Deciphering complex groundwater age distributions and recharge processes in a tropical and fractured volcanic aquifer system

Sánchez-Murillo, R1\*, Irene Montero-Rodríguez1, Corrales-Salazar, L1, Esquivel-Hernández, G1, Castro-Chacón, L2, Rojas-Jiménez, L. D2., Vargas-Víquez J2., Pérez-Quezadas, J3., Gazel, E4., Boll, J5.

1Stable Isotope Research Group and Water Resources Management Laboratory, Universidad Nacional, Heredia, Costa Rica

2Empresa de Servicios Públicos de Heredia, ESPH S.A., Heredia, Costa Rica

3Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad de México, México

4Earth and Atmospheric Science Department, Cornell University, Ithaca, NY, USA

5Civil and Environmental Engineering, Washington State University, Pullman, WA, USA

\*Corresponding Author: [ricardo.sanchez.murillo@una.ac.cr](mailto:ricardo.sanchez.murillo@una.ac.cr)

**Manuscript Components**

**Title:** 16 words

**Abstract:** 221 words

**Main text:** 5,951 words (excluding references)

**Tables:** 2 (tables caption text: 69 words)

**Figures:** 8 in color (figures caption text: 643 words)

**Total references:** 84

**Running title:** *Groundwater age in the humid tropics*

**Abstract**

Groundwater recharge in highly-fractured volcanic aquifers remains poorly understood in the humid tropics, whereby rapid demographic growth and unregulated land use change are resulting in extensive surface water pollution and a large dependency on groundwater extraction. Here we present a multi-tracer approach including δ18O-δ2H, 3H/3He, and noble gases within the most prominent multi-aquifer system of central Costa Rica, with the objective to assess dominant groundwater recharge characteristics and age distributions. We sampled wells and large springs across an elevation gradient from 868 to 2,421 m asl. Our results suggest relatively young apparent ages ranging from 0.0±3.2 up to 76.6±9.9 years. Helium isotopes R/RA (0.99 to 5.4) indicate a dominant signal from the upper mantle across the aquifer. Potential recharge elevations ranged from ~1,400 to 2,650 m asl, with recharge temperatures varying from ~11°C to 19°C with a mean value of 14.5±1.9°C. Recharge estimates ranged from 129±78 to 1,605±196 mm/yr with a mean value of 642±117 mm/yr, representing 20.1±4.0% of the total mean annual rainfall as effective recharge. The shallow unconfined aquifer is characterised by young and rapidly infiltrating waters, whereas the deeper aquifer units have relatively older waters. These results are intended to guide the delineation and mapping of critical recharge areas in mountain headwaters to enhance water security and sustainability in the most important headwater dependent systems of Costa Rica.

**Keywords:** Costa Rica; tropical volcanic aquifer;groundwater apparent age; multi-tracer approach; critical recharge zones.

1. **Introduction**

Costa Rica has a large groundwater storage potential with 76% of the territory likely hosting unconfined aquifers (Astorga and Arias, 2003) resulting in substantial groundwater reservoirs across the country. Approximately 34 km3 infiltrate and recharge shallow (<100 m) and deep reservoirs (100-350 m) from an annual rainfall volume of ~170 km3 (Espinoza et al., 2004). These reservoirs link the headwater areas to the Central Valley of Costa Rica, a large metropolitan area houses ~50% of the country’s population (2.3 million inhabitants) which largely depends on the volcanic Barva-Colima multi-aquifer system (BCS) for its water supply (Espinoza et al., 2004; Sánchez-Murillo et al., 2017; INEC, 2017). Recently, inter-annual rainfall variability is posing new challenges for groundwater resources management (Maldonado et al., 2018; Hidalgo, 2021) in the Central America region. Therefore, a better understanding of rainfall patterns and groundwater age/recharge is crucial for current and future planning under a changing climate.

Groundwater age is defined as the amount of time that has elapsed from when water entered the saturated zone until this water reaches a specific location in the aquifer (i.e., wells, boreholes, springs) where it is sampled for age dating (e.g., Kazemi et al., 2006; Bethke and Johnson, 2008; Zuber and Maloszewski, 2008; Suckow, 2014). Commonly, this parameter is reported as 'apparent age' due to the age differences in the process of convergent mixing of distinct groundwater flows (Torgersen et al., 2013). Younger groundwater reservoirs are more likely affected by the impact of diffuse pollution, changes of land use and contaminant transport, and inter-annual rainfall variability, since flow paths are potentially shorter in comparison with older groundwater (Kazemi et al., 2006; Zuber and Małoszewski, 2008; Newman et al., 2014; Salas-Navarro et al., 2018). Therefore, the inherent complexity of tropical and fractured groundwater systems requires the combination of multiple environmental tracers (e.g., stable and radioactive isotopes, noble and industrial gases or rock weathering solutes) and disciplines to fully understand groundwater age distributions and recharge characteristics.

The Barva aquifer (unconfined unit) has an estimated area of 275 km2, while the Colima aquifer is divided into two semi-confined systems: Lower Colima and Upper Colima, with areas of 230 km2 and 170 km2, respectively (Arias et al., 2006; Madrigal et al., 2017). The BCS is located in the central and northern parts of the Central Valley, adjacent to the Central Volcanic Front and within the slopes of the Barva and Irazú volcanoes (Fig. 1). BCS is influenced by rainfall regimes of both the Caribbean Sea and the Pacific Ocean, with two well-defined seasons (dry season: December to April; wet season: May to November) and a period known as the Mid-Summer Drought, which takes place between July and August and is characterized by a decrease in rainfall (Magaña et al., 1999). A rainfall maximum can also occur in the headwaters of the Barva volcano during the cold front period (December-February). Rainfall varies from 1,300 to 4,500 mm yr-1 depending on elevation, with a potential groundwater recharge between 30% to 55% of the total rainfall volume (Reynolds, 2002; Reynolds-Vargas and Fraile, 2009; Madrigal et al., 2017; Salas-Navarro et al., 2018). The soils in the Central Valley have volcanic origin and are characterized by high infiltration capacity and high permeability (Losilla et al., 2001; Reynolds, 2002), resulting in a large annual replenishment of groundwater storage, but also in a high potential risk for pollutant transport (e.g., nitrates) to deeper aquifers (Madrigal et al., 2017). The latter reinforces the need for a better understanding of the spatio-temporal variability of groundwater recharge processes to properly assess water quality regulations and conservation practices.

The main goal of this study was to determine the groundwater age distribution and to understand the governing recharge processes in the BCS using a multi-tracer approach. Based on the hydrogeological setting, we hypothesized that groundwater recharge is governed by rapid infiltration within the unconfined unit (Barva aquifer) with potential mixing towards the upper semi-confined unit; whereas the lower semi-confined unit is characterized by older waters with minimal mixing. Apparent groundwater ages were estimated using the 3H/3He method, while noble gases measurements were performed to determine recharge temperatures and potential recharge elevations. Water stable isotope ratios were measured to distinguish the prevailing rainfall type in groundwater recharge. Our results highlight aquifer regions that are more vulnerable to anthropogenic impacts as well as critical headwater recharge areas for water protection and conservation in a vertical and horizontally complex multi-aquifer system.

**2. Study area**

**2.1. Climate conditions**

The climate is controlled by the trade winds from the northeast, the seasonal shift of the Intertropical Convergence Zone (ITCZ), cold fronts, and the indirect influence of tropical cyclones (Waylen et al., 1996; Solano et al., 2001; Sánchez-Murillo et al., 2013). In addition, factors such as land relief, oceanic influence (i.e., wind and ocean currents) over the isthmus, and general atmospheric circulations divide the territory into several different climate regions. The Pacific regime is influenced by southwest winds, and rainfall occurs from May to October, having two transition months corresponding to April and November. On the other hand, the Caribbean regime is influenced by trade winds from the northeast, and it does not have a well-defined dry season since the rainfall rate in the least rainy months is between 100 and 200 mm (Sánchez-Murillo et al., 2013).

In general, the high elevation in central Costa Rica are characterized by a cold and rainy climate, characteristic of the mountainous zones; in the middle section, the climate is mild, and in the lowlands, the climate is warm and relatively drier. Mean annual temperature varies from 19°C to 29°C, with a mean of ~23°C; mean annual rainfall ranges from 1,300 mm in the lowlands to 4,300 mm in the headwaters of the Central Valley, and relative humidity is about 82% (Reynolds-Vargas and Fraile, 2009; Salas-Navarro et al., 2018).

**2.2. Hydrogeological conditions**

The Central Valley of Costa Rica consists of Quaternary volcanic rocks which originated mainly from the Barva and to a lesser extent from the Poás and Irazú volcanoes (Darling et al., 1989). This volcanic sequence comprises a series of andesitic lava flows interbedded with pyroclastics in the form of extensive tuffs and ignimbrites, which in turn resulted in large vertical and horizontal hydrogeological complexity. The study area corresponds to the boundaries of the BCS multi-aquifer system, in the northern section of the Virilla River watershed (Fig.1). Geological formations comprise highly fractured and brecciated material from the volcanoes of the Central Volcanic Front, mainly due to the activity of the Barva volcano during the Quaternary period (Reynolds-Vargas and Fraile, 2009). The BCS is divided into two important aquifer systems: Barva and Colima (Fig. 2). The Barva formation is a shallow unconfined aquifer, and the Colima aquifer is subdivided into two semi-confined aquifers: Upper Colima and Lower Colima (Darling et al., 1989; Schosinsky and Vargas, 2001; Arredondo and Soto, 2006; Ruiz et al., 2010). The basement of both aquifers is constituted of low-permeability welded tuffs that allow water accumulation in the upper layers, providing critical water supply to the Greater Metropolitan Area of Costa Rica (Espinoza et al., 2004).

