Short Communication:

Study of Environmental Isotopes and Hydrochemical Characteristics of Groundwater from Springs at Archaeological Sites in Dompu Regency, West Nusa Tenggara, Indonesia

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Abstract: *The existence of groundwater sources in several springs at archaeological sites in Dompu Regency, West Nusa Tenggara, Indonesia, has been widely used by the surrounding community for various needs. However, from a number of the springs, there are springs whose water discharge has decreased. Meanwhile, from a number of existing springs, there is one spring whose groundwater is used every day even though it tastes a bit brackish. For this reason, it is important to conduct a groundwater study in the area with the aim of knowing the characteristics, preliminary identification of recharge areas and quality of groundwater in the study area through an environmental isotope and hydrochemical. The study was conducted by taking a number of groundwater samples from several archaeological sites in Dompu Regency. The results of environmental isotope and hydrochemical analysis show that there are 2 springs (2 archaeological sites), namely the Riwo and Ncona springs, because these two areas are part of the recharge area, which must be preserved by not clearing forest land. Meanwhile, for the quality of groundwater, of the 5 springs located at the archaeological sites, only the Hodo spring is of "poor quality" with the Na–Cl water type; it is unfit for drinking water.*

Keywords: *Dompu groundwater; groundwater characteristics; isotope, hydrochemical; Dompu archaeological sites; water quality*

INTRODUCTION

In several locations of archaeological sites in Dompu Regency, West Nusa Tenggara, Indonesia, there are springs that are still used by the surrounding community. This use has been going on for a long time, since the Ncuhi period until now. Ncuhi is a tribal community group, according to several sources of information from the Dompu community, which existed before the time of the Dompu kingdom. During the Ncuhi era, although they were still in small groups, the people routinely interacted with the surrounding nature, choosing high places such as hills and mountains as a place to live, which were located close to rivers or springs [1-3]. Meanwhile, in the area around the lowlands near the coast, there is a settlement called Ncuhi Tonda, which also has several springs. The location of the springs is part of an archaeological site, traces of the Dompu kingdom in the past. Until now, some of the springs have been widely used by the local community for various daily needs such as for drinking water, washing and ritual places. However, not all groundwater from springs located at the archaeological sites can be used to meet daily needs, especially for drinking water, because there are springs whose water is unfit for consumption. On the other hand, over time, followed by the development of population, settlements, and the large number of clearings of forest land for plantations, this has the effect of reducing groundwater recharge areas, which greatly affects the decrease in groundwater discharge in some springs at the sites. Also, this causes a reduction in the availability of water that supplies agricultural irrigation. For these reasons, it is very important to conduct a groundwater study in the area with the aim of knowing the characteristics of groundwater (such as meteoric water, evaporation water, water-rock interaction, water type, and hydrochemical control of groundwater), preliminary identification of recharge areas and also to determine the quality of groundwater, especially groundwater that is widely used by the community, both for drinking water and for other daily needs. This study was conducted using environmental isotope (^{2}H, ^{18}O, ^{14}C) and hydrochemical approaches (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-).

■ EXPERIMENTAL SECTION

Materials

The materials used in this study were $BaCl_2$, NaOH, $FeSO_4{\cdot}7H_2O$, ethanol (Merck, Germany), polyacrilamide (BDH Chemicals Ltd, England), Carbosorb-E, Permafluor-E (Perkin Elmer, USA), and liquid nitrogen.

Instrumentation

The instrumentations used in this study were liquid water isotope analyzer DLT-100 (LGR, USA), HTS PAL autosampler (LEAP Technologies, USA), liquid scintillation analyzer 2910TR (Perkin Elmer, USA), ion chromatography 883 Basic IC plus (Metrohm, Switzerland), and automatic potentiometric titrator AT-710 (KEM, Japan).

