallery discharge analysis provides practical utility in overcoming local uncertainty associated with volcanic heterogeneity, providing hydraulic parameters for extensive areas representative of the volcanic aquifer system domains. Thus, it provides effective tools for improving fresh groundwater resources assessment.

## 2. Study area

The island of La Palma is located in the northwest of the Archipelago of the Canary Islands (Spain), northeast of the African continent at a subtropical latitude (Fig. 1). The island's dimensions are 47 km (N-S) by 29 km (E-W), and it has a surface area of 708 $km^2$. The Canary Islands constitute the emerged portion of a volcanic massif located on oceanic lithosphere from the Jurassic Age, on the intra-plate domain of the western border of the African plate (Carracedo, 2011; Rodriguez, 2011). Their genesis is associated with the alpine dynamics also responsible for the African Atlas orogeny, which had their climax 20 million years ago during the Miocene. The development of the archipelago is the result of the relative displacement from east to west of a mantle hotspot, currently located at the western end of the archipelago. La Palma island is characterized by the formation of volcanic stratum structures reaching heights of over 3,000 m above the deep seafloor (APHP, 1992; De la Nuez et al., 2008) and the presence of a locally erosive discontinuous structure, known as a "COEBRA structure" (APHP, 1992; Navarro Latorre, 1993) where numerous springs, some with significant flow rates, can be found.

La Palma island presents a complex volcanic aquifer system, composed predominantly of the piling up of basaltic lavas and associated scoria, with intercalation of pyroclastic layers. This island's aquifer system is compartmentalized into blocks, constituting a rift system which is traversed by an intricate network of dykes. Dykes compartmentalize the hydrogeological system and determine the direction of groundwater flow (Fig. 2). The closer these dykes are to areas of rift to the structural axes of La Palma, the denser they become, creating a variety of sealing cells. Dykes act as hydrological barriers by damming groundwater and causing high local piezometric gradients. In addition, the existence of *debris avalanche deposits*, a consequence of important gravitational landslides, may influence the presence of semi-confined or confined areas of the island's aquifers (Poncela, 2009; Poncela, 2015). The insular-scale conceptual model considers that groundwater flow comes down from the summits towards the sea through winding paths hampered by the presence of dykes (Custodio and Llamas, 1983), reaching regional groundwater levels at around 1,800 m inland and at sea level in the coastal zone.

The main water reservoir, defined in accordance with the WFD 2000/60/EC directive, is the LP001 groundwater body (Poncela, 2005; Poncela and Skupien, 2013; Skupien and Poncela, 2007) and includes the main insular aquifer system, the *Taburiente* volcano cone materials (Lower and Upper) and the COEBRA structure (APHP, 1992; APPHLP, 2012; EGDHLP, 2009). LP001 groundwater body area stretches from the north cone halfway to the south cone and down to the coastal fringe, reaching a benchmark of 600 m.a.s.l., including the *Cumbre Nueva* volcano. The area includes the most important summits where high precipitation is received, providing natural recharge for this hydrogeological system. In general, the stacks of lava and scoria from the *Upper Taburiente* volcano favor filtration and subsequent natural recharge to the main aquifer (the *Lower Taburiente* cone). However, there are marked contrasts in permeability due to the lithological heterogeneity present, such as the overlaid series constituting the hydrogeological base. These series can either cut across or be in contact with the structure of COEBRA or the Basal Complex structure, acting as a low permeability basement. Formations such as debris avalanche scars have formed genuine erosive landforms of asymmetric caldera basins, which were the precursors of the main island groundwater reservoirs of La Palma.

Two main flow regimes can be distinguished for the island of La Palma. Firstly, there is a regional flow regime with recharged waters from decades ago, even centuries, and, possibly, mixed with more recent

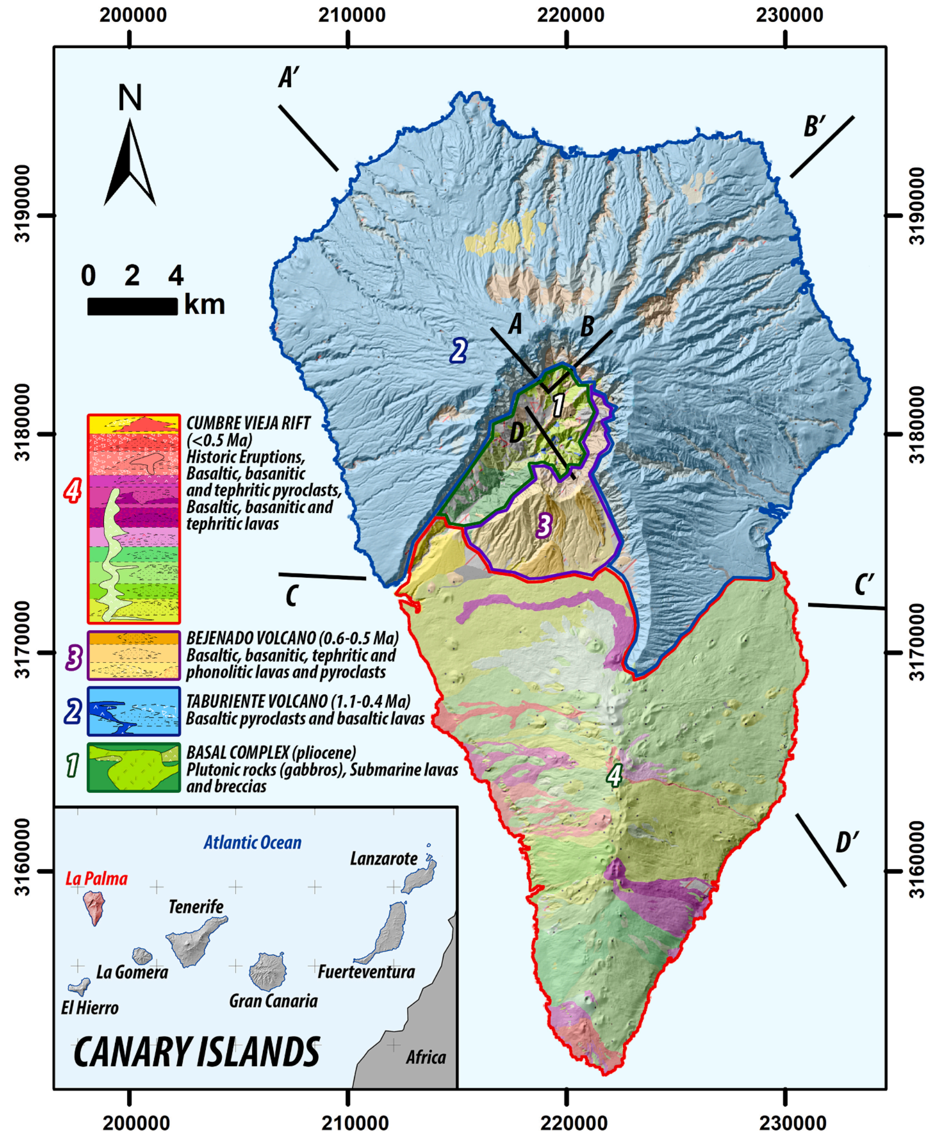

**Fig. 1.** Geological map of the study area in La Palma island, Canary Islands (Spain). Extended geological data and detailed legend can be found in (IGME, 2017). Projection: WGS 1984 Complex UTM Zone 28N, Datum DWGS1984.

waters but with little direct contribution to springs. This flow regime is generally present at elevations below 1,000 m.a.s.l. Nevertheless, water stratification processes at upper levels of the aquifer can be found. Secondly, there is a local flow regime at elevations above 1,000 m.a.s.l. that is characterized by low groundwater residence times, low mineralization and with recent recharge indicators such as significate presence of Tritium contents (>2 UT).