**2.2.1. Barva Formation**

The Barva formation covers an area of 275 km2 with a saturated thickness ranging from 4 to 85 m (Ramírez, 2007; Madrigal-Solís et al., 2017). Transmissivity ranges between 100-500 m2/day (Sánchez-Murillo et al., 2016). The Barva formation has four different members: a) Crater (recent pyroclasts; <15 ka), b) Los Ángeles and Los Bambinos (upper lava flows; 10-30 ka), c) Carbonal (27.4-40 ka) and Porrosatí (coarse volcanic sand and weathered tuffs; <15 ka), and d) Bermúdez (fractured andesitic lavas; 40-270 ka) (Ramírez and Alfaro, 2002; Arredondo and Soto, 2006; Ramírez, 2007). Small perched aquifers occur in areas above 2,000 m asl, also known as Upper Barva, which belong to the Los Bambinos member. These perched aquifers are underlain by a larger unconfined aquifer named Lower Barva, corresponding to the Bermúdez member (Ramírez, 2007; Protti and Sojo, 2015) (Fig. 2).

Historically, recharge of the Barva aquifer has been assumed to occur at high elevations, as moisture recycling and annual rainfall values in the headwaters are typically greater than in the rest of the Valley (Reynolds-Vargas and Fraile, 2009; Castro et al., 2010). However, specific groundwater ages and recharge elevations have not been clearly defined or reported to our knowledge. Simple vertical percolation from upper aquifers, losing rivers, or direct rainfall in areas without overlying aquifers are among the postulated recharge mechanisms (Arias et al., 2006; Ramírez, 2007). According to Reynolds-Vargas and Fraile (2009), it is estimated that most of the recharge occurs from May to December, corresponding to the rainy season of the Pacific rainfall regime. Soils are saturated throughout the year and the estimated recharge is 30% to 55% of the total rainfall volume (Madrigal-Solís et al., 2017 and references therein). Sacramento and Ojo de Agua springs release water from the Barva aquifer, from Los Ángeles and Los Bambinos members and the Bermúdez member, respectively. The volcanic material that constitutes Los Ángeles and Los Bambinos members is characterized by porphyritic andesite blocks (Arredondo and Soto, 2006), and the material from the Bermúdez member includes fractured andesitic lavas (Vargas, 2002; Protti and Sojo, 2015). Therefore, the high permeability of these aquifers is likely to result mainly from the fissures found in such materials (Ramírez and Alfaro, 2002; Ramírez, 2007) (Fig. 2).

**2.2.2. Colima Formation**

The Colima formation (748-330 ka) is separated from the Barva formation by a series of tuffs and ignimbrites known as the Tiribí formation (Ruiz et al., 2010) (Fig. 2). It is considered the main hydrogeological unit of the BCS, due to its high water transfer capacity, from 500 m2/day to more than 5,000 m2/day (Sánchez-Murillo et al., 2016), and its saturated thickness, which is approximately 100 m or greater (i.e., considering both units) (Ramírez, 2007). The high transmissivity values result from intense fracturing, breccias, and vacuoles found in the volcanic material (Vargas, 2002).

This formation is subdivided into three members, including Linda Vista (andesitic composition), Puente Mulas (tuffs and ignimbrites), and Belén (andesitic composition), which are constituted of seven lava flows (Ramírez and Alfaro, 2002). The Puente Mulas member functions as an aquitard that separates the Upper Colima aquifer (Linda Vista member) from the Lower Colima aquifer (Belén member) (Arias et al., 2006). The Colima formation is underlain by the Pacuacua formation (Schosinsky and Vargas, 2001).

The Linda Vista member hosts a smaller perched aquifer called La Libertad, as well as the Upper Colima aquifer, which covers an area of 170 km2 with an average saturated thickness of 45 m (Schosinsky and Vargas, 2001; Arias et al., 2006) (Fig 2). This aquifer is assumed to be recharged via vertical percolation from the Barva and La Libertad aquifers, which in turn receive water from direct rainfall infiltration. The Lower Colima aquifer has an area of 230 km2, with an approximate saturated thickness of 20 m, and is recharged by vertical percolation from the Upper Colima aquifer or by direct rainfall infiltration in areas where it outcrops (Schosinsky and Vargas, 2001; Arias et al., 2006).

Puente Mulas springs discharge water from the Upper and Lower Colima aquifers. With an average flow of 500-700 L/s, both Ojo de Agua and Puente Mulas are classified as high flow springs. In addition, the 15 wells sampled in this study provided mixed water from the Colima formation, where both aquifers (Upper and Lower Colima) are semiconfined. However, the Upper Colima may be an unconfined aquifer depending on the location, and the Lower Colima may be confined or unconfined based on the occurrence of overlying aquifers (Arias et al., 2006).

**3. Materials and methods**

**3.1. Sampling design**

We selected a total of 18 sampling points, including 15 wells and three springs, distributed across an altitudinal range between 868 and 2,421 m asl within the Barva volcano complex. Sampling criteria included the following variables: well depth (shallow and deep), elevation gradient (from recharge to discharge), and type of sampling i.e., the collection of water samples from representative wells (N=15) and large springs (N=3). The aim was to collect groundwater from the Colima (upper and lower) and Barva aquifers along the groundwater flowlines. Figure 1 illustrates the sampling gradient, whereby the highest spring and wells were Sacramento (2,421 m asl), Highland Ranch (1,818 m asl), and Santa Cruz II (1,317 m asl), respectively. There were 13 sampling wells between 1,256 and 994 m asl: Matasanos, Burial, Santiago, Joya III, Miraflores, Claretiano II, San Vicente, Malinches, Esperanza 1A, Trébol, Esperanza II, Aurora II, and Montealegre in descending order of elevation. The lowest elevation sites were Ojo de Agua (891 m asl) and Puente Mulas (868 m asl), which are both large springs and represent the overall BCS discharge in the Virilla river. Figure 1 and Table 1 provide numbering and names of the sampling sites.

**3.2. Noble gas sampling and measurements**

Noble gases (i.e., Xe, Ar, Kr, and Ne) were used to understand groundwater recharge processes, since their concentration in water is governed by Henry’s law and depends on temperature, salinity, and pressure during recharge, allowing the direct determination of the recharge temperature (Kipfer et al., 2002; Aeschbach-Hertig and Solomon, 2013; Brennwald et al*.*, 2013). Groundwater samples often contain an atmospheric noble gas component above the solubility equilibrium (i.e., known as the excess air), which is described as air bubbles trapped in the saturated zone due to a rapidly rising water table (Aeschbach-Hertig and Solomon, 2013). Multiple models have been postulated to resolve inverse solutions and obtain recharge temperatures, of which the closed-system equilibration model (CE) (Aeschbach-Hertig et al., 1999; 2000) is the most realistic because it considers the partial dissolution of excess air and equilibrates the concentration of gases in the water.

Groundwater sampling for noble gas followed the International Atomic Energy Agency standard protocol (IAEA, 2017). This protocol establishes the use of standard Cu-tubes with a sample storage capacity of 20 cm3 for noble gas. All groundwater wells were purged over 20 minutes to guarantee no stagnant water within the well casing, and sampling was conducted once stable values of temperature and electrical conductivity were reached. Cu-tubes were attached to clear vinyl tubing carefully avoiding development of gas bubbles either at the inlet or outlet of the sampling tubes. The tubes were then sealed with two pinch clamps. The large spring systems were sampled using a peristatic pump at a depth >1 m. Samples were sent to the Isotope Hydrology Laboratory of the Department of Nuclear Sciences and Applications of IAEA (Vienna, Austria). Water samples for noble gas measurements were degassed, and then gas fractions were separated by various cryo-trapping steps. This procedure allowed separation of He for isotope measurement on a magnetic sector mass spectrometer (MM5400), and Ne, Ar, Kr, and Xe for concentration determination on quadrupole mass spectrometers. More information on calibration and standardization can be found in Matsumoto et al. (2017).

**3.3. 3H sampling and analysis**

Tritium (3H) is naturally produced in the atmosphere due to cosmic rays, and it enters the hydrologic cycle as tritiated water (HTO) (Eriksson, 1965). The 3H/3He method for identifying groundwater age distributions is based on the radioactive decay of 3H (half-live: 12.32 yr) (see Lucas and Unterweger (2000) for the half-life, and Jenkins and Clarke (1976) & Schlosser et al. (1989) for the original application of T-3He system for groundwater dating) to tritiogenic helium isotope (3He; the 3He concentration resulting from the radioactive decay of 3H). The difficulty involved in this method corresponds to the existence of different sources of helium at the underground level, for example: the potential contributions from helium derived from crust and/or mantle sources (Schlosser et al., 1989; Solomon and Cook, 2000; Barry et al., 2019).