Study Area

The study area is located in several sub-districts in Dompu Regency, West Nusa Tenggara, Sumbawa Island. Geographically, the study area is located at coordinates between 577122.37–664851.09 mE and between 8995593.97–9104580.58 mS. Archaeologically, the study area is a trace of ancient settlements and is generally located close to water sources. Study activities were carried out in the Districts of Woja, Pajo and Pekat. In Woja District, namely in Riwo Village, there is an important site located in the Tonda hills which has a spring at the foot of the hill, namely the Riwo spring, which is not too far from Cempi Bay. Not too far from the Riwo Spring, there is the Ncona Spring located in Temba Lae Village, Pajo District, which is also not too far from Cempi Bay. Several locations that were considered important in the past include the beach, which has springs, namely in Pekat District, south of Mount Tambora, which has three springs, namely the Hodo, Rao and Wau springs. A map of the location for taking water samples from several springs in Dompu Regency can be seen in Fig. 1.

Procedure

Water sampling

Sampling for environmental isotope analysis of ^{18}O and ^{2}H was carried out by taking 30 mL of groundwater samples into an airtight bottle. Air bubbles in bottles should be avoided to prevent evaporation [4]. For environmental radioactive isotope analysis, ^{14}C was taken in the form of precipitated $BaCO_3$ carbonate, which was put into a 1 L plastic bottle. Meanwhile, for hydrochemical analysis, about 300 mL was taken, which was put into a plastic bottle.

Analysis of environmental isotopes (^{2}H, ^{18}O, ^{14}C)

Analysis of stable isotopes was done by laser spectroscopic method, i.e., using Los Gatos research (LGR) DLT-100 liquid water isotope analyzer. The composition of isotopes is expressed as relative ratio (δ) against standard mean oceanic water (SMOW) as Eq. (1) [5];

$$\delta = \frac{\text{Rsample} - \text{RSMOW}}{\text{RSMOW}} \times 1000‰ \quad (1)$$

where δ: $\delta^{2}H$ or $\delta^{18}O$ (in unit ‰) and R : $^{2}H/^{1}H$ or $^{18}O/^{16}O$.

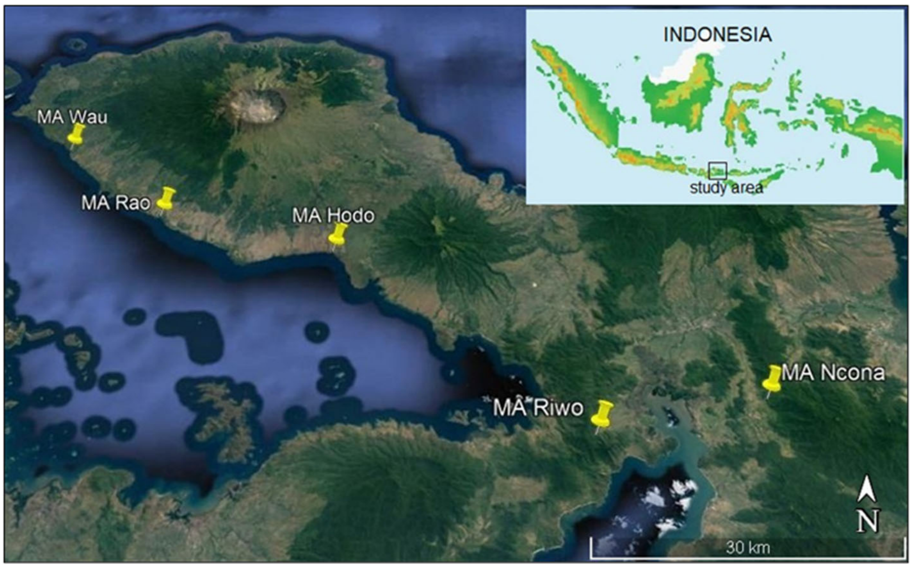

Fig 1. Map of the location of groundwater sampling in the study area

The ^{14}C isotope analysis was carried out using the CO_2 Absorption method on a series of absorption line devices. This method involves a solution of Carbosorb-E/Permafluor-E to absorb CO_2 into a solution of carbamate [6]. Meanwhile, the counting process for the ^{14}C isotope in the carbamate solution was carried out using a liquid scintillation analyzer (LSA).

