Isotopes and Groundwater Recharge

by Putu Ardana

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The Stable Isotopes Approach as Tracers to Investigate the Origin of Groundwater In The Unconfined Aquifer of Denpasar, Bali

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Abstract

Groundwater plays an elemental role in the supply of water for numerous purposes, so the use of groundwater must also pay attention to the balance and preservation of the resource itself. Knowing the origin of the groundwater and the recharge area on an aquifer is essential to determine the conservation model. The purpose of this research is to determine the Denpasar Meteoric Water Line (DMWL), the recharge area, and the origin of groundwater in the unconfined aquifer of Denpasar. The determination of the number and location of samples, both rainwater samples, and groundwater samples, using a purposive sampling approach. A total of 5 samples of rainwater and 18 samples of groundwater were taken at several locations in the Denpasar area. The stable isotopes of $\delta^{18}O$ and $\delta^{2}H$ were carried out using laser spectrometry Picarro L2130-i. This research shows the Denpasar LMWL is $\delta D = 8.5839 \text{ x } \delta^{18}O + 19.876$; from the distribution of oxygen-18 isotope, the low ^{18}O value is dominated in the North and Northeast areas, so here this area can be delineated as the potential recharge area; and based on the isotope ratio, groundwater in the unconfined aquifer of Denpasar can be divided into three geneses groups: (a) Groundwater Genesis-A and B groups represent groundwater systems that come from direct rainfall as well as local recharge with low (depleted) to moderate $\delta^{18}O$ and $\delta^{2}H$ isotope ratios and groundwater groups Genesis-C, which has high (enriched) $\delta^{18}O$ and $\delta^{2}H$ isotope ratios, is located below the slope of the DMWL.

Keywords
Groundwater, isotopes, local meteoric water line, genesis, recharge, depleted, enrich

Introduction

Groundwater presents one of the most important water resources in the world. Groundwater is of crucial position in water resources planning, development, and management (Kumar C & Singh, 2015). The tourism industry, modernization, and population growth that have occurred on the island of Bali in recent years have greatly affected groundwater resources, especially in the city of Denpasar. The city of Denpasar is one of the most populous cities in Eastern Indonesia, with around 725 thousand people (BPS Kota Denpasar, 2021). This puts pressure on the water supply for the entire city, as surface water is more polluted, and there is a high risk of groundwater depletion. If this phenomenon is not controlled, it will impact on the quantity and quality of groundwater, such as land subsidence, water quality degradation and seawater intrusion. Uncontrolled exploitation of groundwater will have a negative impact on the natural balance itself. Numerous solutions to the water supply problem in Denpasar City have been proposed, including utilizing surface water as the primary source of the drinking water supply system (Fakultas Teknik Universitas Udayana, 2014) and utilizing artificial recharge wells or domestic rainwater harvesting well (L. Sudiajeng, Wiraga, Mudhina, Waisnawa, & Sudiarsa, 2020; Lilik Sudiajeng, Wiraga, Parwita, & Santosa, 2017) as a groundwater conservation program (L. Sudiajeng, Parwita, Wiraga, & Mudhina, 2018). These techniques are not sustainable unless and until the source of the groundwater and recharge area is elucidated. Besides, knowing the source or origin of the groundwater and the recharge area on an aquifer is essential to determine the conservation model. There is no clear information regarding the origin of groundwater and the potential recharge area in Denpasar City.

The use of environmental tracers to provide leads in hydrological studies is a well-established practice that aids in the initial conceptualization of hydrological systems at the local and regional scales. The isotopes ^{18}O and ^{2}H are environmental tracers because they are conservative (Kendall & McDonnell, 1998; Pu et al., 2013; Sánchez-Murillo, Brooks, Elliot, & Boll, 2015), that is, it is not affected by the water-rock interaction process at low temperatures (Marfia, Krishnamurthy, Atekwana, & Panton, 2004). In addition, changes in the isotopes of oxygen and hydrogen composition depend on temperature, latitude, longitude, and altitude and are controlled by evaporation and condensation (Craig, 1961; Dansgard, 1964). Natural tracers have been used in a variety of applications, including contaminant hydrogeological studies (Datta, Deb, & Tyagi, 1996; F. Ma, Yang, Yuan, Cai, & Pan, 2007; Nisi, Raco, & Dotsika, 2016; Parlov, Kovač, Nakić, & Barešić, 2019), studies of groundwater residence periods in basins (Banks et al., 2020; Koh, Ha, Lee, Yoon, & Ko, 2012; B. Ma, Jin, Liang, & Li, 2019), assessments of groundwater recharge (Adomako, Maloszewski, Stumpp, Osae, & Akiti, 2010; Hendrayana, Nuha, & Wijatna, A.B. Muhammad, 2019; Huang & Wang, 2017; Oiro, Comte, Soulsby, & Walraevens, 2018; Scanlon et al., 2006; Wu, Wang, Zhang, & Cui, 2016), assessment of the hydraulic properties of certain aquifers (Mattei et al., 2020), tracing hydrological flow paths (Rodgers, Soulsby, Waldron, & Tetzlaff, 2005) and mixing of groundwater from different sources (Chen, Yin, Xie, & Feng, 2014; Huang & Wang, 2018).