High-density polyethylene (HDPE) 1L bottles were used to collect groundwater at each point for later 3H determination. Analyses were carried out at IsoDetect Umweltmonitoring GmbH (Munich, Germany) using electrolytic enrichment followed by decay liquid scintillation counting (Methods ES-100 and ES-400) ([https://www.isodetect.de](https://www.isodetect.de/)). To assess the current 3H composition of rainfall in Costa Rica, monthly composite samples were collected in HDPE bottles from October 2015 until November 2017 (N=19) using a passive collector. Event-based samples were also collected in HDPE bottles from October 15, 2015 until October 5, 2017 (N=42). Rainfall samples were analyzed at the Isotope Hydrology Laboratory (IAEA). Archive 3H activity in rainfall of Central America and Mexico (N=420), the Caribbean domain (N=1,225), and Colombia (N=309) were retrieved from the Global Network of Isotopes in Precipitation (GNIP, IAEA/WMO 2018) for comparison purposes.

**3.4. Stable isotopes sampling and analysis**

Groundwater samples were collected from wells and large spring systems. Spring samples were collected at the closest point of the main seepage. Samples were collected in 50 mL HDPE-lined caps bottles, filled with no head space, and stored at 5°C until analysis. Stable isotope analyses were conducted at the Stable Isotope Research Group facilities of the National University of Costa Rica using a LWIA-45-EP water isotope analyzer (Los Gatos, USA). Calibrated secondary standards were used to normalize the results as well as to assess quality and drift control procedures. 18O/16O and 2H/1H ratios are presented in the established delta notation δ (‰), with reference to the VSMOW-SLAP scale. The analytical long-term uncertainty was: ± 0.5 (‰) (1σ) for δ2H, ± 0.1 (‰) (1σ) for δ18O. Groundwater isotope composition was compared with isotope ratios in rainfall within the Central Valley of Costa Rica (Heredia station, N=593; 2013-2018) in a dual δ18O-δ2H diagram. A groundwater isoscape (δ18O; 100x100 m grid) developed by Sánchez-Murillo and Birkel (2016) was used to compare groundwater values. Typical endmembers representing Pacific and Caribbean-type rainfall were included in Fig. 3 according to Sánchez-Murillo et al. (2020).

**3.5. Potential recharge temperature and elevation**

Different models are available to determine excess air in groundwater samples, for instance the closed-system equilibration (CE) model (Aeschbach-Hertig et al., 2000), the complete dissolution model (Heaton and Vogel, 1981) (both models consider the existence of excess air), and the partial re-equilibration model (Stute et al., 1995; Aeschbach-Hertig et al., 2008). In this study, the CE model was used as it considers the partial dissolution of excess gases and their new equilibration in water, where the heavier gases are mostly dissolved. Therefore, the concentration of the lighter gases in the air bubbles increases (Aeschbach-Hertig et al., 2000; 2008; 2013). Noble gas recharge temperatures (NGT) were estimated with the IAEA iNoble 1.0 program, using temperature (T), pressure (P), and the ratio between initial and final volume of air bubbles (F) as factors to find the most suitable results in relation to the chi square (χ2) values. A total number of 1,000 iterations using the Monte Carlo method were conducted to access NGT, excess air, and ages. As a first input to the program, an elevation and temperature of 2,100 m asl and 16°C were entered as default parameters. Potential recharge temperatures and elevations are closely related as both affect the concentration of the noble gas in water. Once the potential recharge temperatures were obtained, the local environmental lapse rate was used to examine the range of potential recharge elevations in the BCS.

**3.6. Apparent groundwater age and recharge**

Apparent groundwater ages in the BCS were determined by using the 3H/3He method, which considers the 3H activity in the sample and that of its daughter isotope, 3He, produced by the β- decay of 3H. The difficulty of this method lies in the determination of 3Hetrit, for which measurements of other noble gases in the sample are required. 3Hetrit was determined as follows:

where R refers to the 3He/4He ratio measured in the sample; Ra corresponds to the 3He/4He ratio in the atmosphere (1.384x10-6) (Clarke et al., 1976; Stute et al., 1992), 4Hetot and 4He*eq* denote total and equilibrium compositions, and α is the solubility isotope effect (0.983) (Stute et al., 1992; Benson and Krause, 1980), and S means salinity during infiltration; S equals zero because it is assumed that infiltrated water comes from meteoric water or shallow water (Aeschbach-Hertig et al., 1999). The factor 4.021x1014 converts cubic centimeters of gas at standard temperature and pressure per gram of water (cm3 STP/g) to tritium units (TU) (Szabo et al., 1996). The influence of mantle and crust helium on groundwater was analyzed by computing R/Ra (R = 3He/4He ratio measured in the samples, and Ra = 3He/4He ratio present in the atmosphere, 1.384x10-6) and Ne/He ratios. A characteristic value of 2x10-8 was used for 3He/4He radiogenic helium component. Once 3Hetrit concentration was established, the apparent age of each site was determined using Equation 2:

where T1/2 is the half-life of 3H (12.32 yr) (Lucas et al., 2000 and references therein); [3Hetrit] is the helium activity resulting from the decay of 3H, and [3H] is the tritium activity in the sample. The sum of [3H] and [3Hetrit] generally corresponds to the initial tritium value at the time of recharge.

Once apparent ages were estimated, Eq. 3 was applied to determine annual recharge rates (mm/yr). This is useful when apparent ages reflect mixing within multi-aquifer systems (Böhlke, 2002; Healy, 2010):

where *R* is recharge (mm/yr), *ϕ* is the effective porosity (-), *Z* is the saturated aquifer thickness (m) and *τ* is the apparent groundwater age. Based on available literature (Echandi, 1981; Foster et al., 1985; BGS and Senara, 1985; Denyer et al., 1994; Arredondo and Soto, 2006), *ϕ* andZ in the BCS ranged from 0.10-0.25 and 10-158 m, respectively. Minimum, maximum, and mean annual values are reported in mm/yr.

**3.7. Land use**

Based on the suggested boundary of the Barva aquifer (Madrigal-Solís et al., 2017), a land use analysis was carried out to understand the current status of anthropogenic activities that may affect future water quality parameters within the most prominent recharge areas determined by the noble gas tracers. Satellite images were downloaded from the online servers Land Viewer (www.lv.eosda.com) and the United States Geological Survey (USGS) server (https://earthexplorer.usgs.gov/). Images with cloud coverage less than 30% and that did not have radiometric or radiance alterations in their pixels were selected for pre- and post-processing. After downloading the images, atmospheric corrections were conducted to the bands of interest. This correction was carried out in the free software QGIS (2009), under the Semi-Automatic Classification (SCP) tool. This land use classification procedure is based on creating training areas that are directly correlated with the different classes that have already been previously chosen, that is, each pixel was assigned a specific class after having carried out an analysis or visual study of the image to help discriminate and recognize the colors of the assigned class. The classification was conducted under the Maximum Likelihood algorithm, which is the one that best resembles the real distribution of the digital numbers in each category. The final raster was converted to a vector, where a polygonal generalization and simplification was applied. This process consists of obtaining a product in vector format that allows to minimize the impulse noise, which consists of reducing or eliminating some pixels that are incorrect. In addition, we calculated areas (in %) of each of the classifications.

**4. Results**

**4.1. Tritium activity and water isotope ratios in rainfall and groundwater**

A rainfall 3H input curve (1960-2017) retrieved from GNIP (IAEA/WMO, 2018) and reconstructed for the Mesoamerican domain (including Caribbean islands, México, Central America, and Colombia based on the assumption that this region shares rainfall generation and moisture transport conditions; Houze et al., 2015) is shown in Figure 3A. During the bomb 3H peak (Schlosser et al., 1988), rainfall 3H reached up to 800 TU in the region, whereas values below 3.5 TU have been reported in the last decade. In Costa Rica, monthly and event-based rainfall monitoring (2015-2017) revealed a mean 3H composition of 1.14±0.19 TU. Tritium composition ranged from 0.0 to 1.0 TU in wells and springs (Table 1). with greater values within the unconfined aquifer unit (Barva aquifer). Values below 0.5 TU were reported mainly in the semi-confined aquifer units (Colima formation) (Fig. 2).

A dual isotope diagram of daily rainfall (2013-2017) and groundwater within the BCS is presented in Figure 3B. Rainfall exhibited a large range from +2.5 to -20 ‰ in δ18O. Caribbean and Pacific-type rainfall exhibited mean δ18O values of -5.26‰ and -7.57‰, respectively. Wells and springs showed a damped variability ranging from -6 to -10‰ in δ18O (mean -7.6‰; Fig. 3C). All groundwaters had a strong meteoric origin affected by the isotope spatial variability of recharge across the BCS, with no significant effects of surface kinetic fractionation. Overall, samples from the unconfined aquifer units were more depleted than the semi-confined aquifer units.