Analysis of hydrochemical

Analysis of hydrochemicals was done by the following methods: for HCO_3^- using autotitrator, while for Cl^-, SO_4^{2-}, F^-, NO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, using ion chromatography.

■ RESULTS AND DISCUSSION

Environmental Isotope Characteristic

Table 1 shows the analysis results of stable environmental isotopes (^{18}O, ^{2}H) and environmental radioactive isotope ^{14}C from groundwater samples taken from springs at archaeological sites in the study area. From the results of the ^{14}C isotope analysis of groundwater dating from water samples taken from several spring locations in the study area, it can be seen that the age of the groundwater is 320 years BP, and the oldest is 3860 years BP (BP = before present = before 1950, the modern reference international standard for measuring the isotope ^{14}C, where 100 percent Modern Carbon = 0.95 activity of oxalic acid standard). However, the results of this groundwater age analysis must be corrected according to the geological conditions of the study area [7]. According to Geyh, groundwater discharge somewhere does not reflect 100 percent Modern Carbon (pMC), during infiltration [8], this is due to the influence of the dissolution of carbonate from rock along its path. Dissolved carbonates from rocks tend to give a much older age than they should [9]. For this reason, it is necessary to correct the age of groundwater according to the dominant rock type in the study area so that the corrected age is obtained.

The study area is a volcanic area, so to correct the corrected age results, the initial activity between 90–100 pMC is taken. If the initial activity of 95 pMC is taken, then the corrected age data is obtained, as can be seen in Table 1. It can be seen that groundwater from Riwo and Ncona springs have groundwater age of 115 years BP and Modern, respectively, classified as young groundwater age, indicating that the area around the two springs is part of the recharge area of groundwater so that the area should be reforested by planting trees that are able to bind water during the rainy season and most of it can be deposited in groundwater aquifers [10]. The Hodo spring has a relatively old water age of 3550 years BP or has a longer storage period in the aquifer than other springs [11]. Meanwhile, the Rau and Wau springs have a relatively younger age than the Hodo springs,

Table 1. The results of isotopes of ^{18}O, ^{2}H and ^{14}C analysis of the springs in the study area

Springs location	Coordinate	Elevation (m asl)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{14}C activity (PMC)	^{14}C Age (uncorrected, yr BP)	^{14}C Age (empirical model with A_0=95 pMC, yr BP)
Hodo spring	619058.83 mE, 9065746.13 mS	1	−5.17	−33.2	61.84	3860	3550
Rau spring	598116.94 mE, 9071183.80 mS	1	−5.61	−32.9	79.97	1795	1425
Wau spring	585285.98 mE, 9082320.33 mS	1	−5.77	−34.0	81.16	1675	1300
Riwo spring	646211.84 mE, 9041899.79 mS	163	−4.82	−28.0	93.71	520	115
Ncona spring	664987.79 mE, 9046194.42 mS	139	−4.05	−22.3	96.08	320	Modern

namely 1425 years BP and 1300 years BP, respectively; it is also very important to conserve the recharge area. The Hodo, Rau, and Wau springs probably originate from the recharge area on the slopes of Mount Tambora.