Groundwater from La Palma aquifer system shows a sodium and calcium-magnesium bicarbonate hydrogeochemical facies. The low content of chlorides and sulfates facies make the water of excellent quality with low mineralization (under 200 µS/cm), which is highly valued for domestic water supplies and irrigation. The main groundwater extractions take place through galleries and springs. The use of water galleries (Fig. 3) is an extended practice in all the islands of the Canary Archipelago (Custodio et al., 2016; Santamarta and Lario-Bascones, 2015). Historically, in the Canary Islands, groundwater has been exploited and transported by a network of canals going around the islands and the large number of shafts and tunnels that provide water. Excavation of a water gallery involves horizontal linear excavations with a single exit way, usually less than two meters in diameter and with lengths up to 6,600 m (Santamarta, 2013). In many of the productive galleries on La Palma island, the main groundwater discharge zones are located at the intersection of the gallery with an individual dyke or dyke system; in other, less productive galleries, the saturated formations are permeable enough to drain the saturation of the front or fronts, thus reaching a balance in the absence of external influences. La Palma has 78 active galleries, from a census of 162 (Fig. 3) and with a cumulative length of 264.3 km, that exploit 146.14 $hm^3$/year, approximately 61% of total groundwater production (PHP, 2018).

## 3. Methodology

The applied methodology for the hydrogeological characterization of the La Palma volcanic aquifer system can be divided into four stages - data acquisition, calculation of the recession coefficient from the gauging data, calculation of the hydraulic diffusivity of the aquifer system or zones and geostatistical analysis.

### 3.1. Field data acquisition of water gallery discharge rates

In this work, 30 water galleries on the island of La Palma were selected, with representative recession curve datasets available (Fig. 3).

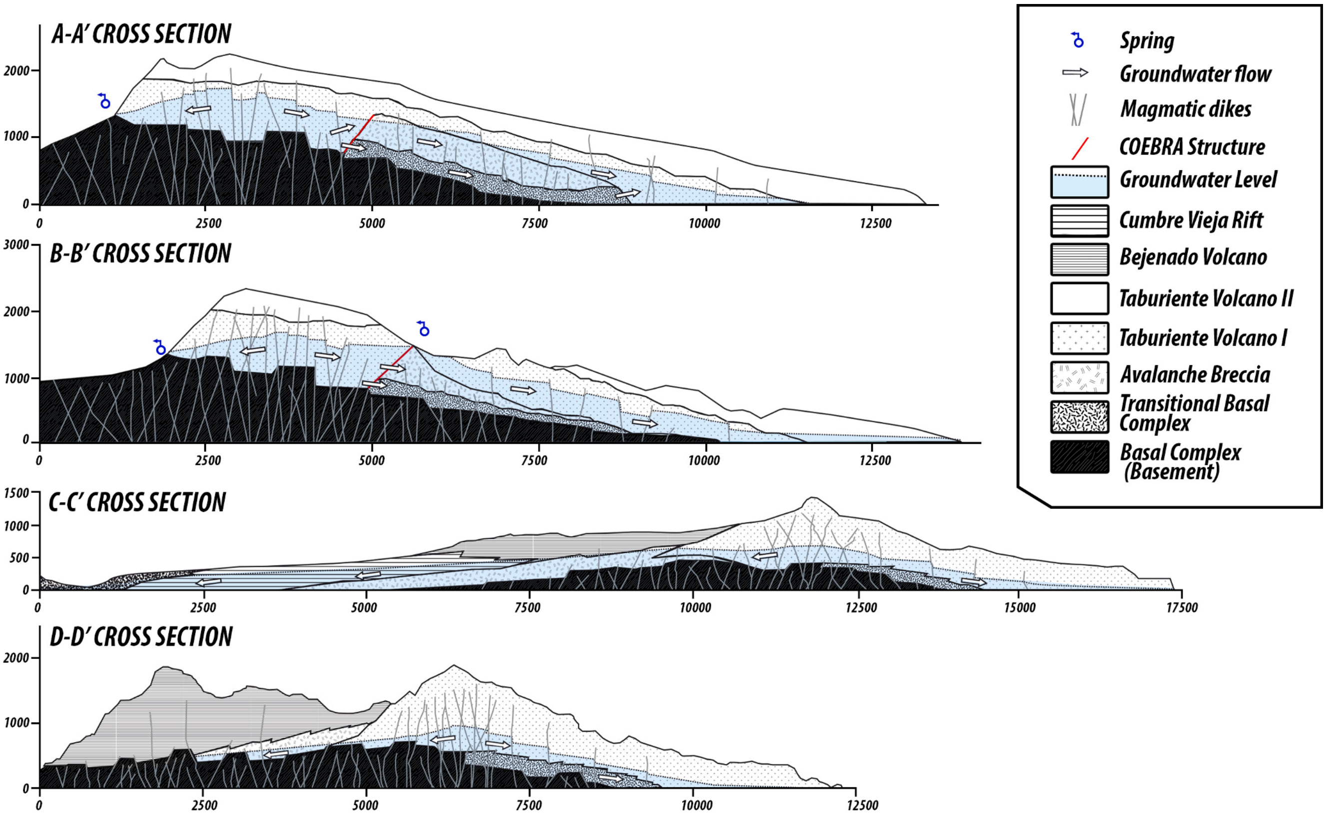

**Fig. 2.** Hydrogeological cross-sections of La Palma island. Locations of sections shown in Fig. 1 from Poncela (2015).