**4.2. Mantle-type helium and excess air within the BCS**

Commonly, R/RA ≈ 1 means that groundwater is in equilibrium with the atmosphere (i.e., relatively recent recharge), whereas R/RA > 1 refers to elevated 3He coming from the relatively degassing of upper mantle sources (up to R/RA~8) , and R/RA < 1 is attributed to helium accumulation from the crust (R/RA~0.05) (Solomon and Cook, 2000; Hershey et al., 2007; Di Piazza et al., 2015; Rizzo et al., 2016; Lee et al., 2017; Ezaki et al., 2019; Hiett et al., 2021). Figure 4 shows the R/RA and Ne/He trend within the BCS. Several wells and springs were grouped near the R/RA of 1 in agreement with atmospheric and solubility (15-30°C) helium isotope ratios. However, within the study sites a clear trend towards larger R/RA values (up to 6) was also detected (Fig. 4). In addition, three wells exhibited high excess air (sites 9, 15, and 11) and one well recorded moderate excess air content (16) (Table 2). The remaining wells and springs were below 2.32 cm3 STP/kg of excess air (Table 2). To our knowledge excess air estimations have not been reported within the volcanic aquifers of Central America, thus a regional comparison is not feasible in this case. However, seasonal water table levels may increase between 5-10 m as a result of the two rainfall maxima (May-June and September-October) (Hund et al., 2018), particularly within the unconfined unit. Seasonal water level dynamics in humid and fractured volcanic aquifers may result in anomalous excess air concentrations. In contrast, small excess air amounts are representative of high storage capacity within the multi-aquifer system (Darling et al., 2017).

**4.3. Apparent groundwater age**

Figure 5A shows estimated 3H/3He apparent ages for each groundwater sample and their reconstructed original tritium activity along with a regional rainfall tritium input (Fig. 5A). The initial tritium values in groundwater correspond to the sum of 3H and 3HeTrit and equal the tritium activity at the time of recharge; this application is useful for groundwater age determination up to 60-70 years (Matsumoto et al., 2017). Samples below the regional rainfall input may represent significant fractions of old (pre-bomb) water mixed with recent recharge across the aquifer (Matsumoto et al., 2017). In contrast, samples with an initial tritium value above the rainfall record indicate the presence of additional non-tritiogenic 3He (i.e., upper mantle source).

In the study area, apparent groundwater ages ranged from 0.0±3.2 up to 76.6±9.9 years. Few samples resulted in relatively older ages, suggesting a significant contribution of 3He from the mantle (Fig. 4). For sample 7 (well depth >300 m; TU=0.0), the model did not converge with an estimated water age. In general, most of the sites plotted along the regional rainfall 3H curve, indicating that our 3H/3He apparent age calculations are consistent with 3H rainfall during recharge.

Figure 5B shows the relationship between tritium, δ18O, and groundwater depth in wells and large springs. Two main groups can be identified: a) wells and springs with relatively high tritium (i.e., near modern rainfall values) and depleted δ18O (water level depth < 200 m) and b) only wells with low or no tritium and enriched δ18O (water level depth > 200 m). The inset in Fig. 5C presents the supporting regional groundwater δ18O isoscape (100x100 m resolution, Sánchez-Murillo and Birkel, 2016), showing the same spatial isotope variability as that found in our discrete samples.

**5. Discussion**

The pioneer hydrogeological work of Darling et al. (1989) in this region identified an anomalous δ18O enrichment trend with depth attributed to recharge at lower elevations mainly via losing streams. Their rationale, however, only considered the effects of a classical altitudinal distillation and secondary surface water evaporation as potential drivers of the isotopic variability. Our results show that the combination of high relief topography and rainfall type dynamics is translated in distinct isotopic spatial patterns within the BCS. Furthermore, Sánchez-Murillo and Birkel et al. (2016) reported significant differences in the isotopic composition of rainfall, groundwater, and surface water within the mountainous regions of Costa Rica, related to the type of precipitation (i.e., convective versus stratiform) and strong orographic effects across the Caribbean (δ18O~5.3±4.0‰) and Pacific (δ18O~7.6±3.9‰) slopes (Fig. 3B). Basically, air masses travelling mainly from the Caribbean Sea experienced a strong orographic effect, resulting in a notable depletion in rainfall isotope ratios across the Volcanic Front, which in turn led to isotopically depleted signatures in groundwater and surface water within this high-altitude area and shallow aquifers. Additionally, orographic depressions (Fig. 1) allow recharge of Caribbean-type parental moisture, and thus, a clear enrichment trend can also be identified within the deeper semi-confined units of the aquifer system (Fig. 3B). Similarly, to the isotope separation, the unconfined unit (Barva formation) exhibited greater TU values than both deeper semi-confined aquifer units (Colima formation).

The hydrogeological separation revealed by stable isotopes ratios and tritium content was also confirmed by helium isotope ratios. Mantle-derived contributions of helium have been widely reported across Costa Rica (Gazel et al. 2009, 2011; Lee et al., 2017; Melián et al., 2019; Barry et al., 2019) (1-5 R/RA in water; up to 7 R/RA in gases), mainly within hydrothermal and fumarole manifestations. The observed increasing R/RA trend was consistent in wells with a depth greater than 200 m. Helium R/RA ratios from the Tubarão aquifer system in the state of São Paulo (Ezaki et al., 2019) (shown in Fig. 4 as a reference), affected by a significant continental crust 4He signal, clearly indicated that the BCS is mostly governed by a strong 3He upper mantle signal (i.e., degassing magma) (Fig. 4) as the well depth increases.

Based on the apparent age and water depth relationship (Fig. 6), the BCS can be divided in two systems: a) young groundwater ages (<20 years) with no significant trend with water depth, suggesting vertical and relatively rapid percolation as well as a potential large degree of mixing with young waters from the Barva aquifer into the upper Colima formation (Fig. 2) (i.e., pumping may capture different flow lines), and b) a clear trend of increasing apparent age (>20 years) with water depth (Colima aquifers; Fig. 2). The spatial water age distribution (Fig. 5) confirms the large degree of vertical and horizontal complexity within the BCS; but it provides relevant information to assess groundwater vulnerability to contaminant transport (i.e., nitrates, emergent pollutants) in the unconfined unit as well as groundwater availability in the semi-confined units.

The identification of critical recharge areas is a key indicator for groundwater management in highly vulnerable tropical and fractured aquifers. The spatial distribution of recharge temperatures can also help to delineate the most prominent recharge elevations. Figure 7 depicts the relationship between the derived NGT and the local environmental lapse rate. Potential recharge elevations ranged from 1,400 to 2,650 m asl, with recharge temperatures varying from 11-19°C with a mean value of 14.5±1.9°C. For samples 11 and 14, the model did not converge with a reasonable NGT.

Based on the current land use (Fig. 8), these elevations correspond mainly to forest (private and governmental protected areas), pasture (with cattle farming), crops (mainly coffee plantations), and expanding urban areas. Recently, more attention has been paid to a historical increasing trend in nitrates from the headwaters to low land urban areas (Reynolds et al., 2006; Madrigal-Solís et al., 2017) mainly across the unconfined unit of the Barva formation. Therefore, based on the relatively young water ages in this unconfined aquifer and potential rapid percolation, there is a large degree of groundwater vulnerability.

Previous recharge estimations, based on soil water balances and sparse meteorological records, have estimated the recharge values between 30% to 55% of the total rainfall volume (3,300-3,500 mm/yr) (Reynolds and Fraile, 2009; Salas-Navarro et al., 2018). Overall, our groundwater recharge estimates range from 129±78 up to 1,605±196 mm/yr with a mean value of 642±117 mm/yr, i.e., 20.1±4.0% of the total mean annual rainfall as effective recharge within the BCS. The delineation of the most prominent recharge elevations and magnitude along with the clear tracer separation within the BAS has significant implications for current and future water resources management plans in this tropical volcanic multi-aquifer system.

The modern climate variability in Central America (Hidalgo, 2021) invokes a better understanding of the effects of climate change such as ‘shocks’ (interannual−scale) and trends (decadal−scale) on groundwater reservoirs (Foster and MacDonald, 2014). This understanding can translate to enhanced management of headwater areas, where recharge occurs (Immerzeel et al., 2020), and headwater dependent areas, where groundwater use occurs (de Graaf et al., 2019), to achieve climate change resilience and characterization of water resource vulnerability (Viviroli et al., 2020).

For development of these enhanced water management scenarios, consistent and long−term tracer measurements in precipitation and groundwater become useful tools to assess the influence of Caribbean (rainfall surplus) versus Pacific (rainfall deficit) groundwater recharge during ENSO periods, which may allow a better orientation of economic and human resources destined to improve a) future groundwater explorations, b) drinking water storage and distribution, c) well production management, and d) land use and urban planning across critical recharge areas (Sánchez-Murillo et al., 2016).

**6. Conclusions**

Costa Rica has a large groundwater storage capacity but detailed tracer studies in large multi-aquifer systems are still scarce. Our study provides a new framework for groundwater resource management in the Barva-Colima system, which hosts over two million inhabitants that largely depend on water supply from this aquifer. Our results indicate a) the existence of younger groundwater (~0.0-20 yr) influenced by modern recharge and land use, and therefore highly susceptible to contaminant transport (i.e., dairy farming, coffee and vegetable plantations, and residential untreated wastewater) within the north and southwest region, and b) older and deeper groundwater (~40-70 yr), with a presumably slower recharge rate, within the east and southeast portion of the aquifer. Apparent age separation was further confirmed by the spatial trends in δ18O and tritium activity. Apparent age and water depth trends indicated rapid percolation within the Barva aquifer versus slow recharge within the Colima aquifer.

Noble gas measurements allowed the determination of potential recharge elevations (~1,400 to 2,650 m asl) within the BCS. The latter should serve to guide the delineation and mapping of critical recharge areas to enhance water security and sustainability in Costa Rica. Similarly, our recharge estimates (mean=642±117 mm/yr, representing 20.1±4.0% of the total mean annual rainfall) emphasize the high storage capacity of tropical, fractured volcanic aquifers of Costa Rica.