In this paper, the use of δ^{2}H and δ^{18}O isotopes to identify the groundwater origin and delineate the recharge area of Denpasar City as a downstream area in the Tabanan-Denpasar groundwater basin with a high level of community clean water demand. The research objectives were (1) to determine the Local Meteoric Water Line (LMWL) of the unconfined aquifer of Denpasar, (2) to determine the groundwater recharge area for the unconfined aquifer of Denpasar, and (3) to determine the genesis or origin of groundwater that appears in the unconfined aquifer of Denpasar. When groundwater sources are understood, better decisions can be made about the sustainable water supply.

Materials and Methods

Study Sites.

The study site was in Denpasar City, located in the southeast of Bali Island, which lies between 08º36'56"S - 08º42'01"S and 115º10'23"E - 115º16'27"E and covers an area of 127,78 km^{2}, respectively, shown in Figure 1. Denpasar City consists of four sub-districts: West Denpasar, North Denpasar, East Denpasar, and South Denpasar. From the area's height, East Denpasar, Denpasar West, and North Denpasar are at altitudes 0-75 meters above sea level. Meanwhile, Denpasar District South is 0-12 meters above sea level. Average air temperature in Denpasar City in 2020 ranges from 26.3°C up to 28.3°C. Temperature amplitude during 2020 is relatively lower than in 2019, where the average temperature of Denpasar last year was in the range of 24.2°C to 32.8°C. Meanwhile, the highest rainfall occurred in February, which reached 388.5 millimetres, where the annual average precipitation was 1.595,7 millimetres. Air humidity in 2020 is 77-81 percent in the field, with pressure air getting 1,011.9 millibars. The average wind speed during 2020 was recorded at 5.35 knots (BPS Kota Denpasar, 2021). As the central city of Bali Province, Denpasar City has a prosperous economy supported by a rapidly growing tourism sector. This is what causes an increase in population each year (930.6 thousand in 2018; 947.1 thousand in 2019, and 725.314 thousand in 2020) which has a linear impact with an increase in the necessities of life, especially clean water.

Fig. 1. The location of the study area

Geological and hydrogeological setting

The study area is located southeast of Bali island. Bali island is composed of a variety of volcanic morphologic units such as eroded early quaternary volcanoes, active stratovolcanoes, thick tephra deposits, pyroclastic flow slopes and closed caldera lakes (Purnomo and Pichler, 2015). Denpasar City consists of Holocene volcanic products and marine sediment in the south. The exposure of basement rocks observed are the Buyan-Bratan group and Batur volcanic were formed from mainly tuff and lahar (Qpbb) (Rai, Shoba, Schegolkova, Dzhamalov, Venitsianov, Santosa, Adnyana, Sunarta & Suada, 2015), shown in Figure 2.