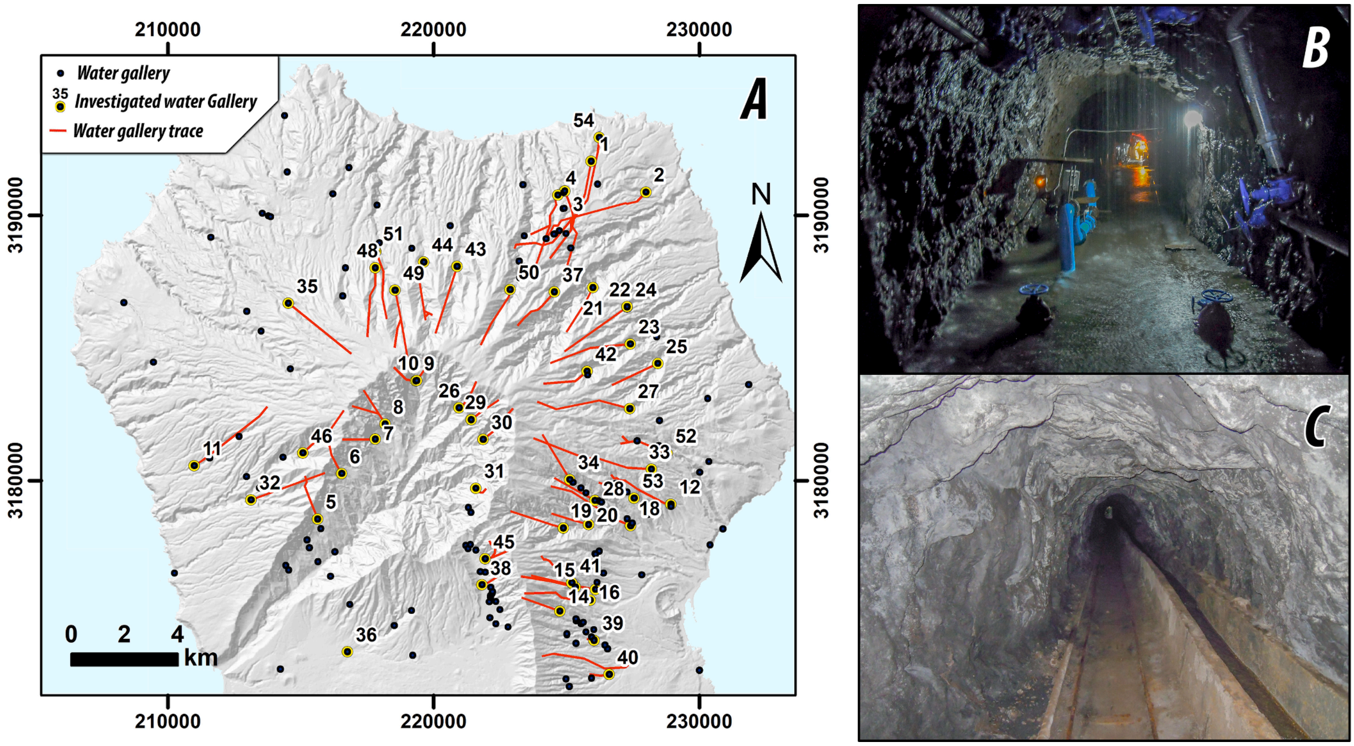

**Fig. 3.** (A) Existent water galleries in the Northern part of La Palma island. Water gallery traces are shown only for investigated galleries. (B) Drainage of a saturated zone and (C) transport by way of canals and piping in a gallery (La Palma).

To ensure representativeness, only galleries showing discharge hydrographs with relative smooth slope and without influence of transient recharge events were selected. This selection allowed a reasonable association similar to exhaustion patterns for equivalent elements inside the system under study (Poncela, 2009; Poncela, 2015; Poncela and Skupien, 2011). Water gallery daily discharge rate data from 1972 to

2015 were obtained from the insular Water Authority (*Consejo Insular de Aguas de La Palma*, CIALP). Water gallery discharge rates were measured by water users' communities under the supervision of CIALP. Water gallery discharge rates have been measured using commercial electromagnetic flowmeters with a measuring accuracy of ± 0.5% of the actual flow rate since the 1990s. Before the 1990s, discharge rates were obtained daily by Cole type Pitot tubes (pitometry technique) to map velocity profiles and, thus, measure discharge rates. The differences between the mean velocities measured by the Pitot tube and by the Acoustic Doppler Velocimeter were restricted to a range of 15%, which is reduced with increasing flow velocities (Almeida and Souza, 2017). The water gallery vector dataset (Line SHP file) was obtained from Canary Islands' administrative authorities.

### 3.2. Calculation of the recession coefficient

Increasing hydrogeological knowledge of volcanic systems requires methodologies capable of predicting drainage flows from galleries and springs, their evolution over time and their area of influence. It is not common in the Canary Islands to find the historical evolution of water discharge of a gallery with a fixed length. In general, galleries tend to become deeper over time to increase or maintain water discharge. On La Palma island, the future evolution and sustainable extraction volumes must be estimated. However, it is not feasible to directly discover a gallery's area of influence, nor its effects on other galleries nearby. To do this requires a series of hypotheses or numerical modelling, which are not always available. The two main groundwater drainage modes that operate through galleries were described by Caloz (1987). The first is the (1) non-influenced state, where gallery drainage hydrodynamics are not affected, or affected to a lesser extent, by adjacent gallery drainage. This state is reflected on the recession curve observed in the non-influenced gallery, as successive segments of the recession curve diminish over time in a homogeneous, continuous and smooth way. The second mode is represented by the (2) influenced state. A drainage gallery under an influenced state shows diverse changes in slope on the recession curve. These variations in slope can be related to changes in hydrodynamic conditions (perforation works in the gallery, obstruction of the gallery, feedback, etc.). Galleries under an influenced state may experience an enhancement or loss of its discharge rates. Enhancement of discharge rates can be caused by, among others causes, perforation works increasing permeability or intense precipitation events, when the vadose zone presents reduced thickness (e.g. galleries at a high elevation close to the summits). In contrast, decay of discharge can be related to siltation of the gallery reducing permeability, an obstruction or the interference of a nearby gallery drainage front. The above situations can be illustrated by three cases adapted from Sáenz de Oiza (2011) (Fig. 4). The first situation is where recharge is zero, similar to what is known as a *dyke gallery*. This situation occurs when a dyke crosses a saturated zone and emptying of the deposit from the exterior surface of the dyke takes place. In this situation, the pressure and water reserves will follow the following expression:

$$e^{-\alpha t} \tag{1}$$

with $\alpha^{-1}$ [T] being the average age of the waters retained in the deposit and t [T] the time. At the initial time of drainage, the discharge rate $Q$ [$L^3 \cdot T^{-1}$] will fit the following equation:

$$Q^{-2} = \alpha t \tag{2}$$

The second situation considers a fixed-constant recharge. In this case, the evolution of water discharge tends to:

$$Q(\alpha,\ t) = Q_b + \ (Q_0 - Q_b) \cdot e^{-\alpha t} \tag{3}$$

where $Q_0$ [$L^3 \cdot T^{-1}$] is the initial discharge rate; $Q_b$ [$L^3 \cdot T^{-1}$] is the base flow corresponding to the recharge from the influence area of the gallery. The third situation considers a transient periodic recharge, characteristic of galleries located at high benchmarks or influenced by seasonal varying water levels.

One method that has often been used in scientific literature to calculate the recession coefficient is the *Decreasing Exponential Method* of Maillet Boussinesq (Custodio and Llamas, 1983). This method is often applied to confined and unconfined aquifers presenting considerable thickness and a constant discharge rate. Typically, these conditions are met in mountain springs but they are also met in drainage from water galleries on La Palma island, where the point of reference is always known.

In this work, 30 water galleries on the island of La Palma were selected, with representative recession curves dataset available (Fig. 3). To ensure representativeness, only galleries showing discharge hydrographs with relative smooth slope and without influence of transient recharge events were selected. This selection allowed a reasonable association similar to exhaustion patterns for equivalent elements inside the system under study (Poncela, 2009; Poncela, 2015; Poncela and Skupien, 2011).