**7. Acknowledgements**

This study was supported by International Atomic Energy Agency grants COS7005, RC-19747, and RLA7024. A Joint Research Agreement (SIA-0378-14) by the National University (Heredia, Costa Rica) and Empresa de Servicios Públicos de Heredia (ESPH, S.A.) was also fundamental. Funding from the Research Office of the National University (Heredia, Costa Rica) through grants SIA-0482-13, SIA-0101-14, SIA-0236-16, SIA-411-17, and SIA-414-17 was crucial for conducting rainfall sampling campaigns. Support from the Isotope Network for Tropical Ecosystem Studies (ISONet) funded by the University of Costa Rica Research Council is recognized. The authors thank to Daniel Martínez and Christian Birkel for early revisions of this manuscript. Analytical support from IAEA to conduct tritium and noble gas analyses is also acknowledged.

**8. Data availability statement**

The data that support the findings of this study are openly available in CUASI Hydroshare at <https://doi.org/10.4211/hs.1beaf29b297b42d394ce4f36f0ab19c3> (Sánchez-Murillo, 2021).

**9. References**

1. Aeschbach-Hertig, W., El-Gamal, H., Wieser, M., Palcsu, L. 2008. Modeling excess air and degassing in groundwater by equilibrium partitioning with a gas phase. *Water Resour Res.*44:1–12. <https://doi.org/10.1029/2007WR006454>
2. Aeschbach-Hertig, W., Peeters, F., Beyerle, U., Kipfer, R. 1999. Interpretation of dissolved atmospheric noble gases in natural groundwater. *Water Resour Res.* 35 (9):2779-2792. <https://doi.org/10.1029/1999WR900130>
3. Aeschbach-Hertig, W., Peeters, F., Beyerle, U., Kipfer, R. 2000. Paleotemperature reconstruction from noble gases in ground water taking into account equilibration with entrapped air. *Nature.* 405:1040–1044. <https://dx.doi.org/10.1038/35016542>
4. Aeschbach-Hertig, W., Solomon, D.K. 2013. Noble Gas Thermometry in Groundwater Hydrology In: *The Noble Gases as Geochemical Tracers*. Springer: Berlin Heidelberg. pp 81–122. https://link.springer.com/chapter/10.1007/978-3-642-28836-4\_5
5. Arias, M., Losilla, M., Arredondo, S. 2006. State of knowledge of groundwater in Costa Rica. *Geological and Mining Bulletin* (in Spanish). 117(1):63–73. <http://www.igme.es/boletin/2006/117_1_2006/Art.5.PDF>
6. Arredondo, Li. S., Soto, G. 2006. Age of the lavas of Los Bambinos member and chronostratigraphic summary of the Barva formation, Costa Rica. *Revista Geológica de América Central*. 34/35:59–71. (in Spanish). DOI: 10.15517/RGAC.V0I34-35.4226
7. Astorga, A. and Arias, M. 2003. Mapa de geoaptitud hidrogeológica de Costa Rica: Implicaciones respecto a la gestión ambiental del desarrollo. Revista Geológica de América Central. <https://revistas.ucr.ac.cr/index.php/geologica/article/download/7778/7433>.
8. Barry, P. H., et al. 2019. Forearc carbon sink reduces long-term volatile recycling into the mantle. Nature, 568 (7753): 487-492, doi:10.1038/s41586-019-1131-5.
9. Benson, B.B., Krause, D. 1980. Isotopic fractionation of helium during solution: A probe for the liquid state. *Journal of Solution Chemistry.* 9 (12):895–909. <https://doi.org/10.1007/BF00646402>
10. Bethke, C.M., Johnson, T.M. 2008. Groundwater Age and Groundwater Age Dating. *Annu Rev Earth Planet Sci.* 36:121–52. https://www.annualreviews.org/doi/full/10.1146/annurev.earth.36.031207.124210
11. Böhlke, J.K. 2002. Groundwater recharge and agricultural contamination. Hydrogeology Journal, 10(1): 153-179. <https://doi.org/10.1007/s10040-001-0183-3>
12. British Geological Service (BGS) & Servicio Nacional de Aguas Subterráneas. Riego y Avenamiento (SENARA), 1985. Hydrogeological map of the Central Valley of Costa Rica. 1:50.000, E.S.R. Limited, England.
13. Brennwald, M.S., Vogel, N., Scheidegger, Y., Tomonaga, Y., Livingstone, D., Kipfer, R. 2013. Noble gas as environmental tracers in sediment porewaters and stalagmite fluid inclusions. In: *The Noble Gases as Geochemical Tracers.* Springer: Berlin Heielberg. pp 123–53. https://doi.org/10.1007/978-3-642-28836-4\_6
14. Castro, G., Chavarría, F., de la Cruz, J., Gelabert, C., Martínez, D., Paniagua, W., et al. 2011. Anthropic impact in the Barva Aquifer Mantle (Heredia, Costa Rica) with emphasis on land use (1992-2006). *Research Journal of the Costa Rican Distance Education University.* (in Spanish) 3: 71–80. https://investiga.uned.ac.cr/revistas/index.php/cuadernos/article/view/208
15. Clarke, W.B., Jenkins, W.J., Top, Z. 1976. Determination of tritium by mass spectrometric measurement of 3He. *International Journal of Applied Radiation and Isotopes.* 27:515–22. <https://doi.org/10.1016/0020-708X(76)90082-X>
16. Espinoza, A., Morera, A., Mora, D., Torres, R. 2004. Drinking water quality in Costa Rica: Current situation and prospects (San José, Costa Rica). Ministerio de Salud - Instituto Costarricense de Acueductos y Alcantarillados – Organización Panamericana de la Salud Organización Mundial de la Salud. (in Spanish). <https://www.paho.org/cor/index.php?option=com_content&view=article&id=143:publicaciones&Itemid=221>
17. Ezaki, S., Iritani, M.A., Gastmans, D., Stradioto, M.R. and Kiang, C.H. 2019. Isotópos de 14C e 4He na datação das águas subterrâneas do aquífero Tubarão, porção leste da bacia do paraná no estado de São Paulo. Águas Subterrâneas. https://aguassubterraneas.abas.org/asubterraneas/article/view/29429
18. Darling, W.G., Parker, J.M., Rodríguez, H.V. and Lardner, A.J. 1989. Investigation of a volcanic aquifer system in Costa Rica using environmental isotopes (No. IAEA-TECDOC-502). https://inis.iaea.org/search/search.aspx?orig\_q=RN:21031096
19. Darling, W.G., Gooddy, D.C., White, D., Matsumoto, T., Han, L.F. and Romeo, N. 2017. Testing tritium-helium groundwater dating in the Chalk aquifer of the Berkshire Downs, UK. Geochemical Journal, 51(5): 409-421. <https://doi.org/10.2343/geochemj.2.0457>
20. de Graaf, I. E., Gleeson, T., van Beek, L. R., Sutanudjaja, E. H., & Bierkens, M. F. 2019. Environmental flow limits to global groundwater pumping. Nature, 574(7776): 90-94. <https://doi.org/10.1038/s41586-019-1594-4>
21. Denyer, P., Kussmaul, S. & Arias, O. 1994: Estratigrafía de las rocas ígneas - en Denyer, P. & Kussmaul, S. (compiladores), 1994: Atlas Geológico de la Gran Área Metropolitana, Costa Rica - Edit. Tecnológica de Costa Rica: 61-70pp.
22. Di Piazza, A., Rizzo, A.L., Barberi, F., Carapezza, M.L., De Astis, G., Romano, C. and Sortino, F., 2015. Geochemistry of the mantle source and magma feeding system beneath Turrialba volcano, Costa Rica. *Lithos*, *232*, pp. 319-335. <https://doi.org/10.1016/j.lithos.2015.07.012>
23. Echandi, E., 1981. Unidades Volcánicas de la Vertiente Norte de la Cuenca del Río Virilla. ‐ Tesis de Licenciatura, ECG‐UCR, 123 pp
24. Eriksson, E. 1965. An account of the major pulses of tritium and their effects in the atmosphere. *Tellus*, 17: 118-130. <https://doi.org/10.1111/j.2153-3490.1965.tb00201.x>
25. Foster, S., Ellis, A., Losilla-Penon, M., Rodríguez-Estrada, H., 1985: Role of Volcanic Tuffs in Ground-Water Regime of Valle Central, Costa Rica. GROUND WATER, Vol. 23, No. 6.
26. Foster, S. and MacDonald, A. 2014. The ‘water security’dialogue: why it needs to be better informed about groundwater. Hydrogeology Journal, 22(7): 1489-1492. <https://doi.org/10.1007/s10040-014-1157-6>
27. Gazel, E., K. Hoernle, M. J. Carr, C. Herzberg, I. Saginor, P. v. den Bogaard, F. Hauff, M. Feigenson, and C. Swisher III. 2011. Plume–subduction interaction in southern Central America: Mantle upwelling and slab melting. Lithos, 121(1): 117-134. <https://doi.org/10.1016/j.lithos.2010.10.008>
28. Gazel, E., M. J. Carr, K. Hoernle, M. D. Feigenson, D. Szymanski, F. Hauff, and P. van den Bogaard. 2009. Galapagos-OIB signature in southern Central America: Mantle refertilization by arc-hot spot interaction, Geochemistry Geophysics Geosystems, 10, doi:10.1029/2008GC002246.
29. Healy, R.W. 2010. Estimating groundwater recharge. Cambridge University Press. pp: 136-165
30. Heaton, T., Vogel, J. 1981. ¨Excess air¨ in groundwater. *Journal of Hydrology*. 50:201–16. <https://doi.org/10.1016/0022-1694(81)90070-6>
31. Hershey, R.L., Heilweil, V.M., Gardner, P., Lyles, B., Earman, S., Thomas, J.M., et al. 2007. Ground-water chemistry interpretations supporting the basin and range regional carbonate-rock aquifer system. *Desert Research Institute*. (41230):12–22.
32. Hiett, C.D., Newell, D.L. and Jessup, M.J. 2021. 3He evidence for fluid transfer and continental hydration above a flat slab. Earth and Planetary Science Letters, 556: 116722. <https://doi.org/10.1016/j.epsl.2020.116722>
33. Hidalgo, H.G. 2021. Climate Variability and Change in Central America: What Does It Mean for Water Managers. Front. Water 2: 632739. doi: 10.3389/frwa.
34. Hund, S.V., Allen, D.M., Morillas, L. and Johnson, M.S. 2018. Groundwater recharge indicator as tool for decision makers to increase socio-hydrological resilience to seasonal drought. Journal of hydrology, 563: 1119-1134. <https://doi.org/10.1016/j.jhydrol.2018.05.069>
35. IAEA/WMO: Global Network of Isotopes in Precipitation – the GNIP Database. Accessible at: <https://nucleus.iaea.org/wiser>. Last accessed: 2018-11-20.
36. Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., Elmore, A.C. and Emmer, A., 2020. Importance and vulnerability of the world’s water towers. Nature, 577(7790): 364-369. <https://doi.org/10.1038/s41586-019-1822-y>
37. Isotope hydrology section I. Groundwater sampling procedures for isotopes hydrology [Internet]. IAEA. [cited 2017 Dec 7]. p. 1–8. Available from: www-naweb.iaea.org/napc/ih/IHS\_publication.html
38. INEC. Population projections by province, canton and district 2011-2016, San José, Costa Rica [Internet]. Available from: [www.inec.go.cr/poblacion](http://www.inec.go.cr/poblacion)
39. Isodetect Umweltmntoring GmbH [Internet]. [cited 2017 Nov 12]. Available from: www.isodetect.de/ablaeufe/analytik/
40. Kazemi, G., Lehr, J., Perrochet, P. 2006. *Groundwater Age.* First edit. Vol. 15. Hoboken, New Jersey: WILEY-INTERSCIENCE. https://onlinelibrary.wiley.com/doi/book/10.1002/0471929514
41. Kipfer, R., Aeschbach-Hertig, W., Peeters, F., Stute, M. 2002. Noble Gases in Lakes and Ground Waters. *Reviews in Mineralogy and Geochemistry.* 47:615–700. <https://dx.doi.org/10.2138/rmg.2002.47.14>
42. Kulongoski, J.T., Hilton, D.R., Izbicki, J.A. 2005. Source and movement of helium in the eastern Morongo groundwater Basin: The influence of regional tectonics on crustal and mantle helium fluxes. *Geochimica et Cosmochimica Acta*. 69(15):3857–72. <https://doi.org/10.1016/j.gca.2005.03.001>