Based on the analysis of stable environmental isotopes of ^{18}O and ^{2}H, it can be seen that the variation of isotope values for $\delta^{18}O$ and $\delta^{2}H$ in the study area varies from −5.61 to −4.05‰ for $\delta^{18}O$ and between −33.2 to −22.3‰ for $\delta^{2}H$. Furthermore, the values of the isotopes $\delta^{18}O$ and $\delta^{2}H$ are plotted in the form of a graph of the relationship between $\delta^{2}H$ vs $\delta^{18}O$, as shown in Fig. 2. From the graph, it can be seen that Wau and Rau's springs have relatively the same environmental isotope values of $\delta^{18}O$ and $\delta^{2}H$, this indicates that the water from the two springs originates from the relatively similar recharge elevation on the slopes of Mount Tambora with the age of the groundwater is also relatively similar as described above. Also, Fig. 2 shows that the Hodo spring probably originates from the same infiltration elevation as the Wau and Rau springs, but when it enters the groundwater aquifer system, it passes through the deeper aquifer layers and dissolves silicate minerals such as plagioclase feldspar {$(Ca,Na)AlSi_3O_8$} at the depth of the aquifer so that the groundwater of the Hodo spring shows the phenomenon of oxygen shift due to the interaction between oxygen from water and oxygen from silicate minerals [12-13]. The Hodo spring groundwater flow through this deeper aquifer layer is supported by its ^{14}C isotope data, which results in a relatively older groundwater age compared to other springs as described above. Furthermore, for Riwo Spring, which is at an elevation of 163 m above sea level and the groundwater

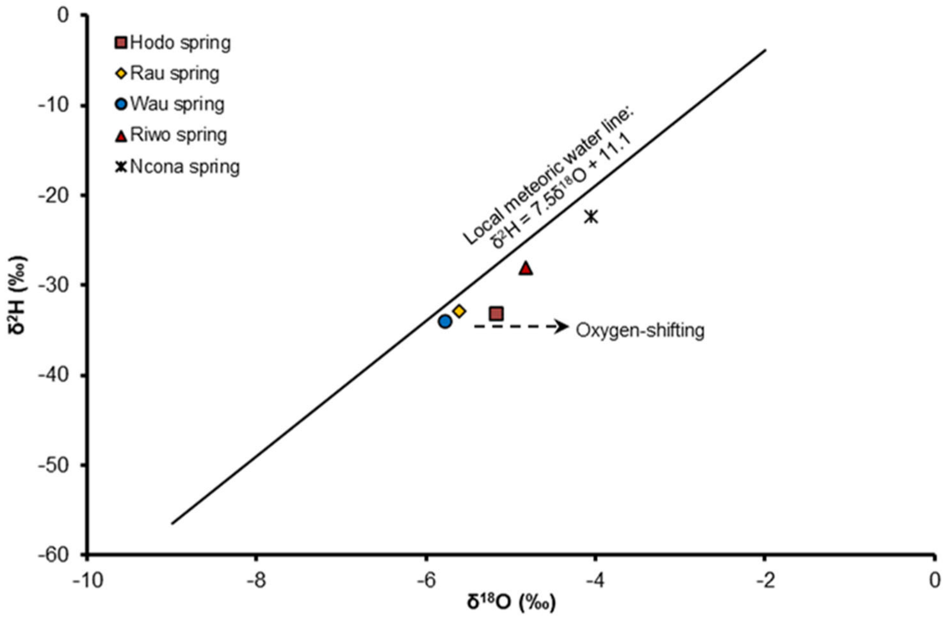

Fig 2. Isotope graph of $\delta^{2}H$ vs $\delta^{18}O$ groundwater from springs in the study area

age is around 115 years BP, it indicates that the recharge area is at an elevation above it. Because the age of the water is relatively young, the area at an elevation above the spring is a recharge area that must be preserved. Likewise, with the Ncona spring, the groundwater is of the modern age, and the isotopic value ($\delta^{18}O$, $\delta^{2}H$) is more enriched than the previous 4 springs; the Ncona spring area is part of a groundwater recharge area that really needs to be preserved for trees that are in the vicinity and no new land is cleared for plantations or settlement.

