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Delineating Ababi Mountains spring recharge zones using combined isotope hydrology and geophysical methods

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Abstract: Sustainable groundwater management requires accurate identification of spring recharge zones, particularly in volcanic regions where water resources are critical. This study aimed to delineate the groundwater recharge zone of the Ababi Spring in Bali's Karangasem Regency by integrating isotope hydrological and geophysical techniques. Water samples were collected from five locations (211–978 m a.s.l.) and analysed for stable isotopes (δ^2H or δD and δ^{18}O). Vertical electrical sounding and audio magnetotelluric surveys were conducted to validate findings and map subsurface structures. The local meteoric water line was established ($\delta^2H = 4.4912\delta^{18}O + 7.1419$) and an isotope-elevation relationship was developed. The spring water exhibited depleted isotopic values (δ^{18}O: −7.706‰, δ^2H: −39.748‰) compared to local precipitation, indicating a higher-altitude source. The analysis identified the recharge zone at approximately 2,118 m a.s.l. Geophysical surveys revealed subsurface structures connecting the recharge area to the spring, with resistivity patterns indicating preferential flow paths going through fractured volcanic rocks. The effectiveness of this integrated approach was further validated through additional isotopic analysis of rainfall at 1,514 m a.s.l. This supported the established isotope-elevation relationship model ($R^2 = 0.6847$). The study demonstrates the value of combining hydrochemical and geophysical methods for accurate recharge zone delineation in a volcanic terrain, particularly in regions with complex hydrogeological settings. These findings provide crucial information for implementing targeted conservation strategies and ensuring sustainable water resource management in the Karangasem region, while establishing a methodological framework applicable to similar volcanic environments.

Keywords: audio magnetotelluric, groundwater recharge, isotope hydrology, spring water, volcanic aquifer

INTRODUCTION

Global water scarcity has become a critical environmental challenge, making access to clean and reliable water sources increasingly difficult (Ngene *et al.*, 2021; Rich *et al.*, 2023). The rising global population intensifies water demand, putting further strain on already limited resources (Roy, Thakur and Debsarkar, 2021; Molajou *et al.*, 2023). To ensure effective management and protection of groundwater, particularly springs, accurately identifying recharge areas is essential (Martínez *et al.*, 2020; Khosravi, Afshar and Molajou, 2022).

Stable isotope experiments are vital for tracing groundwater origins and identifying recharge zones. Isotopic techniques have been successfully applied to study groundwater formation in Indonesia, particularly in Bali (Nuha *et al.*, 2020). For instance, deuterium (δ^2H or δD), the stable hydrogen isotope ^{2}H, and oxygen-18 (δ^{18}O) have been used to demarcate places where groundwater is replenished in the urban regions of Denpasar City and identify recharge areas of springs supplying unprocessed natural water in the Mambal area (Ardana *et al.*, 2022; Chou *et al.*, 2022).

The conservative behaviour of oxygen and hydrogen isotopes in water molecules makes them excellent natural tracers, as they remain largely unaffected by low-temperature water-rock interactions (Kankaala *et al.*, 2023). Groundwater isotope compositions downstream closely match upstream precipitation (Sankoh *et al.*, 2021; Xia *et al.*, 2023). This phenomenon has enabled researchers to use natural isotopes for studying water flow, identifying recharge zones, and tracing of groundwater flow paths (Ossa *et al.*, 2021; Chmielarski *et al.*, 2022).

Limited research has specifically focused on this local groundwater resource. While Toulier *et al.* (2019) and Satrio *et al.* (2024) employed isotope methods to study spring recharge processes in other Indonesian regions, they neglected to prioritise the Ababi Spring or combine their approach with geophysical techniques. Moreover, stable isotope analysis and geoelectric approaches have never been used to map the catchment area of the Ababi Spring.

Hydrogeological investigations at depths of up to 300 m have disclosed structural connections and rock formations. Magnetotelluric methods have successfully identified aquifers and overloaded structures (Ailes and Rodriguez, 2015; Bai *et al.*, 2019). However, relying solely on geochemical or geophysical methods to determine spring recharge areas can be challenging, expensive, and impractical.

To address these limitations, this study combines isotope techniques. The use of vertical electrical sounding (VES) and audio-frequency magnetotellurics (AMT) methods aims to delineate the catchment of the Ababi Spring, located in the hilly area of Abang Regency, Karangasem, Bali. The Ababi Spring plays a vital role in the municipal water supply infrastructure of the Karangasem District, making its catchment area identification essential for implementing effective conservation measures.