43. Lee, H., Fischer, T.P., de Moor, J.M., Sharp, Z.D., Takahata, N. and Sano, Y. 2017. Nitrogen recycling at the Costa Rican subduction zone: The role of incoming plate structure. *Scientific Reports*, *7*(1), p.13933. <https://doi.org/10.1038/s41598-017-14287-y>
44. Losilla, M., Rodríguez, H., Schosinsky, G., Stimson, J., Bethune, D. 2001. Volcanic aquifers and sustainable development in Central America. First edition, San José, Costa Rica: Editorial de la Universidad de Costa Rica. (in Spanish). ISBN 10: [9977676429](https://www.iberlibro.com/products/isbn/9789977676425?cm_sp=bdp-_-ISBN10-_-PLP)
45. Lucas, L.L. and Unterweger, M.P. 2000. Comprehensive review and critical evaluation of the half-life of Tritium. Journal of research of the National Institute of Standards and Technology, 105(4): 541. doi: [10.6028/jres.105.043](https://dx.doi.org/10.6028%2Fjres.105.043)
46. Madrigal-Solís, H., Fonseca-Sánchez, A., and Reynolds-Vargas, J. 2017. Hydrogeochemical characterization of Barva and Colima aquifers in the Central Valley of Costa Rica. Water Technology and Sciences (in Spanish), 8(1), 115-132. http://www.redacademica.una.ac.cr/display/articulo001126
47. Magaña, V., Amador, J.A., and Medina, S. 1999. The midsummer drought over Mexico and Central America, J. Climate, 12 (1967): 1577-1588. [https://doi.org/10.1175/1520-0442(1999)012<1577:TMDOMA>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012%3c1577:TMDOMA%3e2.0.CO;2)
48. Maldonado, T., Alfaro, E.J. and Hidalgo, H.G., 2018. A review of the main drivers and variability of Central America’s Climate and seasonal forecast systems. Revista de Biología Tropical, 66(1-1), pp.S153-S175. DOI [10.15517/rbt.v66i1.33294](https://doi.org/10.15517/rbt.v66i1.33294)
49. Matsumoto, T., Solomon, D.K., Araguás-Araguás, L. and Aggarwal, P., 2017. The IAEA’s coordinated research project on “Estimation of Groundwater Recharge and Discharge by Using the Tritium, Helium-3 Dating Technique”: In Lieu of a preface. Geochemical Journal, 51(5), pp.385-390. <https://doi.org/10.2343/geochemj.2.0500>
50. Melián, G.V., Pérez, N.M., Amador, R.A.M., Hernández, P.A., Ramírez, C., Sumino, H., Alvarado, G.E. and Fernández, M. 2019. Diffuse CO2 Degassing and Thermal Energy Release from Poás Volcano, Costa Rica. In Poás Volcano (pp. 135-154). Springer, Cham. https://doi.org/10.1007/978-3-319-02156-0\_6
51. Newman, B.D., Osenbrück, K., Aeschbach-Hertig, W., Solomon, D.K., Cook, P., Rózánski, K., et al. 2010. Dating of young groundwaters using environmental tracers: Advantages, applications, and research needs. *Isotopes in Environmental Health and Studies.* 46:259–78. http://dx.doi.org/10.1080/10256016.2010.514339
52. Protti, R., Sojo, D. 2015. Map of vulnerability to water pollution, Belén, Heredia, Costa Rica. *Revista Geológica de América Central.* 53:7–23. (in Spanish). DOI: 10.15517/rgac.v53i0.21140
53. QGIS Development Team. 2009. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>.
54. Ramírez, R. 2007. Potential recharge of the Colima and Barva Aquifer, Central Valley, Costa Rica Senara. (in Spanish). <http://www.senara.or.cr/buscador/default.aspx>
55. Ramírez, R., Alfaro, A. 2002. Hydrogeological vulnerability map of a part of the Central Valley of Costa Rica. *Revista Geológica de América Central.* 27:53-60. (in Spanish). DOI: 10.15517/RGAC.V0I27.7804
56. Reynolds-Vargas, J. 2002. Integrated groundwater management: a challenge for the future. Primera Ed. San José, Costa Rica: EUNED. pp.19-32. (in Spanish).
57. Reynolds-Vargas, J., Fraile-Merino, J. and Hirata, R. 2006. Trends in Nitrate Concentrations and Determination of Its Origin Using Stable Isotopes (18O and 15N) in Groundwater of the Western Central Valley, Costa Rica. Ambio, 229-236. https://www.jstor.org/stable/4315727
58. Reynolds-Vargas, J., Fraile, J. 2009. Use of stable isotopes in precipitation to determine recharge zones in the Barva aquifer, Costa Rica. In: *Estudios de Hidrología Isotópica en América Latina 2006*. Vienna, Austria: IAEA-TECDOC-1611. pp. 83–96. (in Spanish). <https://www-pub.iaea.org/MTCD/publications/PDF/TE_1611s_web.pdf#page=90>
59. Rizzo, A. L., Di Piazza, A., de Moor, J. M., Alvarado, G. E., Avard, G., Carapezza, M. L., and Mora, M. M. 2016. Eruptive activity at Turrialba volcano (Costa Rica): Inferences from 3He/4He in fumarole gases and chemistry of the products ejected during 2014 and 2015. Geochemistry, Geophysics, Geosystems. 17: 4478–4494. <https://doi.org/10.1002/2016GC006525>
60. Ruiz, P., Gazel, E., Alvarado, G.E., Carr, M.J. and Soto, G.J. 2010. Caracterización geoquímica y petrográfica de las unidades geológicas del macizo del volcán Poás, Costa Rica (in Spanish). Revista Geológica de América Central, (43): 37-66.
61. Salas-Navarro, J., Sánchez-Murillo, R., Esquivel-Hernández, G. and Corrales-Salazar, J.L., 2018. Hydrogeological responses in tropical mountainous springs. Isotopes in environmental and health studies, 55:1, 25-40. <https://doi.org/10.1080/10256016.2018.1546701>
62. Sánchez-Murillo, R., Delgado, M., Espinach, D., Lobo, M., Mdrigal, F., Morera, A., et al. 2016. Spatial variation of the 222Rn composition in the Barva and Colima Superior aquifers, Costa Rica. *Revista Geológica de América Central.* 55:145–63. (in Spanish) DOI: 10.15517/rgac.v55i0.27072
63. Sánchez-Murillo, R., & Birkel, C. 2016. Groundwater recharge mechanisms inferred from isoscapes in a complex tropical mountainous region. *Geophys. Res. Lett*.10, 5060-5069. <https://doi.org/10.1002/2016GL068888>
64. Sánchez-Murillo, R., Esquivel-Hernández, G., Welsh, K., Brooks, E., Boll, J., Alfaro-Solís, R., et al. 2013. Spatial and temporal variation of stable isotopes in precipitation across Cost Rica: An analysis of historic GNIP records. *Open Journal of Modern Hydrology.* 3:226–40. <http://dx.doi.org/10.4236/ojmh.2013.34027>
65. Sánchez-Murillo, R., Esquivel-Hernández, G., Birkel, C., Correa, A., Welsh, K., Durán-Quesada, A.M., Sánchez-Gutiérrez, R. and Poca, M. 2020. Tracing water sources and fluxes in a dynamic tropical environment: from observations to modeling. Frontiers in Earth Science, 8: 438. <https://doi.org/10.3389/feart.2020.571477>
66. Sánchez-Murillo, R., Esquivel-Hernández, G., Sáenz-Rosales, O., Piedra-Marín, G., et al. 2017. Isotopic composition in precipitation and groundwater in the northern mountainous region of the Central Valley of Costa Rica. Isotopes in Environmental and Health Studies, 53(1): 1-17. <https://doi.org/10.1080/10256016.2016.1193503>
67. Sánchez-Murillo, R. (2021). Environmental tracer data within the Barva-Colima Aquifer system, Costa Rica, HydroShare, <https://doi.org/10.4211/hs.1beaf29b297b42d394ce4f36f0ab19c3>.
68. Schlosser, P., Stute, M., Dörr, H., Sonntag, C. and Münnich, K.O. 1988. Tritium/3He dating of shallow groundwater. Earth and Planetary Science Letters, 89(3-4): 353-362. <https://doi.org/10.1016/0012-821X(88)90122-7>
69. Schlosser, P., Stute, M., Sonntag, C., Otto, K. 1989. Tritiogenic 3He in shallow groundwater. Earth and Planetary Science Letters. 94:245–56. <https://doi.org/10.1016/0012-821X(89)90144-1>
70. Schosinsky, G., Vargas, A. 2001. Hydrogeology of a sector of the left bank of the Virilla River, province of San José, Costa Rica. *Revista Geológica de América Central.* 24:93–102. (in Spanish). DOI: 10.15517/RGAC.V0I24.8552
71. Solano, J., Villalobos, R. 2001. Physiographic aspects applied to a sketch of the geographic geographic regionaización of Costa Rica. *Tópicos Meterológicos y Oceanográficos.* 8(1):26–39. (in Spanish)
72. Solomon, D., Cook, P. 2000. 3H and 3He. In: *Environmental tracers in subsurface hydrology.* pp. 397–420. https://doi.org/10.1007/978-1-4615-4557-6\_13
73. Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J.F., Schlosser, P., et al. 1995. Cooling of tropical Brazil (5°C) during the last glacial maximum. *Science.* 269:379–83. DOI: 10.1126/science.269.5222.379
74. Stute, M., Sonntag, C, Deák, J., Schlosser, P. 1992. Helium in deep circulating groundwater in the Great Hungarian Plain: Flow dynamics and crustal and mantle helium fluxes. *Geochimica et Cosmochimica Acta.* 56:2051–67. <https://doi.org/10.1016/0016-7037(92)90329-H>
75. Suckow, A. 2014. The age of groundwater - Definitions, models and why we do not need this term. *Applied Geochemistry.* 50:222–30. http://dx.doi.org/10.1016/j.apgeochem.2014.04.016
76. Szabo, Z., Rice, D.E., Plummer, L.N., Busenberg, E., Drenkard, S., Schlosser, P. 1996. Age dating of shallow groundwater with chlorofluorocarbons , tritium / helium 3 , and flow path analysis , southern New Jersey coastal plain. *Water Resources Research.* 32:1023–38. <https://doi.org/10.1029/96WR00068>
77. Team, R.C. 2014. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2014. <https://www.r-project.org/>
78. Topping, J. 2012. Errors of Observation and their Treatment (Vol. 62). Springer Science & Business Media. <https://doi.org/10.1007/978-94-011-6928-8>
79. Torgersen, T., Purtschert, R., Phillips, F. M., Plummer, L. N., Sanford, W. E., and Suckow, A. 2013. "Defining groundwater age. Chapter 3”. In: *Isotope methods for dating old groundwater.* <https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1587_web.pdf>
80. Vargas, A. 2002. Springs of a part of the Central Valley of Costa Rica. *Revista Geológica de América Central.* 27:39–52. (in Spanish) DOI: 10.15517/RGAC.V0I27.7803
81. Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. 2020. Increasing dependence of lowland populations on mountain water resources. Nature Sustainability, 3(11): 917-928. <https://doi.org/10.1038/s41893-020-0559-9>
82. Waylen P. R., Caviedes C.N., and Quesada M.E. 1996. Interannual variability of monthly precipitation in Costa Rica. *J. Clim.* 9:2606-2613. [https://doi.org/10.1175/1520-0442(1996)009<2606:IVOMPI>2.0.CO;2](https://doi.org/10.1175/1520-0442(1996)009%3c2606:IVOMPI%3e2.0.CO;2)
83. Zuber, A., Maloszewski, P. 2008. Lumped parameter models. Chapter 2. In: *Environmental Isotopes in the Hydrogeologycal Cycle: Principles and Aplications*. Vienna, Austria. pp. 5–36.
84. Houze, R.A., Rasmussen, K.L., Zuluaga, M.D. and Brodzik, S.R. 2015. The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the Tropical Rainfall Measuring Mission satellite. *Reviews of Geophysics*, 53(3): 994-1021. <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015RG000488>