Discharge rates, plotted in logarithmic scale against time, were investigated by analyzing the exponential (linear in logarithmic scale) regression fit (Fig. 5). This exponential decay law was described by Maillet-Boussinesq (Custodio and Llamas, 1983) as:

$$Q = Q_0 e^{-\alpha t} \tag{4}$$

where: $Q$ [$L^3 \cdot T^{-1}$] is the discharge rate at time $t$ [T], $Q_0$ [$L^3 \cdot T^{-1}$] is the discharge rate at the time of peak discharge, and $\alpha$ [$T^{-1}$] is the recession coefficient that depends on the geometric and hydrological characteristics of the underground reservoir. By estimating the value of the recession coefficient, a zone of volcanic heterogeneous aquifer of several kilometers can be characterized. Reservoir volume $V$ [$L^3$] can be calculated by:

$$V = \frac{Q}{\alpha} \tag{5}$$

When discharge hydrographs show multiple sections of recession reflecting the influence of different recharge episodes, the total

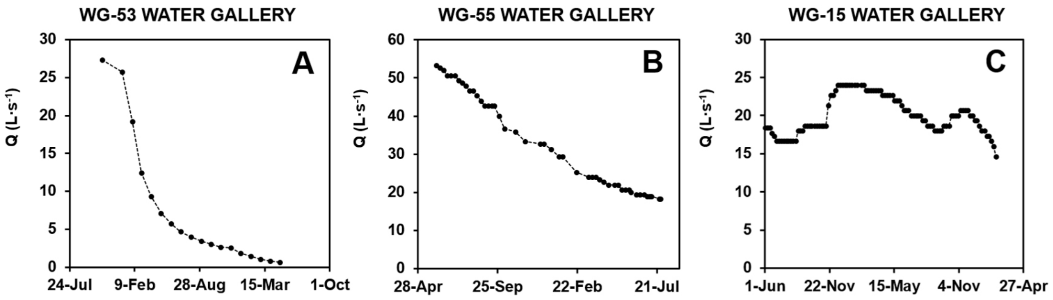

**Fig. 4.** Typology of discharge curves as a function of natural recharge: (A) type I, (B) type II and (C) type III.

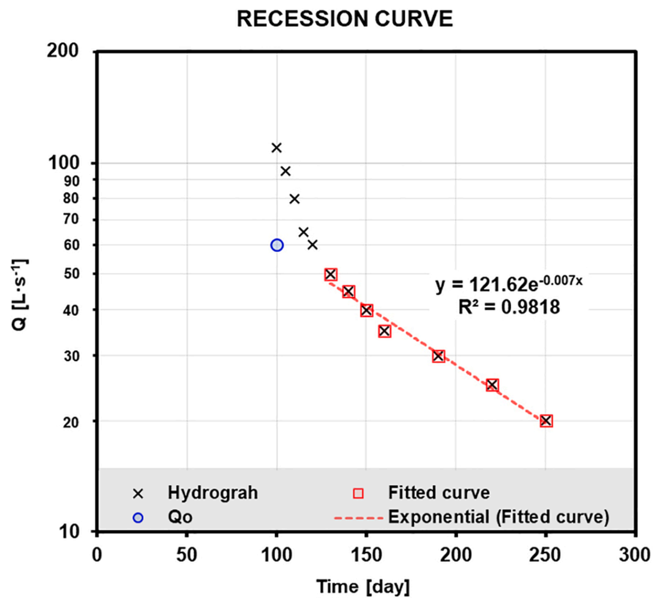

**Fig. 5.** Calculation of the coefficient taken from the linear section of the relation LogQ-Time.

discharge is the sum of the contributions of the respective flows and the different sections, and it can be evaluated by means of:

$$Q_T = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} Q_{0i} e^{-\alpha_i t} \qquad (6)$$

By studying discharge from galleries and springs, the value of the recession coefficient that assesses the relationship between hydrogeological parameters is obtained. Depending on the complementary information available, it is possible to estimate parameters individually.

### 3.3. Calculation of hydraulic diffusivity, transmissivity and storativity

Once recession coefficients of the selected water galleries were obtained, the hydraulic diffusivity of the aquifer system in the area of influence of each gallery was calculated by means of the Rorabaugh-Singh equation (Custodio and Llamas, 1983):

$$\alpha = \frac{\pi^2 T}{4SL^2} \qquad (6)$$

where $T$ [$L^2 \cdot T^{-1}$] is the transmissivity of the aquifer; $S$ [-] is the dimensionless storage coefficient, $\alpha$ [$T^{-1}$] is the recession coefficient that depends on the geometric and hydrological characteristics of the subterranean reservoir, and $L$ [L] is the distance to the groundwater catchment divisor line or a characteristic length. Eq. (7) can be reformulated in terms of hydraulic diffusivity $D$ [$L^2 \cdot T^{-1}$] as:

$$D = \frac{T}{S} = \frac{\alpha 4L^2}{\pi^2} \qquad (7)$$

Eqs. (6) and (7) allow working with two of the main hydrogeology parameters, $T$ and $S$. Transmissivity was then obtained from the estimation of porosity conducted from recovery tests conducted in the hydraulic bulkhead gates in galleries. The proposed approach presents the following limitations: (1) continuity between the point of discharge and piezometric head is required, (2) the tested gallery section should not present significant punctual discharge from geological discontinuities such as fractures, and (3) absence of dykes acting as major flow barriers.

Characteristic distances have been taken up to the groundwater catchment boundary, approximately perpendicular to the area of summits. This parameter can present a given grade of uncertainty when there is no detailed knowledge of the geology of the gallery, or when the groundwater catchment boundary is not precisely known (null groundwater flow boundary condition). Nevertheless, many galleries in La Palma present a quasi-steady state hydraulic regime, and important knowledge of the local geology is available, reducing the uncertainty associated with the hydrogeological characterization of aquifer materials. In addition, detailed analysis of the discharge hydrographs was conducted, to prevent the interpretation of galleries with a major presence of preferential pathways (discontinuities, faults, etc.).

Along water gallery bulkhead gates are typically installed in dikes, acting as a flow barrier to regional groundwater flow. Bulkhead gates allow the control of water gallery discharge according to water demand. When a bulkhead gate is closed after several months open, pressure sensors record pressure recovery; obtained pressure measurements were transformed into meters of water column and used as residual drawdowns. Since galleries discharge is continuously recorded, it is possible to interpret this recovery as a standard recovery test, which is often applied in hydrogeology to evaluate storativity. The solution to this problem, proposed in 1935 by Theis (Custodio and Llamas, 1983), was applied in this work, allowing us to obtain regionalized test results. Storativity of extensive areas of the volcanic aquifer system composed of lavas, scoria and dykes, with the influence of rocks associated with the insular basement known as Basal Complex, was evaluated (Fig. 6).

Uncertainty was evaluated in hydraulic parameters assuming a normal (Gaussian) distribution; uncertainty of estimations is expressed by the standard deviation (σ) and given as ± σ, comprising 68.3% of the possible realizations (Custodio et al., 2015). Average, minimum and maximum uncertainties are also given dimensionless as the coefficient of variation (CV).