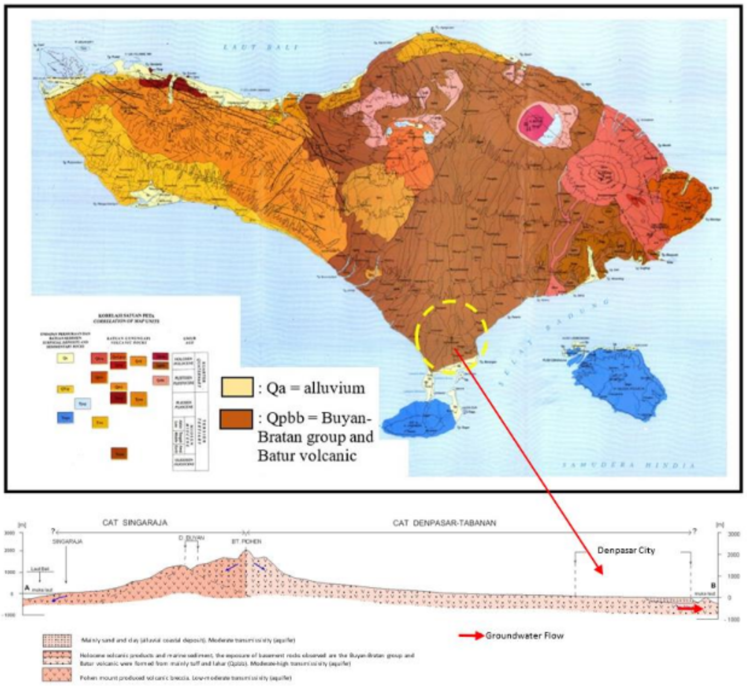

Fig. 2. The geological map of Bali island and Denpasar

The aquifer in the Denpasar area is a discharge area from the Tabanan-Denpasar groundwater basin. Based on the lithological composition of rocks and their permeabilities, the Denpasar area is young volcanic products consisting of volcanic breccias, sandy tuffs, and laharic deposits mostly composed of unconsolidated materials sands to boulders grained size, locally lavas. Moderate to high permeability, especially high in laharic deposits and vesicular lavas. Whereas based on the occurrence of groundwater and productivity of aquifer, Denpasar is divided into two types, namely aquifer in which flows is intergranular and aquifer in which flow both through fissures and interstices. The aquifer in which flows are intergranular with an extensive and highly productive aquifer. This aquifer has moderate to high transmissivity, water table or piezometric head of generally near land surface with more than 10 l/sec wells yield. In the north of Denpasar, the aquifer type is aquifer in which flow both through fissures and interstices with an extensive and highly productive aquifer. The aquifer of largely varying transmissivity, and depth to the water table varies in a wide ring, and wells generally yield more than 5 l/sec (Sudadi, Setiadi, Denny, Arief, Ruchijat & Hadi, 1986). The depth of the aquifer in Denpasar ranges from 2 to 160 meters in East Denpasar with rock compositions of sand, sandstone, compact sand, loose sand, clay sand, volcanic ash/tuff, and gravel (Buana, Wiyanti, & Suyarto, 2019).

In South Denpasar, the depth of aquifers is 24 meters with a rock composition of medium-sized sand and brown sand, which is an aquifer that can drain and store medium-sized groundwater wells and has a high graduation rate of medium-sized sand and medium-sized brown sand (Wahyuni, Suyarto, & Kusmiyarti, 2019). The depth range of 2 to 20 meters in West Denpasar with rock compositions of black sand, loamy sand, and breccia (Lestari, Trigunangsih, & Wiyanti, 2019), and North Denpasar with a depth of 22 to 64 meters with rock composition sandy tuff and sandstone (Wahyuni, Suyarto, & Kusmiyarti, 2019). Based on the hydrogeological conditions, the Denpasar area is dominated by shallow aquifer or unconfined aquifer. The hydrogeological settings are shown in Figure 3.

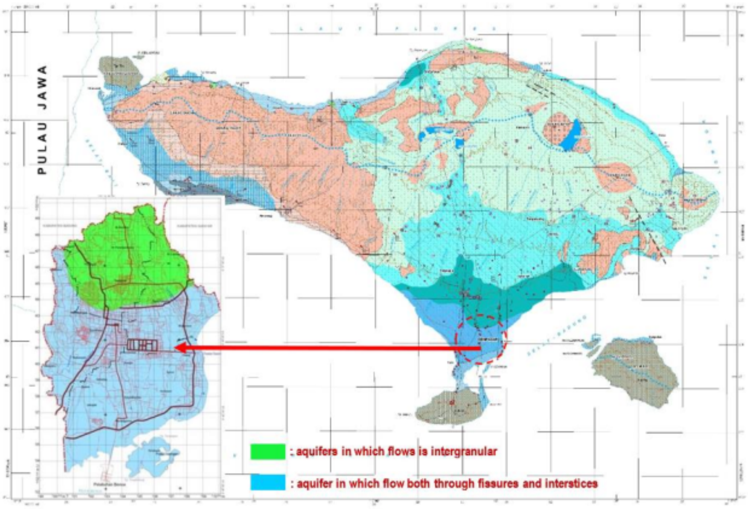

Fig. 3. The hydrogeological map of Bali island and Denpasar

Research Methods

The research method is divided into secondary data collection, field survey, and laboratory analysis. The secondary data collected were the geological, hydrogeological, and groundwater basin map of the island of Bali, and the map of groundwater flow and hydraulic conductivity in the unconfined aquifer of Denpasar. The field survey method includes the placement of rainfall storage equipment, and measurement of the coordinates of the position of rain collectors, dug wells, drilled wells, deep wells, and springs. This research was conducted using composition analysis ^{18}O and ^{2}H against the water sample from five rainwater samples that have taken from the Denpasar area with different elevations and from hydrogeological objects in the form of dug well, boreholes, deep boreholes, and spring water, shown in Figure 4. The determination of the number and location of samples, both rainwater samples and groundwater samples, using a purposive sampling approach. Fieldworks are performed for sampling water from December 2020 until March 2021, and for rainwater, the sample is taken three times at significant different rainfall i.e January, February, and March 2021. A sampling of rainwater which was carried out from January to March was based on data on the characteristics of rainfall in the previous period in the study area where the month had a significant difference in the average monthly rainfall. Eighteen water samples were collected from different water sites. Samples for stable isotopes analysis were collected in a polyethylene bottle of 100ml. The stable isotopes analyses were carried out using laser spectrometry Picarro L2130-i in the Hydrogeology and Hydrogeochemistry Laboratory Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology (ITB).

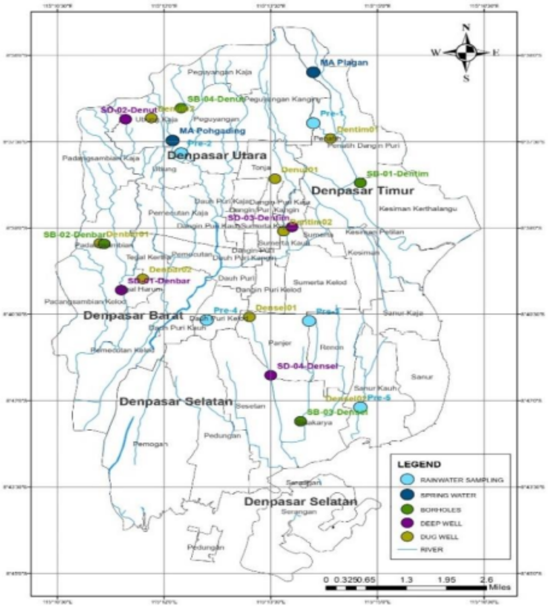

Fig. 4. The location of the groundwater and precipitation samples

The research procedure can be described by the following flow chart shown in Figure 5.