**Table 1:** Noble gas (cm3 STP/g) and tritium (TU) compositions in groundwater and spring samples within the BCS.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site (No. in Fig.1)** | **He**  **(cm3STP/g)** | **Error** | **Ne (cm3STP/g)** | **Error** | **Ar (cm3STP/g)** | **Error** | **Kr (cm3STP/g)** | **Error** | **Xe (cm3STP/g)** | **Error** | **Tritium (TU±1σ)** |
| Sacramento (1) | 3.56E-08 | 3.58E-10 | 1.47E-07 | 1.27E-09 | 2.75E-04 | 2.57E-06 | 6.40E-08 | 1.02E-09 | 9.12E-09 | 1.92E-10 | 1.0±0.1 |
| Highland Ranch (2) | 3.82E-08 | 2.96E-10 | 1.62E-07 | 8.05E-10 | 2.62E-04 | 2.74E-06 | 5.69E-08 | 1.76E-09 | 7.91E-09 | 2.76E-10 | 0.9±0.1 |
| Santa Cruz II (3) | 4.00E-08 | 3.08E-10 | 1.75E-07 | 8.60E-10 | 2.92E-04 | 3.05E-06 | 6.24E-08 | 1.84E-09 | 8.86E-09 | 2.61E-10 | 0.5±0.2 |
| Burial (4) | 4.63E-08 | 3.56E-10 | 1.78E-07 | 8.61E-10 | 2.97E-04 | 2.04E-06 | 6.48E-08 | 1.22E-09 | 8.34E-09 | 2.34E-10 | 0.5±0.1 |
| Santiago (5) | 4.77E-08 | 3.67E-10 | 1.79E-07 | 8.83E-10 | 2.97E-04 | 3.23E-06 | 6.35E-08 | 1.87E-09 | 8.77E-09 | 2.58E-10 | 0.5±0.1 |
| Matasanos (6) | 4.50E-08 | 5.78E-10 | 1.79E-07 | 4.72E-09 | 2.95E-04 | 1.94E-06 | 5.91E-08 | 1.84E-09 | 8.90E-09 | 5.03E-10 | 0.8±0.2 |
| Joya III (7) | 7.74E-08 | 7.84E-10 | 1.59E-07 | 1.43E-09 | 2.52E-04 | 2.05E-06 | 5.42E-08 | 1.04E-09 | 7.46E-09 | 1.43E-10 | 0.0±0.1 |
| Claretiano II (8) | 5.95E-08 | 6.04E-10 | 1.70E-07 | 1.53E-09 | 2.86E-04 | 2.40E-06 | 6.07E-08 | 1.31E-09 | 8.34E-09 | 1.57E-10 | 0.5±0.2 |
| Miraflores (9) | 1.40E-07 | 8.44E-10 | 5.09E-07 | 2.55E-09 | 4.50E-04 | 3.08E-06 | 8.14E-08 | 1.53E-09 | 9.89E-09 | 2.65E-10 | 0.3±0.2 |
| San Vicente (10) | 4.86E-08 | 3.74E-10 | 1.80E-07 | 8.81E-10 | 2.92E-04 | 3.02E-06 | 6.55E-08 | 1.94E-09 | 9.58E-09 | 2.80E-10 | 0.4±0.1 |
| Esperanza II (11) | 4.22E-07 | 3.94E-09 | 1.54E-06 | 7.34E-09 | 8.25E-04 | 8.57E-06 | 1.31E-07 | 3.88E-09 | 1.35E-08 | 3.97E-10 | 0.5±0.1 |
| Esperanza 1A (12) | 8.89E-08 | 8.84E-10 | 1.80E-07 | 1.59E-09 | 2.99E-04 | 2.84E-06 | 6.58E-08 | 1.09E-09 | 8.87E-09 | 1.82E-10 | 0.3±0.1 |
| Malinches (13) | 4.64E-08 | 3.57E-10 | 1.92E-07 | 1.05E-09 | 3.03E-04 | 3.33E-06 | 6.35E-08 | 1.87E-09 | 9.01E-09 | 2.65E-10 | 0.4±0.2 |
| Trébol (14) | 3.37E-08 | 3.77E-10 | 8.20E-09 | 1.37E-10 | 1.23E-05 | 2.00E-07 | 3.26E-09 | 6.93E-11 | 4.03E-10 | 2.14E-11 | 0.1±0.1 |
| Montealegre (15) | 1.37E-07 | 1.04E-09 | 4.71E-07 | 4.23E-09 | 4.50E-04 | 3.75E-06 | 7.91E-08 | 1.83E-09 | 9.77E-09 | 2.33E-10 | 0.7±0.2 |
| Aurora II (16) | 5.52E-08 | 4.25E-10 | 2.29E-07 | 1.38E-09 | 3.54E-04 | 2.42E-06 | 7.45E-08 | 1.41E-09 | 9.73E-09 | 2.63E-10 | 0.8±0.1 |
| Ojo de Agua (17) | 4.31E-08 | 3.33E-10 | 1.83E-07 | 9.22E-10 | 2.93E-04 | 2.00E-06 | 6.18E-08 | 1.14E-09 | 8.03E-09 | 2.30E-10 | 0.8±0.1 |
| Puente Mulas (18) | 4.00E-08 | 3.08E-10 | 1.65E-07 | 8.09E-10 | 2.73E-04 | 2.82E-06 | 6.16E-08 | 1.81E-09 | 8.53E-09 | 2.53E-10 | 0.8±0.1 |