Traditional hydrogeological data alone cannot identify groundwater recharge areas (Zamrsky, Oude Essink and Bierkens, 2024). While this problem can be addressed by employing isotope techniques (Ahmed, Chen and Khalil, 2022), they fail to determine the specific pathways of underground water flow. In contrast, geophysical surveys provide accurate subsurface structural data but cannot independently determine hydrologic relationships (Xu *et al.*, 2019).

This study pioneers an interdisciplinary approach integrating stable isotope analysis, VES, and AMT surveys to provide complementary findings for identifying the Ababi Spring's recharge origin and subsurface flow system. By combining geochemical and geophysical methods, this research enables a more consistent understanding of groundwater basin dynamics (Aguedai *et al.*, 2022) and marks a significant advancement in the hydrogeology of this vital water resource.

The main objective of this study is to determine the restored region at the Ababi Spring by employing isotope techniques and to confirm the current linkages to the indicated restoration zone through geoelectrical investigations. This integrated approach combines stable isotope analysis of water molecules with electrical resistivity profiling and electromagnetic sounding techniques.

This study utilises isotope hydrology to track the origins of water sources and employs geophysical methods to identify geological features and hydrostratigraphy (Palano, 2022). The present investigation represents a pioneering application of these integrated methodologies to accurately and consistently analyse the restoration mechanism of the Ababi Spring.

MATERIALS AND METHODS

STUDY AREA

The investigation focused on Ababi Village in Karangasem Regency, Bali Province. The Ababi Spring, the primary subject of this study, is situated at coordinates 8°24'8.14" S and 115°35'12.85" E. This region spans 10.86 km^2, with a mean altitude of 573 m above sea level (m a.s.l.). Situated on the south-eastern slopes of Mount Agung, the village features a diverse landscape. Higher elevations characterise the northern section of the village, while the eastern and central regions consist of gentle hills interspersed with rice paddies. In contrast, the western and southern areas are predominantly flat. The climate in the area is mild, with afternoon temperatures between 29 and 35°C.

For this study, six strategic sampling sites were selected across different elevations in the study area to capture spatial variations in groundwater characteristics and validate flow patterns. These sites, ranging from 387 to 1,300 m a.s.l., were chosen based on their accessibility and representation of different topographic positions along the hypothesised groundwater flow path. Table 1 presents the locations and elevations of these sampling sites.

Table 1. Sample sites

Site name	Coordinates	Elevation (m a.s.l.)
Tanah Aron 1	8°21'58" S, 115°32'58" E	1,300
Tanah Aron 2	8°22'3" S, 115°32'9" E	1,200
Tanah Aron 3	8°22'10" S, 115°32'22" E	1,089
Ababi 1	8°23'16" S, 115°34'17" E	541
Ababi 2	8°2'22.2" S, 115°34'48" E	425
Above water spring	8°23'53" S, 115°35'2" E	387

Source: own elaboration.

HYDROGEOLOGICAL SETTING

The Amlapura aquifer system, located within the Karangasem area of Bali, spans approximately 213.6 km^2 and includes the settlement of Ababi (Scott Jansing, Mahichi and Dasanayake, 2020). This basin is characterised by diverse annual precipitation, ranging from 1,000 to 3,500 mm, and possesses significant groundwater sources. The estimated potential of the shallow aquifer system is 60 mln m^3·y^{-1}, while the deep aquifer system is expected to hold around 2 mln m^3·y^{-1}. The basin's topography is varied, featuring plains, undulating hills, and volcanic cones, with elevations up to 3,500 m a.s.l. The landscape is sculpted by a radial drainage pattern from the volcanic cone (Sutawidjaja and Sugalang, 2007).

The Amlapura basin exhibits a complex and diverse geological composition. Alluvial deposits form the principal aquifers along rivers and coastal areas, while Agung volcanic rocks (Qhva) and Seraya volcano rocks contribute to the basin's lithology

(Suryanata *et al.*, 2024). Within this hydrogeological framework, a spring with a discharge rate of 5 $dm^3 \cdot s^{-1}$ serves as the focal point of this study. The presence of this spring, in the context of the basin's complex lithology and aquifer systems, underscores the importance of delineating its recharge area and understanding its flow connections to ensure sustainable water resource management in the region (Dey and Majumdar, 2024).

STABLE ISOTOPES

This study utilised stable isotope techniques to elucidate the origin and recharge mechanisms of the Ababi Spring. Oxygen (^{16}O, ^{17}O, ^{18}O) and hydrogen (^{1}H, ^{2}H, ^{3}H) isotopes are natural tracers in hydrological systems due to their inherent presence in water molecules. Their relative abundances are influenced by fractionation processes occurring throughout the hydrological cycle, including evaporation and condensation (Feng, Liu and Li, 2020; Kim *et al.*, 2022; Rizvi *et al.*, 2023).