Hydrochemical Characteristic

Hydrochemical composition and water type

Table 2 shows the results of hydrochemical analysis of groundwater from springs at archaeological sites in the study area with an average ionic balance of 2.69%. In general, the groundwater of Hodo Spring has a higher cation-anion composition than other springs. This is in line with the results of isotopic analysis of ^{18}O, ^{2}H and ^{14}C, which indicated that the Hodo Spring originated from deep aquifer flows which were characterized by high concentrations of Na^{+} reaching 300.58 mg/L and Cl^{-} at 470.45 mg/L. In addition, the high sulfate (SO_4^{2-}) in the Hodo Spring is probably caused by deposits of sulfate minerals (such as gypsum, $CaSO_4{\cdot}2H_2O$) [14], which are deposits of the remnants of the past eruption of Mount Tambora dissolved in groundwater flows. The concentration of Na^{+} and Cl^{-} ions from Hodo Spring also exceeds the threshold for drinking water health requirements based on the Minister of Health of the Republic of Indonesia No. 492 in 2010, and the WHO standard in 2011 are 200 and 250 mg/L, respectively. The hydrochemical compositions of other springs, namely Rau, Wau, Riwo, and Ncona, have ion concentrations below the threshold for drinking water health requirements, so they are safe for drinking water and for other daily needs.

Based on the Piper diagram (Fig. 3), it is shown that groundwater from the Hodo spring has the water type of Na–Cl, which is the character of salt water or brackish water. Meanwhile, for Ncona and Riwo springs, the water type is Ca–Mg–HCO_3, indicating the dominant hydrochemical composition originated from dissolving minerals such as dolomite. The water type of Ca–Mg–HCO_3 from the two springs also indicates that the surrounding area is a groundwater recharge area for groundwater in the discharge area at the elevation below. This is in line with the results of isotope analysis, especially the ^{14}C isotope, which obtained a Modern age and close to Modern age. Furthermore, Rau spring has the