### 3.4. Geostatistical analysis

The 30 water galleries investigated on the island of La Palma, representative of their respective geological domains concentrated in the northern part of the island, enabled the application of geostatistical methods (Bear, 1979; Oliver and Webster, 2015) to establish spatial distribution models of transmissivity and storativity, and subsequent mapping. Ordinary kriging was used for predicting values of the selected hydrogeological parameters at unobserved places of La Palma island, without bias and with minimum variance. Although geostatistical analysis does not require data to follow a normal distribution, transmissivity data presenting a skewness coefficient of 3.23 were transformed to common logarithms (lognormal kriging). Transmissivity variogram considering $\log_{10}$ transformation showed significant improvement in the kriging diagnostics. The hypothesis of normality of storativity data presenting a skewness coefficient of 3.88 and the data were subjected to the Box-Cox transformation (transgaussian kriging). Quadratic (second order) polynomial trend was removed from storativity data to avoid increasingly steep experimental variogram with the lag distance. From the experimental semivariograms, two theoretical models of semivariograms were adjusted for each hydrogeological parameter evaluated. A spherical semivariogram model was used for transmissivity as:

$$\gamma(h,\theta) = \begin{cases} \theta_s \left[ \frac{3|h|}{2\theta_r} - \frac{1}{2}\left(\frac{|h|}{\theta_r}\right)^3 \right] for 0 \le |h| \le \theta_r \\ \theta_s for \theta_r < |h| \end{cases} \qquad (8)$$

where $\gamma$ is the estimated variable, $\theta_s$[$m^2$] is the sill value, $h$ is the lag vector, $|h|$[m] is the length of $h$ as the distance between two locations and $\theta_r$ [m] is the range of the model. The semivariogram for storativity was modelled according to a stable semivariogram model:

$$\gamma(h,\theta) = \theta_s \left[ 1 - \exp\left( -3\left(\frac{|h|}{\theta_r}\right)^{\theta_e} \right) \right] \qquad (9)$$

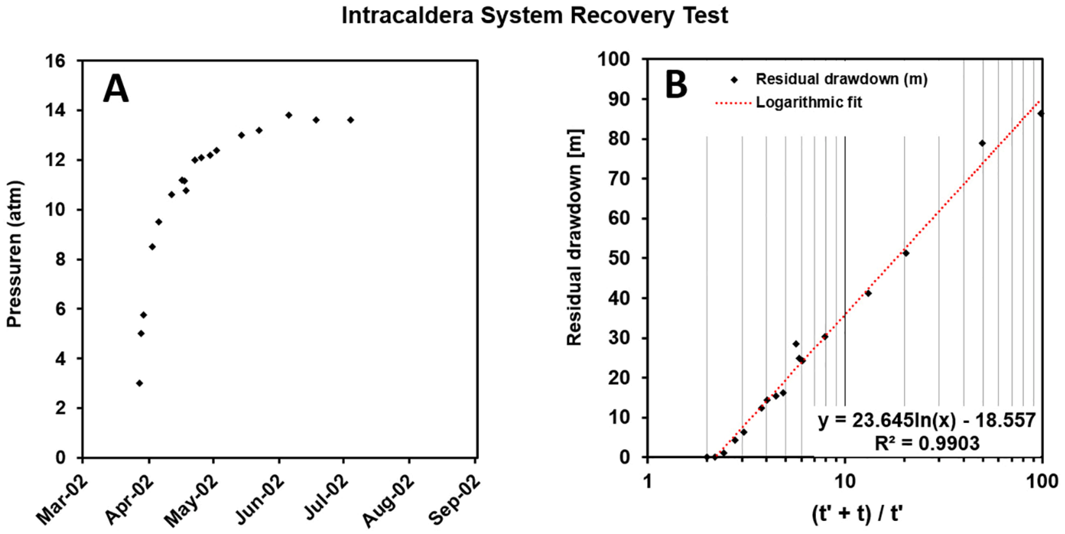

**Fig. 6.** Interpretation of the recovery test (A), starting from the hydraulic bulkhead gate of the gallery WG-26. Application using the weighted data in an intra-crater zone in the northern sector of La Palma island (B).

where $\theta_e$ [m$^2$] is the partial sill value, with $0 \le \theta_e \le 2$. The semivariogram model was selected following a cross-validation technique (Webster and Oliver, 2007).

## 4. Results and discussion

Results obtained from the methodology are presented in Table 1. The recession coefficient values obtained by the exponential decay method showed a range between $10^{-3}$ and $10^{-4}$ day$^{-1}$. The western area of La Palma island showed values in the range of $2{\cdot}10^{-4}$ to $4{\cdot}10^{-4}$ day$^{-1}$ while the northern and eastern areas of the island showed values in the range of $10^{-3}$ and $3{\cdot}10^{-4}$ day$^{-1}$. In general, the recession coefficient values found correspond to reservoirs with a great capacity for groundwater storage, sometimes higher than several hm$^3$ as shown in the north-eastern area (12–20 hm$^3$). The typology of synthetic water flow recession curves of the galleries found for each sector of La Palma island is shown in Fig. 7. The northern area shows typical patterns of type I galleries, with substantial emptying of the reservoir until a certain degree of stabilization is achieved. The eastern and western areas present characteristic averages similar to type II. This characterization has not

**Table 1**
Resulted values of the recession coefficients and hydrogeological parametrization for the 30 investigated water galleries on La Palma island.