The investigation quantified isotope ratios of deuterium ($D/^{1}H$) and oxygen-18 ($^{18}O/^{16}O$) in water samples, comparing them to the Standard Mean Ocean Water (SMOW) ratio. This comparison is crucial as seawater represents the primary evaporation source in the global water cycle. Most freshwater samples typically exhibit negative δ^2H and $\delta^{18}O$ values, expressed in per million (‰) notation (Zhong *et al.*, 2021; Qiu *et al.*, 2022; Waldeck *et al.*, 2022).

Oxygen isotopes are used to determine the height at which the spring is recharged. This approach is based on the principle that precipitation at higher elevations generally displays lower $\delta^{18}O$ values due to temperature-dependent fractionation processes (Hemmerle *et al.*, 2021). The symbols $(\delta^2H)SMOW$ and $(\delta^{18}O)SMOW$, expressed in ‰, are abbreviated as δ^2H and $\delta^{18}O$, respectively. The term δ_{sample} was employed to denote the relative abundance of isotopes in a given sample (Hemmerle *et al.*, 2021; Rich *et al.*, 2023):

$$\delta_{\mathrm{sample}} = \frac{\mathrm{R_{sample}} - \mathrm{R_{std}}}{\mathrm{R_{std}}} 100\% \tag{1}$$

where: R_{sample} = isotope ratio in the sample, R_{std} = isotope ratio in the reference standard (SMOW).

This study analysed large quantity of ^{18}O to ^{16}O and ^{2}H to ^{1}H in water samples, comparing them to SMOW ratios. These isotope ratios fluctuate throughout the water cycle due to variations in their physical properties. Various processes, including phase changes and chemical reactions, can induce isotope fractionation (Pang *et al.*, 2017). Barring modifications typically exhibit ^{18}O and ^{2}H concentrations aligning with the home-grown impressive liquid route, representing the isotopic structure of local precipitation.

The $D/^{18}O$ isotope ratios are influenced by elevation and precipitation patterns. As precipitation frequency and amount decrease, δ^2H and $\delta^{18}O$ values increase. To account for the impact of rain events and precipitation frequency on isotope ratios at each sampling site, weighted average calculations were employed using the following equations (Jiang *et al.*, 2024; Liotta *et al.*, 2008):

$$\frac{\delta^{18}\mathrm{O} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_i} \delta_{\mathrm{i}}{}^{18}\mathrm{O}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_i}} \tag{2}$$

$$\delta^2\mathrm{H} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_i} \delta_{\mathrm{i}}{}^{2}\mathrm{H}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P_i}} \tag{3}$$

where: P_i = precipitation quantity in the interval from one measurement point to the next in mm per month, $\delta_i{}^{18}O$ and $\delta_i{}^{2}H$ = relative abundances of oxygen-18 and deuterium compared to the standard mean ocean water in the corresponding moisture collection, expressed in parts per thousand.

This approach provides a more accurate representation of the average isotopic signature of local rainfall by considering the influence of precipitation volume and frequency on observed isotope ratios. By accounting for these factors, researchers can better understand the relationship between elevation, precipitation patterns, and the resulting isotopic structure of water.

ELECTRICITY SOUNDING VERTICALLY (VES)

The VES technique is a geophysical method that assesses subsurface electrical properties by using electrodes to send direct current into the ground and then measuring the potential difference. The depth of current penetration correlates with electrode spacing, enabling the visualisation of resistivity stratification. This study employed a Naniura NRD-300 HF instrument and auxiliary equipment, including a laptop, electrodes, a power source, cables, connectors, and clamps. The survey utilised a Schlumberger array configuration, comprising four linearly aligned electrodes with variable spacing. In this setup, the outer electrodes function as current electrodes, while the inner pair measures the potential difference (Koefoed).

The apparent resistivity values obtained from the VES survey were plotted on logarithmic graphs and compared against a Schlumberger master curve to differentiate and partition the resistivity values (Bhatnagar *et al.*, 2022; Vijayaprabhu *et al.*, 2024). This comparison enables the determination of electrical properties and spatial dimensions of various underground strata by aligning the measured data with a standard reference curve.