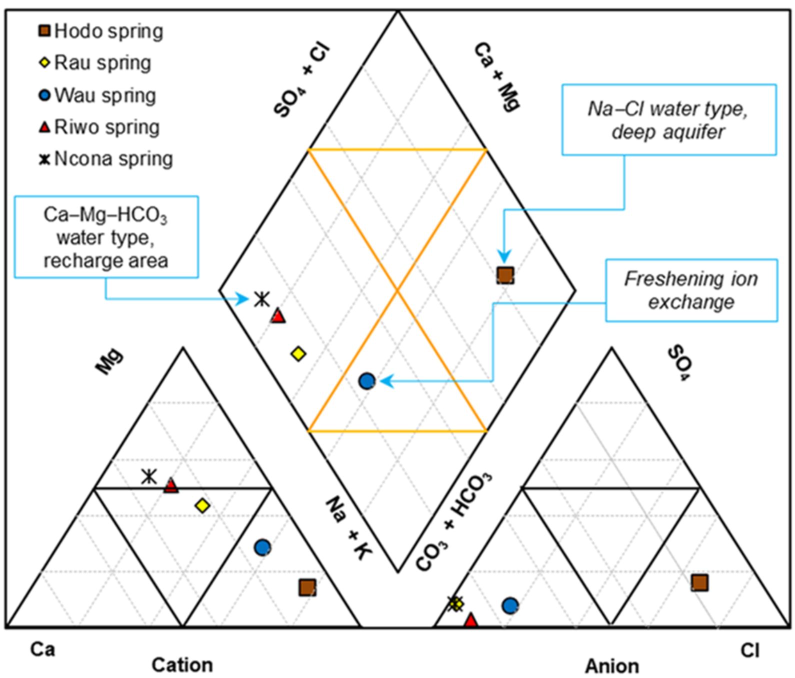

Fig 3. Piper diagram of groundwater from springs in the study area

Table 2. The results of hydrochemical analysis of groundwater in the study area

Spring location	Cation-anion (mg/L)								% balance	TDS	Total hardness	pH
	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-				
Hodo	300.58	50.02	27.59	30.34	470.45	211.12	160.61	1.36	4.87	1254	193.8	7.31
Rau	24.44	15.22	14.57	16.81	2.72	204.54	16.23	2.36	3.29	298	105.6	6.98
Wau	34.14	9.51	7.05	9.16	18.09	142.00	12.55	0.88	4.69	235	55.3	7.90
Riwo	22.95	4.37	27.11	29.82	15.58	263.43	7.62	0.35	0.04	371	190.5	7.14
Ncona	12.58	2.09	26.92	26.92	3.02	229.40	17.27	0.01	0.54	319	178.1	6.28

Table 3. Hydrochemical characteristics of spring groundwater in the study area

Spring location	Cation-anion concentration	Water type	Groundwater status
Hodo	Na, Cl and SO_4 exceed the threshold	Na–Cl	Brackish
Rau	Normal	Ca–HCO_3	Freshwater
Wau	Normal	Mixed type	Freshwater
Riwo	Normal	Ca–Mg–HCO_3	Freshwater
Ncona	Normal	Ca–Mg–HCO_3	Freshwater

water type of Ca–HCO_3, which is the dominant hydrochemical composition originating from the dissolution of calcite minerals. Meanwhile, Wau spring has mixed Ca–Na–HCO_3 water type with dominant Na^+ and HCO_3^- ions, indicating an exchange of Ca^{2+} or Mg^{2+} ions from groundwater replaced by Na^+ from silicate minerals through a freshening process so that the concentration of Na^+ ions in groundwater increases. The different water types between Hodo spring (Na–Cl) and other springs indicate differences in genesis and differences in the aquifer through which groundwater passes, as described in the discussion above [15]. Table 3 shows the hydrochemical characteristics based on the cation-anion concentration, water type and groundwater status of the springs in the study area.

Hydrochemical control of groundwater

Based on the Gibbs diagram, in general, there are three types of processes that control the chemical mechanism of groundwater, namely precipitation or rainfall, evaporation crystallization, and rock-water weathering in a study area [16-17]. Gibbs made a simple but effective diagram using TDS vs $Na^+/(Na^+ + Ca^{2+})$ and TDS vs $Cl^-/(Cl^- + HCO_3^-)$ ratios to identify factors influencing the hydrochemical of groundwater [18-19]. Fig. 4(a) and 4(b) show the hydrochemical processes in water samples from springs in the study area. It can be seen that the hydrochemical of Hodo spring is controlled by the dissolution process or rock-water weathering dominance. While other springs, especially Riwo and Ncona springs, tend to be controlled by rainwater or depend on relatively high rainwater, during long dry seasons, not much groundwater reserves are deposited or stored properly in the aquifer. This condition is probably due to reduced recharge areas around the two springs due to reduced forest land. The following Table 3 shows the hydrochemical characteristics based on the cation-anion concentration, water type and groundwater status of the springs in the study area.

Groundwater quality

Another characteristic of the five springs is the water quality index (WQI), which is calculated based on the hydrochemical data above. Table 4 shows the hydrochemical parameters used to calculate WQI of the groundwater in the study area.

As a reference in determining the WQI, the 2011 WHO international standard on the 2011 WHO guidelines for drinking water quality was used [20-21]. Based on the results of the WQI calculation, as can be seen in Table 5, Hodo Spring it has a value of 140.24 with the status of "poor water" or water that is not suitable for drinking water, while groundwater from other springs has the status of "good water" and "excellent water".