| Water gallery | Number of estimations (N) | Recession coefficient | Discharge peak | Characteristic length | Hydraulic diffusivity | Transmissivity | | | Storativity | | | Reservoir volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [–] | [day$^{-1}$] | [m$^3$·day$^{-1}$] | [km] | [m$^2$·day$^{-1}$] | [m$^2$·day$^{-1}$] | | | [–] | | | [hm$^3$] |
| **WG2** | 1 | 8.00E-04 | 1446 | 7.50 | 18237.81 | 547.50 | | | 0.0300 | | | 1.81 |
| **WG3** | 4 | 1.79E-03 | 2262 | 4.70 | 16031.61 | 481.50 | ± | 2.00E+02 | 0.0300 | ± | 2.14E-05 | 1.26 |
| **WG4** | 2 | 1.73E-04 | 2836 | 4.50 | 1421.50 | 42.75 | ± | 3.45E+01 | 0.0301 | ± | 2.15E-04 | 16.38 |
| **WG5** | 1 | 2.00E-04 | 826 | 0.25 | 5.07 | 0.15 | | | 0.0296 | | | 4.13 |
| **WG6** | 1 | 3.00E-04 | 3436 | 0.50 | 30.40 | 0.90 | | | 0.0296 | | | 11.45 |
| **WG7** | 3 | 1.19E-02 | 1763 | 0.05 | 12.03 | 0.30 | ± | 1.98E-01 | 0.0249 | ± | 2.72E-03 | 0.15 |
| **WG8** | 2 | 1.73E-04 | 1260 | 0.10 | 0.70 | 0.02 | ± | 1.59E-02 | 0.0321 | ± | 4.36E-03 | 7.28 |
| **WG9** | 1 | 1.00E-04 | 2723 | 0.20 | 1.62 | 0.05 | | | 0.0278 | | | 27.23 |
| **WG10** | 1 | 1.00E-04 | 2608 | 0.25 | 2.53 | 0.08 | | | 0.0296 | | | 26.08 |
| **WG11** | 2 | 9.49E-05 | 2530 | 3.30 | 418.71 | 12.75 | ± | 1.06E+00 | 0.0305 | ± | 2.67E-04 | 26.67 |
| **WG12** | 6 | 8.31E-04 | 2174 | 2.60 | 2278.06 | 162.00 | ± | 1.83E+02 | 0.0711 | ± | 1.10E-04 | 2.61 |
| **WG14** | 2 | 4.24E-04 | 963 | 3.50 | 2106.36 | 49.50 | ± | 7.37E+01 | 0.0235 | ± | 1.19E-04 | 2.27 |
| **WG15** | 2 | 2.45E-04 | 1797 | 0.50 | 24.82 | 0.75 | ± | 2.12E-01 | 0.0302 | ± | 0.00E+00 | 7.34 |
| **WG16** | 1 | 2.00E-04 | 466 | 0.25 | 5.07 | 0.15 | | | 0.0296 | | | 2.33 |
| **WG17** | 5 | 4.86E-04 | 4282 | 1.80 | 637.64 | 19.50 | ± | 2.01E+01 | 0.0306 | ± | 3.71E-04 | 8.82 |
| **WG26** | 3 | 1.61E-03 | 7428 | 0.30 | 58.85 | 1.80 | ± | 1.09E+00 | 0.0306 | ± | 2.40E-04 | 4.60 |
| **WG28** | 1 | 1.00E-03 | 1791 | 1.70 | 1171.27 | 35.25 | | | 0.0301 | | | 1.79 |
| **WG29** | 2 | 2.83E-04 | 7711 | 0.30 | 10.32 | 0.30 | ± | 1.59E-01 | 0.0291 | ± | 0.00E+00 | 27.26 |
| **WG34** | 1 | 1.10E-03 | 5433 | 1.00 | 445.81 | 13.50 | | | 0.0303 | | | 4.94 |
| **WG36** | 2 | 1.20E-03 | 1780 | 1.50 | 1094.27 | 33.00 | ± | 3.50E+01 | 0.0302 | ± | 0.00E+00 | 1.81 |
| **WG39** | 4 | 3.60E-04 | 1065 | 2.00 | 583.64 | 17.25 | ± | 1.30E+01 | 0.0296 | ± | 3.26E-04 | 2.96 |
| **WG41** | 1 | 5.38E-04 | 445 | 1.00 | 223.83 | 6.75 | | | 0.0302 | | | 0.83 |
| **WG42** | 1 | 6.00E-04 | 1760 | 1.50 | 533.35 | 16.50 | ± | 1.54E+00 | 0.0309 | ± | 7.48E-04 | 4.69 |
| **WG43** | 2 | 3.74E-04 | 1756 | 2.70 | 1105.48 | 33.00 | ± | 3.13E+01 | 0.0299 | ± | 2.56E-04 | 3.15 |
| **WG45** | 2 | 1.41E-04 | 446 | 0.13 | 0.90 | 0.03 | ± | 1.59E-02 | 0.0335 | ± | 4.19E-03 | 28.65 |
| **WG49** | 2 | 2.00E-04 | 5731 | 0.25 | 5.07 | 0.15 | ± | 1.59E-01 | 0.0296 | ± | 0.00E+00 | 2.44 |
| **WG53** | 3 | 1.27E-03 | 3093 | 2.50 | 3212.55 | 165.00 | ± | 2.71E+02 | 0.0514 | ± | 2.04E-04 | 9.10 |
| **WG54** | 3 | 4.16E-04 | 3786 | 3.20 | 1726.52 | 51.75 | ± | 1.92E+01 | 0.0300 | ± | 1.74E-04 | 15.46 |
| **WG55** | 8 | 4.52E-03 | 954 | 4.20 | 32344.25 | 970.50 | ± | 5.77E+02 | 0.0300 | ± | 1.36E-05 | 0.21 |
| **WG56** | 3 | 1.86E-04 | 2869 | 5.20 | 2,034.67 | 60.75 | ± | 5.30E+01 | 0.0299 | ± | 9.88E-05 | 22.16 |

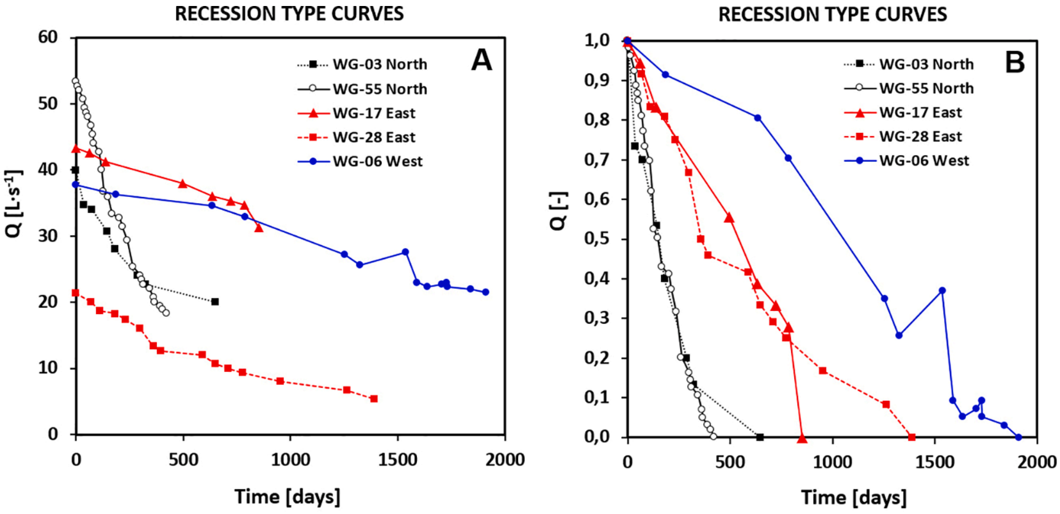

**Fig. 7.** Typology of synthetic water flow recession curves of the galleries of La Palma in absolute flow rates and adimensional flow rates.

considered galleries influenced by the natural seasons of the recharge, type III, that exist throughout the whole volcanic aquifer system. The recession coefficient values show quite defined intervals within their variability, characteristic of systems with a great “memory” with important storage capacity, capable of supplying several cubic hectometers during the periods investigated in this work.

Although the relationship between surface recharge and precipitation is direct, infiltrated water must pass through the unsaturated zone. Volcanic islands tend to present extreme thickness of several hundred meters of partially saturated volcanic materials in areas of relief, and the existence of much less permeable layer intercalations can give rise to perched aquifers (d’Ozouville et al., 2008). A second characteristic of the unsaturated zone in volcanic materials is fracturing. Vertical fractures tend to be preferential flow paths of infiltrated water from the topographic surface, which is progressively embedded into the porous matrix and minor fractures (Faybishenko et al., 2000). On La Palma island, the average thickness of the unsaturated zone ranges from 400 to 1,000 m. Although preferential percolation paths in the unsaturated zone have not been yet investigated in detail in La Palma, groundwater is being extracted from inside the core of the rock massif which forms the aquifer system. This means that galleries penetrating several kilometres (2 to 4 km) into the rock massif, at altitudes between 300 and 1,000 m above mean sea level, show peaks of the registered discharge hydrographs usually associated with large storm events or with damped peaks. This is as a consequence of the storativity of the system often influenced by continuous episodes of climatic droughts. In galleries at altitudes above 1,000 m above mean sea level, the peaks of the hydrographs are strongly related precipitation events of almost any magnitude; thus, depletion curves are only useful (unaffected by precipitation events) for hydraulic parameter estimation during times of severe drought. It should be noted that such fluctuations in discharge rates due to random recharge events during depletion represent a limitation in the applicability of the proposed methodology. Sufficiently long time series of discharge rates are needed to identify relative smooth slopes without influence of transient recharge events.