AUDIO MAGNETOTELLURIC (AMT) SURVEY

The Audio-Magnetotelluric (AMT) method is a passive geophysical technique that investigates subsurface electrical conductivity at various depths by applying electromagnetic pulses within the frequency range of 5 to 1,000 Hz (Consoli *et al.*, 2020). By detecting the Earth's naturally existing electromagnetic waves, the method determines electrical conductivity (Grayver, 2024). The AMT and magnetotelluric (MT) surveys rely on two external electromagnetic (EM) signals from the magnetosphere and atmosphere. Telluric currents run horizontally across the Earth's surface due to these electromagnetic waves interacting with the crust. By analysing these telluric currents in conjunction with corresponding magnetic pulses, researchers can characterise the subsurface electrical conductivity structure (Sorokin *et al.*, 2023).

In this study, the AMT method employed orthogonal sensors to detect electric and magnetic fluctuations using orthogonal sensors. The collected sequential measurements were analysed using spectral decomposition techniques, and resistivity distribution models were derived from the MT data using forward model and inversion methods. Field testing was conducted using VES and AMT methods to validate the results obtained from isotope analysis.

RESULTS AND DISCUSSION

WATER SAMPLING LOCATION

Rainwater samples were collected from four carefully chosen locations, each with an elevation difference of at least 100 m. In addition to the rainwater sampling points, the study also analysed the spring water at the outflow point of the Ababi Spring. The specific sampling sites are detailed in Table 2.

Table 2. Water sample

Location	Water type	Elevation (m a.s.l.)	Coordinates
Ababi Spring	spring	378	8°23'59" S, 115°34'58" E
Autotama	rainwater	211	8°25'44" S, 115°35'31" E
Ababi (lower)	rainwater	386	8°23'54" S, 115°35'0" E
Ababi (upper)	rainwater	596	8°23'13"S, 115°34'2"E
Tanah Aron	rainwater	978	8°22'17" S, 115°32'38" E

Source: own study.

A specialised collection system was installed before the onset of rainfall to ensure the integrity of the rainwater samples. Once sufficient amount of water had been collected during a rain event, the sample was carefully transferred to a bottle, taking precautions to prevent any air from being trapped by securely fastening the lid. Airtight bottles were used to minimise the risk of air contamination, and proper storage techniques were employed to reduce the potential for evaporation. After the samples were collected and securely stored, they were moved to the Laboratory of Hydrogeology and Hydrogeochemistry at the Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung (ITB), for additional examination.

STABLE ISOTOPES ANALYSIS

The analysis of rainwater and spring water samples yielded significant insights. The isotopic analysis of water samples revealed a clear relationship between elevation and isotope ratios. Rainwater collected at lower elevations (211 m a.s.l.) showed enriched isotope compositions, with δ^2H at −12.416‰ and δ^{18}O at −4.366‰. In contrast, samples or specimens collected from higher elevations demonstrated increased isotopic scarcity, with hydrogen isotope values reaching lower levels and oxygen-18 registering −7.706‰. This pattern strongly supports the "altitude effect" theory, where isotope composition becomes more depleted with increasing elevation. The spring water sample, collected at 378 m a.s.l., showed isotope ratios (δ^2H: −39.748‰, δ^{18}O: −7.706‰) similar to those of high-elevation rainwater, suggesting a higher-altitude source for the spring water.

These observations strongly support the "altitude effect" theory, which posits that the isotope composition of rainfall, as indicated by (δ^2H)SMOW and (δ^{18}O)SMOW, becomes more depleted at higher elevations (Chou *et al.*, 2022). This effect is primarily due to the preferential rainout of heavier isotopes as air masses ascend and calm, leaving the remaining water vapour progressively depleted in heavy isotopes (Xia *et al.*, 2023).

The local geological context, characterised by the volcanic terrain of Mount Agung, likely influences the observed isotopic patterns. Volcanic landscapes often exhibit complex hydrogeological systems with the potential for rapid infiltration and groundwater flow through fractured rock masses (Xu *et al.*, 2019). This geological setting may contribute to the observed isotopic variations by facilitating rapid transport of precipitation from higher elevations to lower-lying springs (Zhang *et al.*, 2023).

A local meteoric water line (LMWL) graph shows the correlation between rainfall samples' elevation and isotope ratios in the Ababi area. The resulting LMWL for the Ababi area, as shown in Table 3, is described as follows:

$$\delta^2\mathrm{H} = 4.4912\delta^{18}\mathrm{O} + 7.1419 \quad (4)$$

Table 3. Isotope data for rainwater and spring water samples

Sample type	δ^{18}O (‰)	δ^2H (‰)
Rainwater 1	−4.366	−12.416
Rainwater 2	−4.507	−13.120
Rainwater 3	−4.654	−13.711
Rainwater 4	−4.749	−14.187
Spring water	−7.706	−39.748

Note: local meteoric water line (LMWL) equation: δ^2H = 4.4912δ^{18}O + 7.1419 (R^2 = 0.9778). Global meteoric water line (GMWL) equation: δ^2H = 8δ^{18}O + 10.
Source: own study.