**Table 2:** Noble gas recharge temperature (NGT; °C), excess air (cm3 STP/kg), sum χ2, [3He]Trit(TU), and 3H-3He age (yr) in groundwater and spring samples within the BCS. NC corresponds to samples were model failed to converge for NGT or water age. The asterix denote two sties with large χ2 values.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site (No in Fig. 1)** | **NGT (°C)** | **±** | **Excess Air (cm3 STP /kg)** | **±** | **Sum (χ2)** | **[3He]Trit (TU)** | **±** | **3H-3He**  **Age (yr)** | **±** |
| Sacramento (1) | 11.04 | 0.24 | 0.15 | 0.01 | 0.3 | 3.18 | 0.70 | 26.0 | 3.2 |
| Highland Ranch (2) | 17.36 | 0.43 | 0.92 | 0.04 | 0.9 | 0.00 | 0.28 | 0.0 | 3.2 |
| Santa Cruz II (3) | 13.40 | 0.34 | 1.35 | 0.05 | 5.0 | 0.03 | 0.23 | 1.4 | 4.2 |
| Burial (4) | 12.87 | 0.22 | 1.50 | 0.05 | 2.2 | 12.90 | 1.15 | 58.2 | 4.7 |
| Santiago (5) | 13.15 | 0.24 | 1.56 | 0.06 | 0.6 | 19.03 | 1.17 | 65.8 | 7.3 |
| Matasanos (6) | 13.35 | 0.22 | 1.86 | 0.07 | 7.4 | 0.00 | 0.56 | 8.8 | 8.4 |
| Joya III (7) | 19.42 | 0.26 | 0.94 | 0.03 | 1.8 | 127.3 | 1.60 | NC | NC |
| Claretiano II (8) | 14.69 | 0.22 | 1.26 | 0.06 | 2.6 | 59.7 | 0.90 | 11.4 | 21.3 |
| Miraflores (9) | 15.77 | 0.20 | 19.97 | 0.31 | 0.1 | 21.27 | 1.27 | 76.0 | 9.9 |
| San Vicente (10) | 12.89 | 0.22 | 1.58 | 0.06 | 1.2 | 21.29 | 1.24 | 70.5 | 6.2 |
| Esperanza II (11)\* | NC | NC | 77.05 | 0.88 | 105.0 | 10.2 | 0.90 | 53.6 | 5.3 |
| Esperanza 1A (12) | 12.96 | 0.29 | 1.66 | 0.07 | 0.0 | 152.2 | 2.20 | 51.8 | 19.9 |
| Malinches (13) | 13.23 | 0.26 | 2.32 | 0.11 | 1.6 | 4.37 | 0.52 | 43.5 | 7.6 |
| Trebol (14)\* | NC | NC | 0.00 | 0.03 | 927.5 | 99.0 | 1.30 | 39.3 | 25.8 |
| Montealegre (15) | 14.34 | 0.25 | 18.05 | 0.44 | 1.6 | 3.76 | 1.64 | 33.3 | 8.7 |
| Aurora II (16) | 15.30 | 0.14 | 4.01 | 0.15 | 0.0 | 0.01 | 0.41 | 2.0 | 5.6 |
| Ojo de Agua (17) | 14.29 | 0.23 | 1.88 | 0.08 | 1.2 | 0.19 | 0.40 | 3.9 | 5.1 |
| Puente Mulas (18) | 15.20 | 0.32 | 0.96 | 0.05 | 0.0 | 2.40 | 0.68 | 25.4 | 4.2 |

**Figure 1:** Study area overview including sampling sites (numbered green dots). The inset shows the relative location of the study are within the Central Valley of Costa Rica. Wells (2-16) and large springs (1 and 17-18) were sampled for water stable isotopes, 3H/3He, and noble gases across an elevation gradient from 868 (Site 18) to 2,421 m asl (Site 1). A-A' and B-B' denote lithological cross sections from N-S and E-W, respectively (See Fig. 2). The main urban area (city of Heredia) is located to the north of the Virilla river. The summit of the Barva and Irazú volcanoes and Palma Depression (main moisture pass from the Caribbean slope) are included for reference.

**Figure 2:** Lithological cross sections within the study area. Upper (A) and lower (B) panels represent N-S and E-W transects, respectively. Numbers correspond to wells and springs locations in Fig. 1. Vertical panel C shows a simplified geological sequence and hydraulic regime modified after Darling et al. (1989).

**Figure 3:** A) Regional tritium (in TU) time series in Central America and México (blue squares), the Caribbean domain (pink triangles), Colombia (gray circles), and recent measurements in Costa Rica (red rhombi; monthly and event-based; 2015-2017). B) Stable isotope variability (2013-2018) of rainfall in the study area (gray crosses) and wells and springs isotope ratios (cyan filled-squares). GMWL (black line) and Costa Rica MWL (blue line; Sánchez-Murillo et al., 2013) are included as references. C) Inset showing a zoom in wells and springs isotope ratios. Groundwater fluctuates between -9‰ and -6‰, as a result of the spatial (west to east and orographic effects) rainfall signal influence over groundwater recharge. Blue and pink bi-directional error bars denote Pacific and Caribbean rainfall types according to Sánchez-Murillo et al. (2020)

**Figure 4:** Ne/He and R/Ra ratios across the aquifer system. Green dots denote wells and springs sampled within this study (numbers refer to locations in Fig.1). The blue triangle and pink rhombi represent atmospheric and solubility ratios (between 15-30 °C), respectively. Influence of mantle 3He is clearly depicted in samples 7,8, 12, and 14. As a reference, influence of radiogenic 4He from continental crust is represented by a subset of samples (pink squares) collected within the Tubarão aquifer (São Paulo, Brazil) (Ezaki et al., 2019).

**Figure 5:** A) Tritium and tritiogenic helium [3He]Trit (TU) and apparent recharge year for groundwater samples (blue squares) within the BCS. A regional tritium curve is included as a reference (gray curve). Few samples resulted in relatively older ages, suggesting a significant contribution of 3He from the mantle (red polygon). B) Tritium (TU) and water table depth (m) relationship. C) The inset map shows a δ18O groundwater isoscape (100x100 m grid) extracted from Sánchez-Murillo and Birkel (2016). Barva (uncofined unit) and -in lesser degree- upper Colima (semi-confined unit) are characterized by TU>0.7, whereas the lower Colima (semi-confined unit) is better described by enriched and low tritium activities. Site numbers corresponding to Fig.1. are included for spatial reference.

**Figure 6:** Apparent groundwater age (yr) versus depth below the surface (m). Blue rectangles include sites potentially reflecting rapid vertical percolation and large degree of mixing between Barva and upper Colima formations. Site numbers corresponding to Fig.1. are included for spatial reference.

**Figure 7:** Relationship between estimated noble gas temperature (NGT, °C) and potential recharge elevations (m asl). Blue empty circles describe the local environmental lapse rate from mean annual meteorological records.

**Figure 8:** Land use types within the suggested boundary (blue polygon) of the Barva aquifer (Madrigal-Solís et al., 2017) in 2019. Six main land use types were identified: forest, parture, crops, urban, bare soil, and nursiries. The elevation gradient is represented by the solid black lines. The most prominent recharge areas cover elevations from 1,400 up to 2,700 m asl. Sampling sites are denoted by green dots. A-A' and B-B' denote lithological cross sections from N-S and E-W (Fig. 2), respectively.