This proposed methodology is underpinned by all the preliminary hydrogeological studies carried out on La Palma island departing from the analysis of water flow depletion in many working galleries (Fig. 3B and 3C). Previous knowledge of the geology of the subsoil and the selection of the most representative sections allowed us to define the existent typical curves and characteristics of different discharge mechanisms, depending on geological conditions (Caloz, 1987; Sáenz de Oiza, 2011). Interpretation of recession curves has been previously applied to other islands in the Canary archipelago, in specific locations and to individual water galleries. Its application at an insular scale, as the presented methodology, to the main water production infrastructures of La Palma island has provided a novel approach in addressing volcanic formation heterogeneity at a regional scale. This approach represents a possible previous estimation of hydraulic parameters and uncertainty before numerical modelling of volcanic island groundwater. Therefore, it is a useful tool for island water management planning, required for EU Water Framework Directive implementation (Poncela, 2009; Poncela, 2015; Poncela and Skupien, 2011; Skupien and Poncela, 2011).

Using the analysis of recovery tests derived from manometrics on pressures from the hydraulic bulkhead gates of the galleries, it has been shown that in the volcanic aquifer system of La Palma the transmissivity values fit quite well within the range of values given by storage coefficients between 1% and 7% (average variations between 2% and 5%). The results obtained showed transmissivity values of the volcanic aquifer system in the northern area of the island of 15–30 $m^2·day^{-1}$, and between 100–150 $m^2·day^{-1}$ up to 300 $m^2·day^{-1}$ in eastern zones.

Regional transmissivity and storativity predictions using ordinary kriging are shown in Fig. 8A and Fig. 8B, respectively. The resultant maps are of practical importance for groundwater management, especially in the northern part of the island where the aquifer system is most stressed. These maps are of great interest as a preceding step for the development of numerical models. Isolated values of transmissivity or storativity from well tests are almost useless in a highly heterogeneous volcanic environment. A large number of hydraulic parameters estimated form wells is required for application of geostatistical methods in volcanic islands (Rotzoll and El-Kadi, 2008). The experimental variograms used for spatial-variability analysis for transmissivity and storativity maps are shown in Fig. 8C and Fig. 8D, respectively. The parameters for the stable model fit using Eq. (9) are$\theta_s = 10.65$ $m^2$, $\theta_r$=11,853.49 m and$|h| = 1{,}319.01$ m and 2.69 the nugget for the transmissivity. The parameters for the spherical model fit using Eq. (8) were$\theta_s = 1.3·10^{-2}$ $m^2$, $\theta_r$=5,194.49 m, $|h|$= 901.11 m and $2.88·10^{-4}$ the nugget for the storativity. The transmissivity values obtained from locations separated distances closer than 11 were spatially autocorrelated. Storativity showed a range of only 5 km. Therefore, transmissivity values obtained are all spatially autocorrelated at island scale, while the storativity presents weaker spatial correlation over large distances, and only closer points are predicted adequately. Future hydrogeological characterization of the island aquifer system will require denser storativity points to represent heterogeneity of this value if the proposed methodological approach is followed. Lower transmissivities were predicted in the center of the island, clearly coinciding with the caldera of Taburiente volcano, the largest structure on the island and where the

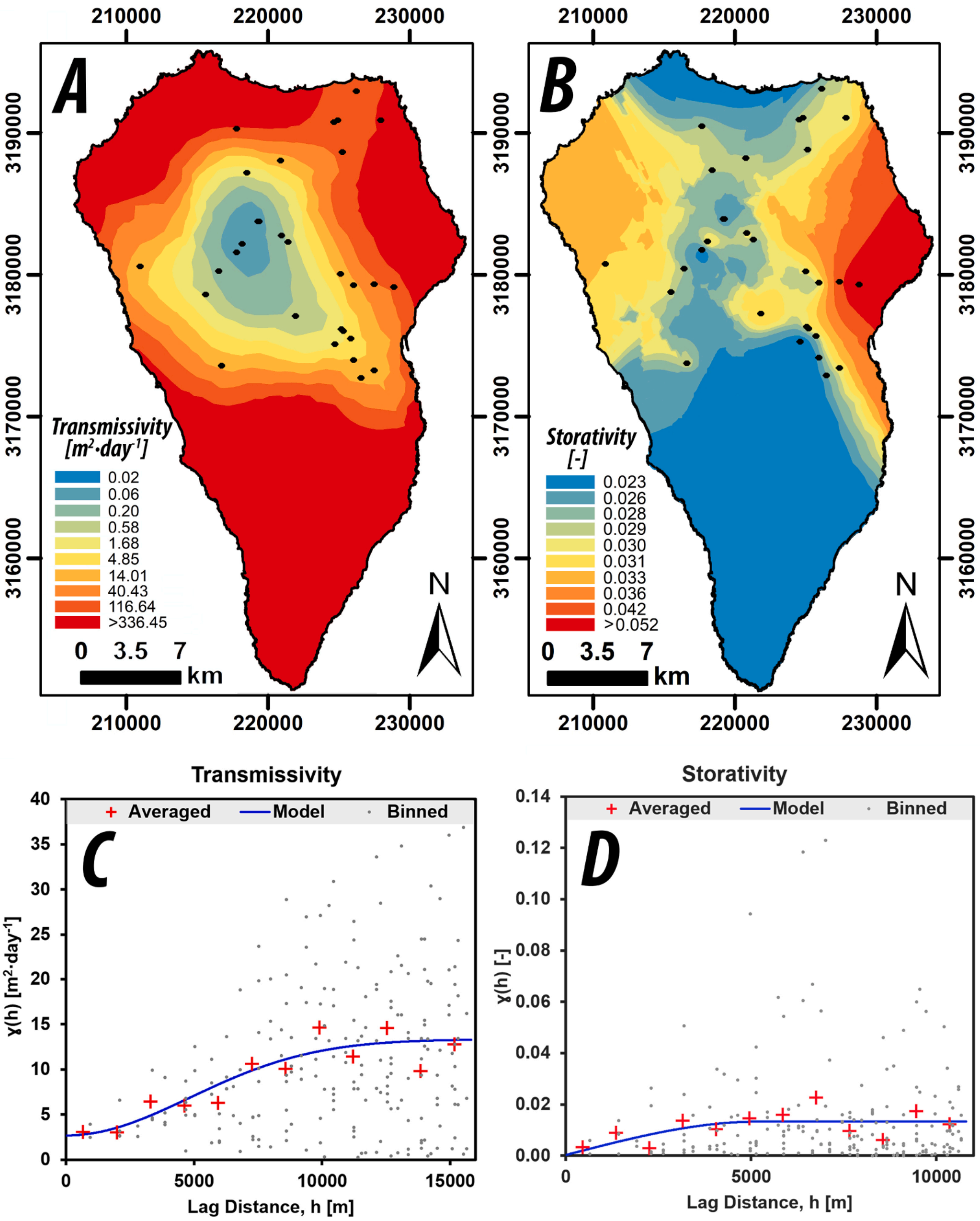

**Fig. 8.** Distribution of the spatial variation of hydraulic transmissivity (A) and storativity (B) on La Palma island. Experimental variograms of the spatial correlation of the transmissivity (C) and storativity (D) for La Palma island and models fitted (stable and spherical semivariogram models, respectively).

largest heights are found. This pattern agrees with transmissivity values obtained from the pumping test in the coastal volcanic aquifers, which presents ranges between 500 and 1,500 $m^2 \cdot day^{-1}$. The obtained Root-Mean-Square (RMS) error of prediction for transmissivity was 234.03 $m^2 \cdot day^{-1}$, and the average standard error was 325.21 $m^2 \cdot day^{-1}$. Storativity RMS error was $9.3 \cdot 10^{-3}$ (<1%), the average standard error was $4.6 \cdot 10^{-3}$.