With an R^2 value of 0.9778, the equation δ^2H = 8δ^{18}O + 10 represents the Global Meteoric Water Line (GMWL), which is situated below this LMWL. The LMWL and GMWL are positioned differently because the Ababi region of Indonesia has a more tropical climate on the GMWL. This situation reflects the influence of local climatic conditions on precipitation isotope ratios (Rizvi *et al.*, 2023). The lower slope of the LMWL compared to the GMWL suggests the influence of evaporation processes on local precipitation, which is common in tropical environments with high humidity and temperature (Kim *et al.*, 2022). Future studies should consider long-term sampling to account for potential seasonal effects on the isotopic signature of precipitation and spring water.

It was discovered that the GMWL for the Ababi area, denoted by δ^2H = 8δ^{18}O + 10, was situated above the LMWL. This discrepancy can be attributed to the tropical climate of Bali, Indonesia, contrasting with the non-tropical regions typically represented by the GMWL. Nevertheless, the derived LMWL exhibited general conformity with the GMWL.

The isotope analysis of the Ababi Spring water revealed ^{18}O and D isotope composition values of −7.706 ±0.008 and −39.748 ±0.211, respectively. Using the equal interval method for classification, the groundwater samples formed distinct groups below the LMWL (Tab. 2). Due to its location, the spring water appears to come from a higher elevation source rather than from nearby rainfall occurrences.

These findings highlight the complex interplay between topography, geology, and climate in shaping the isotopic signature of water resources in the Ababi area. Synthesis of isotopic analysis results with regional geological and hydrological information offers a comprehensive basis for elucidating the local aquifer system's water source and subterranean circulation patterns.

ESTIMATING ABABI SPRING RECHARGE ELEVATION

The link between the ^{18}O and ^{2}H components, the LMWL, and the isotope data suggests that area precipitation does not directly replenish the Ababi Spring. In order to ascertain the height of the recharge area, the correlation between ^{18}O isotope composition and rainwater sample elevation was utilised. The negative isotope values suggest natural fractionation and evaporation processes in the recharge area. Table 4 illustrates the correlation between ^{18}O isotope content and elevation for the rainwater samples.

Table 4. Rainwater sample altitude and ^{18}O isotopes

Sampling location	Altitude (m)	$\delta^{18}O$ (‰)
Autotama	211	−4.366
Ababi (lower)	386	−4.507
Ababi (upper)	596	−4.654
Tanah Aron	978	−4.749

Note: linear regression equation: $\delta^{18}O$ = −0.0006Altitude − 4.1174 (R^2 = 0.6847).
Source: own study.

Water samples were collected from various locations across an elevation gradient, ranging from 211 to 978 m a.s.l. The Ababi Spring water sample was collected at 378 m elevation, while rainwater samples were collected from four sites: Autotama (211 m), lower Ababi (386 m), upper Ababi (596 m), and Tanah Aron (978 m). The $\delta^{18}O$ values of these samples showed a general depletion trend with increasing elevation, ranging from −4.749‰ at the highest site to −4.366‰ at the lowest site. Despite its relatively low elevation, the spring water sample showed a significantly depleted $\delta^{18}O$ value of −7.706‰, further supporting the hypothesis that the spring is recharged from a high-elevation source.

The LMWL was established using weighted regression, which relies exclusively on rainfall samples. The LMWL is deemed a functional input in investigating hydrology and ascertaining the source and composition of the Ababi groundwater. Table 4 illustrates how elevating rainwater samples and the ^{18}O isotope ratio result in a linear association.

This finding suggests that as elevation increases, the ^{18}O isotope ratio becomes more depleted, indicating that the isotope composition of rainfall is influenced by altitude.

We correlated the oxygen-18 isotopic composition with the topographic height of precipitation collection sites to identify the altitude at which the aquifer replenishment occurs. This approach is based on the well-established principle that precipitation at higher elevations generally displays more depleted $\delta^{18}O$ values due to temperature-dependent fractionation processes (Benettin *et al.*, 2018). The linear regression model describing this relationship is represented by:

$$\delta^{18}\mathrm{O} = -0.0006\mathrm{Altitude} - 4.1174 \quad (5)$$

The model has an R^2 value of 0.6847 to indicate a moderate fit. Equation (6) shows their relation:

$$\mathrm{Altitude} = -1666.67\delta^{18}\mathrm{O} - 6862.33 \quad (6)$$

Equation (6) and the water examples' isotope proportion ($\delta^{18}O$) value can be used to calculate the recharge area at the Ababi Spring. The Spring has a $\delta^{18}O$ value of −7.706 ±0.008‰ and is 378 m a.s.l. The computations derived from Equation (6) indicate that the source region for the Ababi Spring's water supply is situated at an altitude in the upper reaches of the local topography, as depicted in Figure 1.