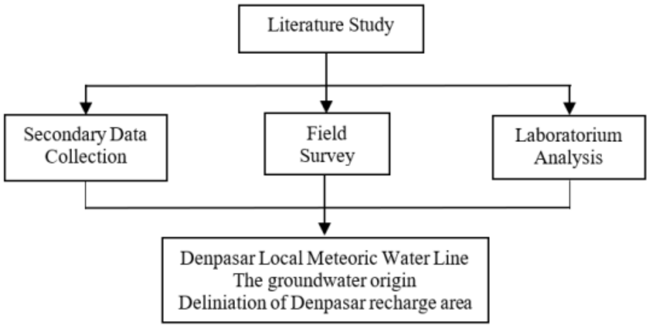

Fig. 5. The location of the groundwater and precipitation samples

The abundance of ^{18}O and ^{2}H in water is not measured absolutely but in the form of abundance relative to a reference standard V-SMOW, originally defined by the International Atomic Energy Agency. The ^{2}H/^{1}H and ^{18}O/^{16}O isotope ratios are measured and analyzed to determine the effect of elevation and precipitation on the isotopic composition of rainwater. Following that, the equations derived from the study of the effect of elevation on the isotopic composition (^{18}O, D) of precipitation falling on the Denpasar City subsystem are referred to as the Denpasar Meteoric Water Line (DMWL) equation. The source of groundwater can be determined using equations relating to the effect of elevation on the ^{18}O isotope ratio. The value of ^{2}H and ^{18}O isotope ratio from rainwater samples is expressed relative to SMOW and using Equation 1 (Clark, 2015; Kresic & Stevanovic, 2010):

$$\delta = \frac{R_{sample}-R_{std}}{R_{std}} \; x \; 1000 \text{‰} \tag{1}$$

With:

R_{sample} = isotope ratio ($^{2}H/^{1}H$ for hydrogen and $^{18}O/^{16}O$ for oxygen) of water sample
R_{std} = isotope ratio ($^{2}H/^{1}H$ for hydrogen and $^{18}O/^{16}O$ for oxygen) of sea water
δ = isotope ratio ($^{2}H/^{1}H$ for hydrogen and $^{18}O/^{16}O$ for oxygen) of water sample relative to the SMOW, ‰

The slope of the oxygen and hydrogen isotopes meteoric water line is proportional to the temperature relationship between δD and $\delta^{18}O$ during condensation, whereas the intercept value is determined by the evaporative conditions in the water source region. The majority of precipitation on a global scale generally follows this pattern. Additionally, the intercept is referred to as deuterium excess (DE) (Dansgard, 1964). The DE in water is useful for studying the movement of water at the atmosphere–biosphere–lithosphere interfaces. This parameter can more reliably identify evaporation than the slope of the δD vs ^{18}O line, because the latter can be greater than the slope of the recharging sources when the sources are variable, potentially leading to the incorrect conclusion that no evaporation occurred (Barnes & Turner, 1998). The DE values of water samples were estimated using the relation defined by Dansgaard (Dansgard, 1964) and using Equation 2:

$$d = \delta^{2}H - 8 \; x \; \delta^{18}O \tag{2}$$

Rainwater samples have a lower ^{2}H and ^{18}O ratio than seawater samples do, as the higher the elevation, the slower the temperature, the more vapor condenses. Rainfall at this higher elevation results in a decrease in the ^{2}H and ^{18}O isotope ratios. As a result of this phenomenon, groundwater at a higher elevation has a lower ^{2}H and ^{18}O value than groundwater at a lower elevation.

Apart from elevation, the ^{2}H and ^{18}O values are also affected by precipitation. The more precipitation, the more the ^{2}H and ^{18}O ratios of rainwater are depleted; the less precipitation, the more enriched. Due to the fluctuation of precipitation, pressure, air temperature, and relative humidity, the values of ^{2}H and ^{18}O in each sample location should be calculated using Equation 3 and 4 (Clark, 2015; Kresic & Stevanovic, 2010).

$$\delta^{18}O = \frac{\sum_{i=1}^{n} P_i \delta_i{}^{18}O}{\sum_{i=1}^{n} P_i} \tag{3}$$

$$\delta^{2}H = \frac{\sum_{i=1}^{n} P_i \delta_i{}^{2}H}{\sum_{i=1}^{n} P_i} \tag{4}$$

With:

$\delta^{18}O$ = average isotope ratio ^{18}O relative to SMOW in rainwater, ‰
$\delta^{2}H$ = average isotope ratio ^{2}H relative to SMOW in rainwater, ‰
$\delta_i{}^{18}O$ = isotope ratio ^{18}O relative to SMOW in rainfall to (i), ‰
$\delta_i{}^{2}H$ = isotope ratio ^{2}H relative to SMOW in rainwater to (i), ‰
P_i = amount of rainfall between the sample (i-1) to (i), mm per month