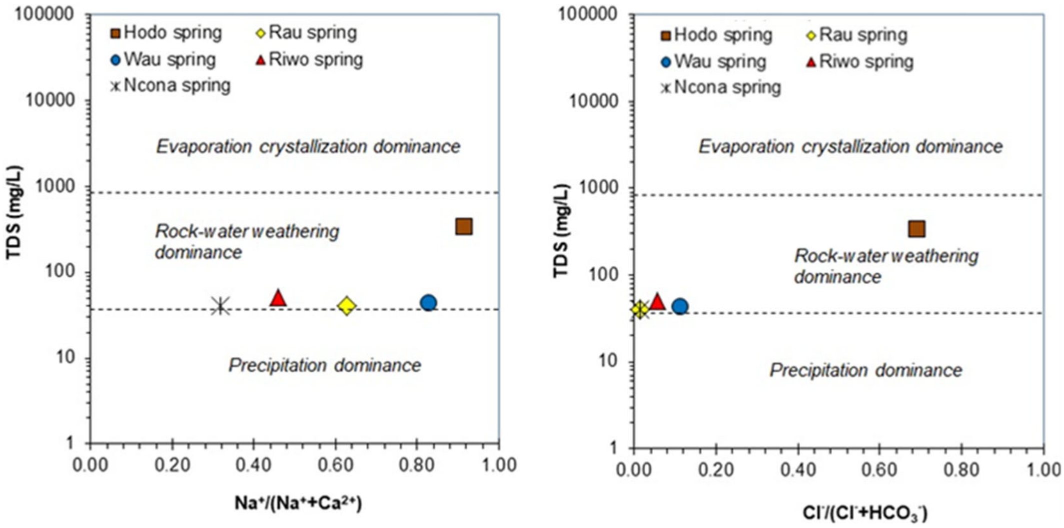

Fig 4. Hydrochemical control of groundwater from springs in the study area

Table 4. The hydrochemical parameters for calculating WQI of groundwater from springs in the study area

Parameter	Weight (W_i)	Relative weight (W_i)	Maximum concentration (WHO Standard, 2011), C_i
Na^+	4	0.129	200 mg/L
K^+	3	0.097	12 mg/L
Ca^{2+}	4	0.129	100 mg/L
Mg^{2+}	4	0.129	50 mg/L
Cl^-	3	0.097	250 mg/L
HCO_3^-	2	0.065	125 mg/L
SO_4^{2-}	1	0.032	250 mg/L
NO_3^-	1	0.032	50 mg/L
Hardness	2	0.065	500 mg/L
pH	4	0.129	6.5–8.5
TDS	3	0.097	600 mg/L

Table 5. Calculation results of groundwater quality from springs in the study area

Spring location	WQI	Groundwater quality
Hodo	140.24	Poor water
Wau	41.07	Excellent water
Rau	51.21	Good water
Riwo	53.86	Good water
Ncona	45.77	Excellent water

■ CONCLUSION

Isotope and hydrochemical characteristics of several springs at archaeological sites in Dompu Regency, i.e., Riwo and Ncona springs with Ca–Mg–HCO_3 water type have a groundwater age of 115 years BP and Modern, respectively, classified as young groundwater age. The area of these two springs is part of the recharge area, which is controlled by the presence of rainwater, so this area really needs reforestation, and no new land clearing is carried out in the existing forest. Hodo spring is typical of brackish water with Na–Cl water type, the age is relatively old compared to other springs and flows through deep aquifers. Meanwhile, the high concentration of SO_4^{2-} ion but has a relatively neutral pH in the Hodo spring is thought to come from sulfate mineral deposits (such as gypsum) which are dissolved in groundwater. The sulfate mineral deposit itself is estimated to be a product of the volcanic activity of Mount Tambora in the past; The results of the calculation of the water quality index, except for the Hodo spring, other springs are still classified as freshwater which fulfills health requirements as groundwater suitable for drinking water.

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■ AUTHOR CONTRIBUTIONS

I Nyoman Rema designed and directed the study. Sonny Christophorus Wibisono and Luh Suwita Utami provide a description of the Dompu civilization and the Dompu archaeological site. Nyoman Arisanti, I Gusti Ngurah Jayanti and I Wayan Rupa were involved in sampling in the study area. Satrio carried out data processing, data interpretation and wrote articles.

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