This approach allows for determining the approximate elevation of the recharge area based on the isotopic composition of the spring water, providing valuable insights into the hydrological system of the Ababi Spring.

The reliability of this estimate is supported by its consistency with local topography and previous studies in similar volcanic settings (Aguedai *et al.*, 2022; Xia *et al.*, 2023). However, the moderate R^2 value suggests that these findings should be interpreted with caution. The scatter in our data highlights the complex nature of isotope-elevation relationships in tropical volcanic environments and underscores the need for more comprehensive sampling strategies in future studies (Rizvi *et al.*, 2023).

Our approach provides a valuable first-order estimate of the Ababi Spring's recharge elevation. This information is crucial for implementing targeted conservation strategies and ensuring the long-term sustainability of this vital water resource.

WATER FLOW MODEL VALIDATION

To corroborate the isotope-based findings and gain deeper insights into the subsurface structure and groundwater flow paths, we employed electrical resistivity measurements (VES) and low-frequency electromagnetic sounding (AMT) techniques. These geophysical methods provided complementary data, enabling a more comprehensive understanding of the hydrogeological system supporting the Ababi Spring. Table 1 depicts locations of rainwater collection sites and areas where VES and AMT data were gathered for validation.

Given the area's steepness and andesite rock outcropping, lava-rich rock formations originating from Mount Agung are prevalent. Additional rainwater samples with ^{18}O and ^{2}H ratios were analysed, and the results are presented in Table 5. The Telaga Beteng sampling site, located at 8°21'46" S, 115°31'40" E, is situated at an elevation of 1,514 m a.s.l.

This high-altitude location provided crucial data for validating the study's isotope-elevation relationship model. Analysis of rainwater collected at the site yielded $\delta^{18}O$ and $\delta^{2}H$ values of −5.125 ±0.008‰ and −36.104 ±0.211‰ respectively, supporting the hypothesis of isotopic depletion with increasing elevation and corroborating the estimated recharge zone for the Ababi Spring. Uncertainties in isotope measurements were calculated using standard analytical techniques for stable isotope analysis. The specific method used was replicate sample analysis, which provides a measure of precision for each isotope ratio. This is evidenced by the uncertainty values reported in Table 5, where $\delta^{18}O$ has an uncertainty of ±0.008‰ and $\delta^{2}H$ has an uncertainty of ±0.211‰.

The thickness and continuity of these layers varied across the study area, with the intermediate layer being more prominent at higher-elevation sites (Sallée *et al.*, 2021). This observation aligns with our isotope-based recharge elevation estimate, suggesting that the fractured volcanic rocks in the higher elevations serve as the primary recharge pathway for this research location (Fenta *et al.*, 2020).