In some rainwater samples, the values of ^{2}H and ^{18}O are linear and follow Equation 5, referred to as the LMWL. The research established that for non-evaporated rainwater, equation 4 is highly dependent on geographical variables, most notably temperature, humidity, thickness, and precipitation. Given that d = 10 for rainwater samples collected globally at 91 rainfall stations, it can be written as the Global Meteoric Water Line (GMWL) (Clark, 2015; Craig, 1961; Kresic & Stevanovic, 2010), as shown in Equation 6.

$$\delta D, \text{‰} = a \; x \; \delta^{18}O + d\text{‰} \tag{5}$$

$$\delta D, \text{‰} = 8 \; x \; \delta^{18}O + 10\text{‰} \tag{6}$$

Results and Discussion

Stable isotopes in precipitation.

Considering the location of rainwater samples, Table 1 shows the coordinate data for rainwater samples collected in Denpasar City. On the location map, the coordinates of rainwater samples are plotted, as shown in Figure 4.

Tab. 1. Coordinates and elevation of rainwater samples

Code	Location	Latitude	Longitude	Altitude (masl)
Pre-1	Penatih	8°37'11"S	115°14'05"E	74
Pre-2	Ubung	8°37'42"S	115°12'15"E	52
Pre-3	Panjer	8°40'37"S	115°14'01"E	16
Pre-4	Sanglah	8°40'36"S	115°12'35"E	15
Pre-5	Sanur	8°42'07"S	115°14'44"E	5

Table 2 illustrates the method for determining the rainwater isotope ratio relative to SMOW and in conjunction with the effect of precipitation at each elevation. The value data $(D)_{SMOW}$ and $(^{18}O)_{SMOW}$ have been adjusted to account for the factors affecting the variability of rainwater hydroisotope ratios. Precipitation data at the sampling location is carried out in situ, namely by placing a simple and regularly measured rainwater collection device every month (during sampling).

Tab. 2. Isotope ratio data of rainwater samples as the function of elevation

Code	Location	Average isotope compotition	
		$\delta^{18}O$, ‰	$\delta^{2}H$, ‰
Pre-1	Penatih	-8.649	-54.617
Pre-2	Ubung	-7.588	-45.051
Pre-3	Panjer	-7.700	-45.980
Pre-4	Sanglah	-7.341	-43.937
Pre-5	Sanur	-7.663	-45.300

The rainwater samples collected at low elevation have a more enriched isotope composition, with -7,663 for $(^{18}O)_{SMOW}$ and -45,30 for $(D)_{SMOW}$; on the other hand, rainwater samples collected at a high elevation have more depleted isotope ratios, with -8,649 for $(^{18}O)_{SMOW}$ and -54,617 for $(D)_{SMOW}$. The results of this measurement are consistent with the theory that states that as elevation increases, the isotope composition $(D)_{SMOW}$ and $(^{18}O)_{SMOW}$ in rainwater becomes depleted, and conversely. If the isotope ratio variation data for (D) SMOW and $(^{18}O)_{SMOW}$ rainwater samples as a function of elevation in Table 2 are plotted on the graph ^{18}O - D, the graph shown in Figure 6 and the Denpasar Meteoric Water Line (DMWL) equation are obtained as follows:

$$\delta D = 8{,}5839 \; x \; \delta^{18}O + 19{,}876 \tag{7}$$

with value of $R^2 = 0{,}9846$.