The standard deviation of the N-estimations of transmissivity and storativity estimations are presented in Table 1. Transmissivity estimations showed an averaged uncertainty of 103.9 $m^2 \cdot day^{-1}$ (64 %) with its minimum of 0.02 $m^2 \cdot day^{-1}$ (8%) and its maximum of 577.36 $m^2 \cdot day^{-1}$ (132%). This averaged standard deviation represents an acceptable value if we consider that the variation in hydraulic conductivity of volcanic formations is almost nine orders of magnitude (Singhal and Gupta, 2010). Storativity estimations showed much smaller averaged values of uncertainty of $3.12 \cdot 10^{-2}$ (3 %) with a minimum of $1.01 \cdot 10^{-8}$ (0 %) and a maximum of $4.36 \cdot 10^{-3}$ (14%). The spatial distribution of uncertainty expressed as standard deviation is shown in Fig. 9. Transmissivity uncertainty is larger in the northeast (Fig. 9A) with maximum in a water gallery high density zone, where galleries are even superposed. This peak of uncertainty can be explained by the absence of repeatability due to hydraulic interference between water galleries. This pattern is only found in transmissivity uncertainties. Storativity uncertainties show a different pattern with higher deviations close to the summits (Fig. 9B). This indicates that estimations of this parameter are conditioned by altitude affected by the recharge effects in high storativity zones and are perhaps even affected by aquifer perched conditions. No interaction between sea water fluctuation and groundwater discharge seems to affect estimations. The flow hydrographs of the 30 investigated galleries are more than 300 masl and more than 2 km from

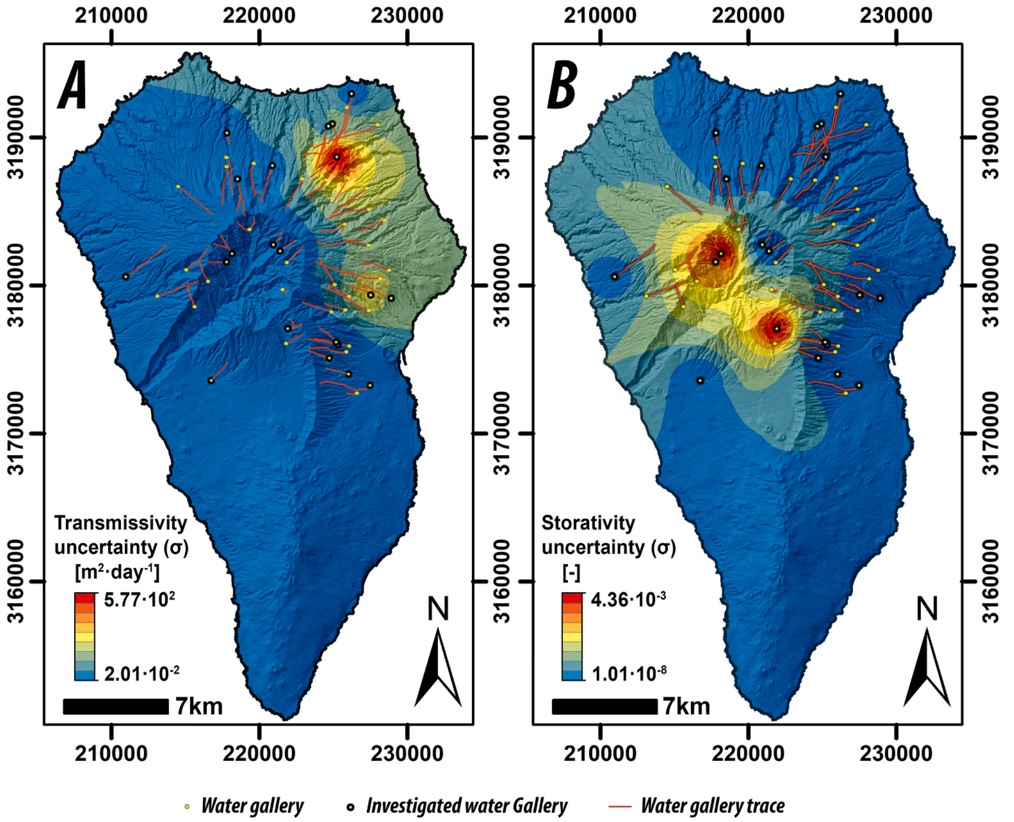

**Fig. 9.** Distribution of the spatial variation of hydraulic transmissivity uncertainty (A) and storativity uncertainty (B) on La Palma island.

the coast. The transmission of tidal fluctuation through coastal aquifers tends to follow a linear increase of time lag and a tidal efficiency decrease exponentially with distance from the sea (Erskine, 1991).

## 5. Conclusion

Interpretation of drainage recession curves of deep water galleries in heterogeneous volcanic systems has been presented as a novel methodology to incorporate volcanic formation heterogeneity in the hydrogeological characterization of insular aquifers. The following conclusions were drawn, based on the results obtained from the application of the proposed methodology to the volcanic island of La Palma (Canary Islands, Spain):

- The values obtained from the alpha coefficient of recession ranged between $1{\cdot}10^{-3}$ and $4{\cdot}10^{-4}$ $\mathrm{day}^{-1}$, showing a spatial distribution clearly influenced by the insular geology. They are indicative of substantial groundwater reservoirs that, in the case of some galleries, are able to supply several (even dozens) of cubic hectometers, depending on the period considered.
- The calculation of hydraulic diffusivity using recession coefficients allowed establishment of aquifer system zones that reasonably match regional hydrogeological information obtained through other methods. On average, these methods have established weighted storage coefficients for volcanic materials of between 3% and 7%, and averaged transmissivities of 5–150 $\mathrm{m}^2{\cdot}\mathrm{day}^{-1}$.
- The uncertainty analysis of hydraulic parameter estimations (transmissivity and storativity) allowed identification of spatial correlation of transmissivity uncertainties, with zones in the island presenting a high density in water galleries. This raises the importance of interference increasing the uncertainty of estimations, using the proposed methodology. Uncertainties related to storativity estimations were spatially correlated with island summits showing higher storativity; they are probably related to recharge events and the possible existence of perched aquifers.
- Two main limitations in the applicability of the proposed methodology were identified. (1) The need for galleries that show smooth drainage recession curves without influence of transient recharge events. Sufficiently long time series of discharge rates are needed to overcome this limitation. (2) The availability of water galleries that are several kilometers deep to apply this proposed approach. However, the fact that water galleries are several kilometers in length makes it possible to estimate effective hydraulic parameters of a heterogeneous aquifer at a larger scale than standard vertical groundwater wells.

Drainage recession curve analysis of deep water galleries in heterogeneous volcanic systems has potential as an alternative technique for the hydrogeological characterization of volcanic aquifer systems. It provides a representative estimation of hydraulic parameters and its uncertainty estimation, information which is of great value prior to numerical modelling of volcanic aquifer systems. Therefore, it represents a useful tool to evaluate renewability of groundwater resources and its governance in volcanic environments.

### *CRediT authorship contribution statement*

**Roberto Poncela:** Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. **Juan C. Santamarta:** Writing – review & editing, Investigation, Funding acquisition. **Alejandro García-Gil:** Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition. **Noelia Cruz-Pérez:** Writing – review & editing. **Elzbieta Skupien:** Writing – review & editing. **Javier García-Barba:** Writing – review & editing.

## 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.

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