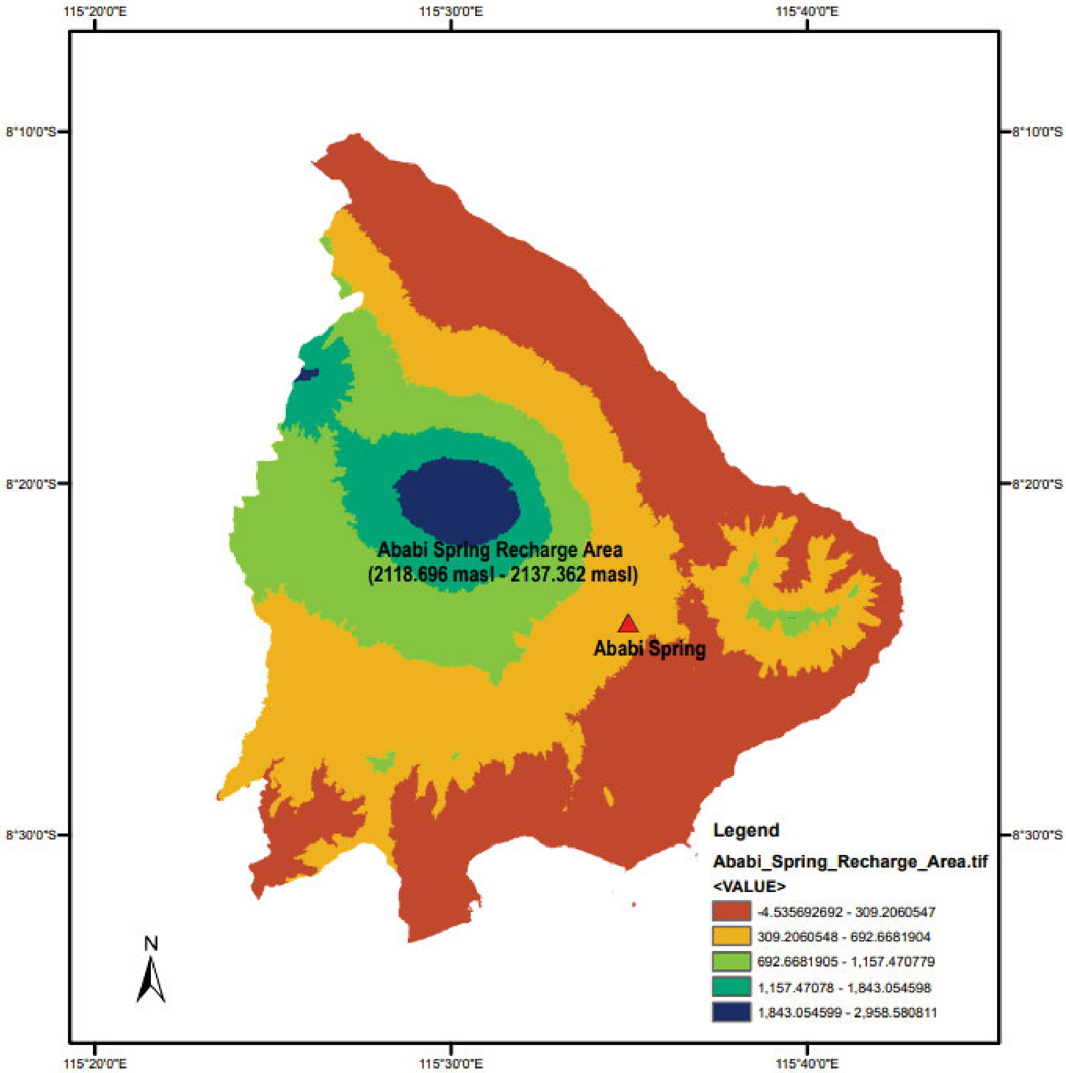

Fig. 1. Ababi Spring recharge area; source: own study

Table 5. Results of isotope testing

Isotope	Measured value	Uncertainty
	‰	
$\delta^{18}O$	−5.125	±0.008
$\delta^{2}H$	−36.104	±0.211

Source: own study.

Equation (6) can be used to obtain the oxygen isotope equation corresponding to the increasing recharge region of the Ababi Spring by entering the isotope ratio value. The results confirm previous findings, indicating a recharge elevation of 2,118 m a.s.l. The VES and AMT data support the hypothesis that the water flows inside strata with low resistivity values. These low-resistivity zones are potential aquifers or water pathways, as shown in Table 6. Table 6 presents the integrated results of VES and AMT surveys across six sampling locations, showing a clear

Table 6. Integrated results of vertical electrical sounding (VES) and audio-frequency magnetotellurics (AMT) surveys

Site location	Elevation (m a.s.l.)	Layer depth (m)	Resistivity (Ωm)	Interpreted lithology	Water flow indication
Tanah Aron 1	1,300	0–50	350–450	volcanic breccia	low potential
		50–150	80–120	fractured andesite	moderate flow
		>150	20–40	saturated zone	high flow
Tanah Aron 2	1,200	0–45	380–460	volcanic breccia	low potential
		45–130	70–110	fractured andesite	moderate flow
		>130	15–35	saturated zone	high flow

cont. Tab. 6

Site location	Elevation (m a.s.l.)	Layer depth (m)	Resistivity (Ωm)	Interpreted lithology	Water flow indication
Tanah Aron 3	1,089	0–40	400–480	volcanic breccia	low potential
		40–120	60–100	fractured andesite	high flow
		>120	10–30	saturated zone	high flow
Ababi 1	541	0–35	420–500	volcanic breccia	low potential
		35–100	50–90	fractured andesite	high flow
		>100	5–25	saturated zone	high flow
Ababi 2	425	0–30	450–520	volcanic breccia	low potential
		30–90	40–80	fractured andesite	high flow
		>90	5–20	saturated zone	high flow
Above spring water	387	0–25	470–550	volcanic breccia	low potential
		25–80	30–70	fractured andesite	high flow
		>80	5–15	saturated zone	high flow

Source: own study.

pattern of subsurface structure and water flow characteristics. The resistivity values and interpreted lithology demonstrate three distinct layers: an upper volcanic breccia layer with high resistivity (350–550 Ωm), a middle layer of fractured andesite with moderate resistivity (30–120 Ωm), and a lower saturated zone with low resistivity (5–40 Ωm). These layers consistently show potential groundwater pathways, particularly in the fractured andesite and saturated zones. A groundwater flow modelling approach was employed to validate these findings by incorporating data from VES and AMT. As indicated by Table 4, the data were gathered at six key locations that extended from recharge to discharge areas.