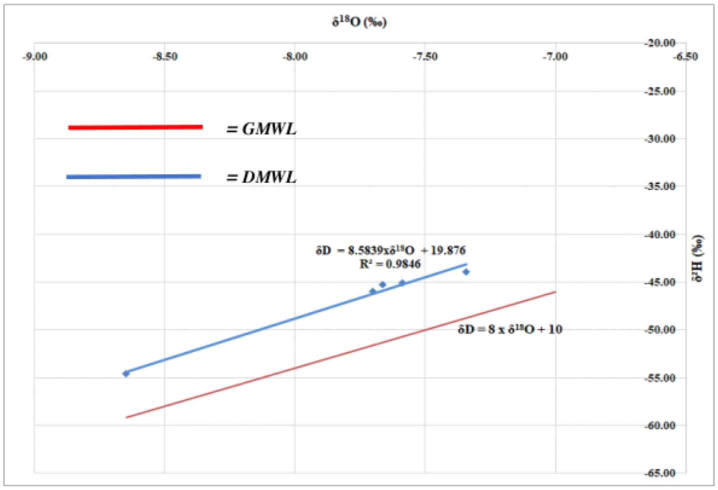

Fig. 6. DMWL and GMWL curve

Stable isotopes in groundwater

The results of ^{18}O and ^{2}H isotope testing consisting of 18 samples from both springs (MA), shallow wells (SD), bore wells (SB), and deep wells (SBD) can be seen in Table 3. The results of the analysis show that the values of ^{18}O isotope composition for water samples from shallow groundwater ranged from -7,733 ‰ to -5,961 ‰ with an average of -6,603 ‰ and a standard deviation value of 0,001 and ^{2}H isotope composition ranged from -45,647 ‰ to -31.709 ‰ with an average of -36,781 ‰ and a standard deviation value of 0,06. For water samples from boreholes ranged from -5,476 ‰ to -4,757 ‰ with a mean of -5,210 ‰ for ^{18}O isotope composition and a standard deviation value of 0,01 and the ^{2}H isotope composition ranged from -29,277 ‰ to -24,626 ‰ with an average of -26,883 ‰ and values standard deviation 0,01. Furthermore, the values of ^{18}O isotope composition for water samples from deep wells ranged from -6,004 ‰ to -4,972 ‰ with an average of -5,405 ‰ and a standard deviation value of 0,01 and the ^{2}H isotope composition ranged from -31,821 ‰ to -25,025 ‰ with an average of -27,897 ‰ and a standard deviation value of 0,07. Whereas the values of ^{18}O isotope composition for the water samples from springs ranged from -5,985 ‰ to -5,919 ‰ with an average of -5,952 ‰ and a standard deviation value of 0,01 and the ^{2}H isotope composition ranged from -31,566 ‰ to -31,391 ‰ with an average of -31,479 ‰ and a standard deviation value of 0,04. Based on the results of the analysis of the ^{18}O and ^{2}H isotopes, it can be seen that the standard deviation of groundwater samples is relatively uniform.

Tab. 3. The results of the analysis of the isotope composition of ^{18}O and ^{2}H

Code	Alt.	Des.	$\delta^{18}O$ (‰)		$\delta^{2}H$ (‰)		d-excess
			$\delta^{18}O$	std	^{2}H	std	
Dentim01	47	Dug Well	-6.778	0.025	-38.052	0.026	16.172
Dentim02	34	Dug Well	-6.518	0.020	-35.832	0.029	16.312
Densel01	14	Dug Well	-6.601	0.025	-37.193	0.179	15.615
Densel02	5	Dug Well	-6.603	0.022	-36.732	0.044	16.092
Denbar01	30	Dug Well	-5.961	0.034	-31.709	0.024	15.979
Denbar02	22	Dug Well	-6.372	0.019	-35.504	0.092	15.472
Denut01	45	Dug Well	-6.258	0.025	-33.582	0.037	16.482
Denut02	76	Dug Well	-7.733	0.014	-45.647	0.108	16.217
SB-01-Dentim	46	Borholes	-5.476	0.008	-29.227	0.023	14.581
SB-02-Denbar	34	Borholes	-5.447	0.008	-27.589	0.020	15.987
SB-03-Densel	9	Borholes	-4.757	0.013	-24.626	0.005	13.43
SB-04-Denut	62	Borholes	-5.159	0.027	-26.089	0.147	15.183
SD-01-Denbar	26	Deep Well	-5.249	0.006	-26.837	0.046	15.155
SD-02-Denut	65	Deep Well	-4.972	0.029	-25.025	0.030	14.751
SD-03-Dentim	40	Deep Well	-6.004	0.004	-31.821	0.030	16.211
SD-04-Densel	10	Deep Well	-5.395	0.021	-27.906	0.051	15.254
MA-1	67	Spring Water	-5.985	0.011	-31.566	0.098	16.314
MA-2	74	Spring Water	-5.919	0.026	-31.391	0.041	15.961

The classification of the ^{18}O and ^{2}H isotope compositions is carried out using the equal interval method, namely dividing the values of the data into groups that have the same range of values. Based on this classification, the groundwater samples in the study area were divided into 3 groups, which can be seen in Figures 7 and Tables 4, 5, and 6. The results of the plotting of the ^{18}O and ^{2}H isotope composition against the meteoric water line in Denpasar show that the water samples from springs and shallow wells (dug wells) are on the meteoric line while water samples from boreholes and boreholes are slightly off the mark from the meteoric water line in Denpasar (below the local meteoric line). Based on the ^{18}O and ^{2}H isotope plotted graphs, it shows that in general there are three groups of water samples based on the isotope composition of ^{18}O and ^{2}H. Applying a linear regression model, the relationship between $\delta^{2}H$ and $\delta^{18}O$ can be expressed as Equation 8:

$$\delta D = 7,2584 \; x \; \delta^{18}O + 11,205 \qquad (8)$$

with value of $R^2 = 0,9898$.

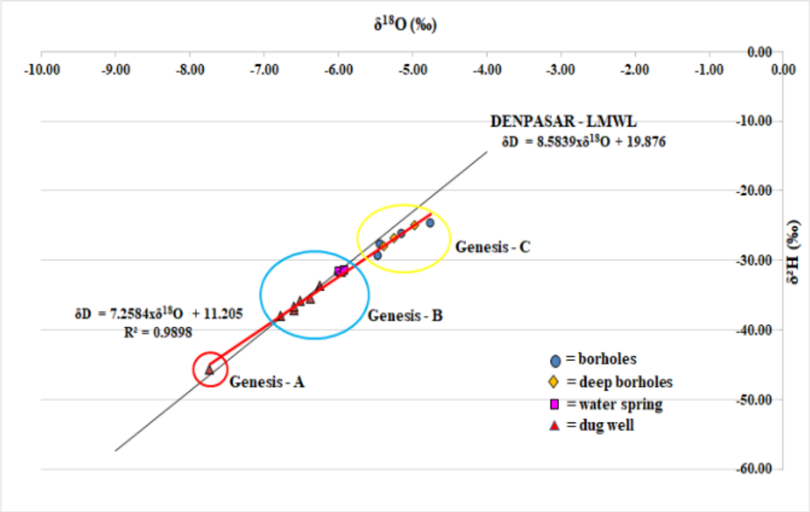

Fig. 7. Plot the 18O and 2H isotopes of a groundwater sample against the DMWL

An example of water with low ^{18}O and ^{2}H isotope composition (depleted) is a shallow well (dug well) located in the Ubung Kaja area (North Denpasar) with an elevation of 76 m.a.s.l. The water example has an ^{18}O isotope composition of -7,733 ‰ and ^{2}H of -45,647 ‰, as shown in Table 4. These groundwater samples are included in Group A

Tab. 4. The results of the analysis of the isotope composition of ^{18}O and ^{2}H

Code	Description	*δ¹⁸O (‰)*	*δ²H (‰)*
Denut02	Dug Well	-7.733	-45.647

Water samples with moderate ^{18}O and ^{2}H isotope compositions are dug wells Dentim01, Dentim02, Densel01, Densel02, Denbar01, Denbar02, and Denut01; deep well SD-03-Dentim; Pohgading springs and Plagan springs. These groundwater samples are included in Group B. The water sample has an average ^{18}O isotope composition of -6.3 ‰ and an average ^{2}H of -34.338 ‰ with a standard deviation of 0.318 for ^{18}O and 2.613 for ^{2}H, respectively, as shown in Table 5.

Tab. 5. Water samples with the isotope composition of ^{18}O and ^{2}H is moderate

Code	Description	*δ¹⁸O (‰)*	*δ²H (‰)*
Dentim01	Dug Well	-6.778	-38.052
Densel02	Dug Well	-6.603	-36.732
Densel01	Dug Well	-6.601	-37.193
Dentim02	Dug Well	-6.518	-35.832
Denbar02	Dug Well	-6.372	-35.504
Denut01	Dug Well	-6.258	-33.582
SD-03-Dentim	Deep Well	-6.004	-31.821
MA Pohgading	Spring Water	-5.985	-31.566
Denbar01	Dug Well	-5.961	-31.709
MA Plagan	Spring Water	-5.919	-31.391
Average		-6.300	-34.338
SD		0.318379	2.613106

Meanwhile, water samples with high (enriched) ^{18}O and ^{2}H isotope compositions are deep wells SD-04-Densel, SD-01-Denbar, SD-02-Denut; borholes SB-01-Dentim, SB-02-Denbar, SB-04-Denut, and SB-03-Densel. These groundwater samples are included in Group C. The water sample has an average ^{18}O isotope composition of -5.208 ‰ and an average ^{2}H of -26.757 ‰ with a standard deviation of 0.267 for ^{18}O and 1.638 for ^{2}H, respectively, as shown in Table 6.

Tab. 6. Water samples with the isotope composition of ^{18}O and ^{2}H are enrich

Code	Description	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
SB-01-Dentim	Boreholes	-5.476	-29.227
SB-02-Denbar	Boreholes	-5.447	-27.589
SD-04-Densel	Deep Boreholes	-5.395	-27.906
SD-01-Denbar	Deep Boreholes	-5.249	-26.837
SB-04-Denut	Boreholes	-5.159	-26.089
SD-02-Denut	Deep Boreholes	-4.972	-25.025
SB-03-Densel	Boreholes	-4.757	-24.626
Average		-5.208	-26.757
SD		0.2668	1.638441

Origin of groundwater and groundwater recharge area

The determination of groundwater genesis can be seen through the similarity of $\delta^{2}H$ and $\delta^{18}O$ values. The isotope ratio of the sample is then plotted in the graph $\delta^{2}H$ vs $\delta^{18}O$ and compared with local and/or global meteoric lines, which can be seen in Figure 7. If the values of δD and $\delta^{18}O$ from two or more sample points have the same value, it can be concluded that water soils come from the same source (have the same genesis) or are in the same flow pattern. Based on Figure 7, there are 3 groups of groundwater samples with almost the same genesis. The results of measurements of deuterium and oxygen-18 content in the samples plotted in Figure 7 show that groups A and B are located around the local meteoric line (Denpasar Meteoric Water Line) with stable isotope content of ^{18}O and ^{2}H which are relatively low or depleted to moderate. This shows that the groundwater in groups A and B is water that mostly comes from meteoric water (rainwater) so it can be estimated that the groundwater comes from relatively the same local recharge. Meanwhile, in group C which is dominated by boreholes and deep wells, the location of deuterium and oxygen-18 is lower than the local meteoric line. The slope formed based on the location of deuterium and oxygen-18 has shifted to a smaller direction than the initial LMWL line. The characteristics of groundwater are not much different from groups A and B, which come from rainwater that has infiltrated as shallow groundwater. Deep well water that is included in this group is estimated because the construction of deep wells with a screen position is also in a shallow aquifer.