Integrating these geophysical results with isotopic data significantly strengthens our understanding of the Ababi Spring's hydrogeological system. Geophysical data provide physical evidence of flow paths inferred from isotopic analysis, while the isotopic data offer insights into the origin and movement of water through the subsurface structures identified by VES and AMT.

Overall, our findings directly address the study's main objective by providing evidence for the recharge zone's location through both isotopic and geophysical data. The isotope analysis pinpointed the recharge elevation, while the VES and AMT data confirmed the subsurface flow paths, collectively delineating the Ababi Spring's recharge area.

While this study successfully integrated isotope and geophysical techniques to identify the Ababi Spring's recharge zone, several limitations should be acknowledged. Firstly, the isotope analysis relied on a relatively small sample size, with only four rainwater sampling locations and one spring water sampling point. Although these samples provided meaningful insights, a more extensive sampling network could better capture spatial variations in isotopic signatures across the study area. The moderate R^2 value (0.6847) in our isotope-elevation relationship suggests some uncertainty in our recharge elevation estimates.

Secondly, our sampling campaign did not capture seasonal variations in isotopic compositions. Given Bali's tropical climate, with distinct wet and dry seasons, the isotopic signatures of precipitation and spring water likely vary throughout the year. This temporal limitation may affect the representativeness of our findings, as seasonal changes in precipitation patterns, temperature, and humidity could influence the isotope fractionation processes and ultimately impact our recharge zone estimates.

The geophysical modelling relied on several assumptions that should be considered. The VES and AMT interpretations assumed relatively homogeneous subsurface layers, whereas volcanic terrains typically exhibit complex heterogeneity in rock properties and fracture networks. Additionally, the models also assumed steady-state conditions in groundwater flow, which may not fully represent the dynamic nature of the hydrogeological system.

Additionally, our study did not account for potential mixing of water sources along the flow path. While the isotopic data suggests a high-elevation recharge source, contributions from intermediate elevations or different aquifer units cannot be completely ruled out without more detailed hydrochemical analysis.

CONCLUSIONS

This study demonstrates the effectiveness of combining multiple hydrochemical and geophysical techniques to delineate groundwater recharge zones in complex volcanic terrains. By integrating stable isotope analysis with VES and AMT surveys, we successfully identified the recharge zone of the Ababi Spring and validated the subsurface flow pathways connecting it to the spring outlet. The multi-method approach provided more reliable results compared to single-method investigations, offering a robust framework for similar studies in comparable geological settings.

The findings have significant implications for water resource management in volcanic regions. First, the successful delineation of recharge zones using this integrated approach provides water resource managers with a proven methodology for identifying critical areas requiring protection. This is particularly relevant in volcanic terrains, where complex geological conditions and rapid urbanisation often challenge traditional hydrogeological investigations. Second, the study demonstrates how combining isotopic and geophysical data can reveal the vertical and lateral extent of groundwater flow systems, essential information for sustainable aquifer management.

The research also highlights the importance of high-elevation areas in maintaining spring discharge in volcanic settings. This understanding is crucial for developing targeted conservation strategies, especially in regions facing increasing pressure from land-use changes and climate variability. Moreover, the methodology developed in this study can be adapted for investigating other springs in volcanic environments, particularly in regions where water resources are under stress from population growth and environmental change.

From a policy perspective, this research provides scientific basis for establishing protection zones around spring recharge areas. By clearly delineating source areas, policymakers can implement evidence-based regulations for land use and development regulations in critical recharge zones. This is particularly relevant in Bali and similar regions where springs serve as vital water sources for both domestic and agricultural needs.

Future research should include long-term monitoring of spring discharge rates and isotopic signatures to understand temporal variations. Conducting detailed hydrogeochemical analyses along identified flow paths, and investigation of potential climate change impacts on recharge processes would provide deeper insights. Additionally, applying this integrated approach to other springs in volcanic settings would help validate its broader applicability and refine the methodology for different geological contexts.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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