Based on the comparison of groundwater deuterium and oxygen-18 plotting with the Denpasar local meteoric line, the results show that the main source of recharge an aquifer in the Denpasar area is meteoric water or rainwater. This is consistent with the aquifer of Denpasar which is dominated by an unconfined aquifer that is strongly influenced by hydro-climatological factors, one of which is influenced by precipitation. The distribution of oxygen-18 isotope in the Denpasar City aquifer can be seen in Figure 8, with a low ^{18}O value which is dominated in the North and Northeast areas of Denpasar, specifically Peguyangan Kangin and Penatih area, towards the South of Denpasar.

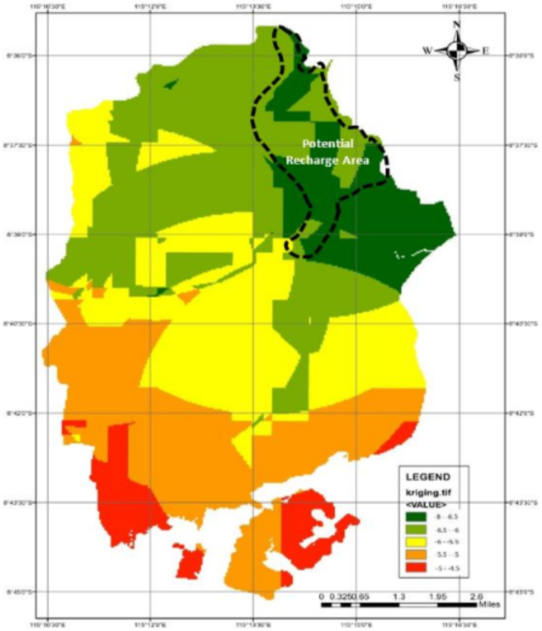

Fig. 8. Distribution of $\delta^{18}O$ of the aquifer in Denpasar with Kriging Interpolation

This is also following the groundwater movement in the aquifer of Denpasar, shown in Figure 9a. Based on secondary data in the form of field survey results on the groundwater level of shallow wells obtained the average groundwater level of 5.63 meters below ground level in the North area (altitudes from sea surface are 0-75 meters) and 1.53 meters below ground level in the South area (altitude from sea surface are 0-12 meters) of Denpasar aquifer. So, groundwater flow patterns in the aquifers of Denpasar flows from the North area to the South area (Politeknik Negeri Bali, 2014). It moves mainly under gravity from areas of high groundwater levels or pressure to areas of low groundwater levels or pressure. Paying attention to the flow pattern, groundwater flow in the recharge area tends to move away from the groundwater level and towards a lower level (Purnama, Tivianton, Cahyadi, & Febriarta, 2019). When there is a difference in groundwater level between one place and another, a hydraulic gradient will occur, which will cause groundwater flow or movement. Groundwater recharge area or recharge area is an area that has characteristics of downward movement of groundwater affected by gravity or groundwater movement that follows the slope of the aquifer (Riastika, 2012).

In addition, the composition of the ^{18}O and ^{2}H isotopes can also be compared with the hydraulic conductivity map of the Denpasar aquifer, shown in Figure 9b, the oxygen-18 isotope composition with a range of -8 ‰ to -6.5 ‰ based on Kriging interpolation intersects with the area with the highest conductivity value (K = 1.1 – 2.81 mm/hour) in the Denpasar aquifer. The hydraulic conductivity values are 1.1 – 2.81 mm/hour and 1.1 – 2.20 mm/hour in the North Denpasar area, 1.1 – 1.66 mm/hour in the West Denpasar area, and 1.1 – 2.12 mm/hour in the South Denpasar area (Politeknik Negeri Bali, 2014). The rate of groundwater flow is determined by hydraulic conductivity and hydraulic gradient. The hydraulic gradient is defined as the change in the head (water level decrease) per unit distance. The greater the hydraulic conductivity, the lower the flow resistance. The driving force of gravity transports groundwater through aquifers along the hydraulic gradient from areas of the high head to regions of the low head, generally (for unconfined aquifers) according to the land surface slope (Moore, 2012). Potential groundwater recharge areas have fast infiltration rates – relatively fast, high hydraulic conductivity – very high, and are composed of rocks with good porosity (Purnama et al., 2019). The potential energy in a recharge area decreases with depth, allowing water to flow downward. Groundwater flow between the recharge and outflow areas is primarily horizontal, with relatively slight slopes (Moore, 2012).

The spatial distribution of $\delta^{18}O$‰ values of the unconfined aquifer in Denpasar, shown in Figure 8, illustrates that recharge occurs from the north and flows to the south. Stable isotope composition agrees with postulated flow direction from previous researchers (Seyler, Witthüser, & Holland, 2016; Timmerman, 1985). Based on the results of isotope testing and validated with a map of groundwater movement and hydraulic conductivity in the Denpasar aquifer, the Northern and Northeast area of Denpasar, specifically the Peguyangan and Penatih areas, can be estimated as a potential recharge area in aquifers in the city of Denpasar because the average of groundwater level in North and Northeast area higher than South area and North area and has the highest hydraulic conductivity value of 1.1 – 2.81 mm/hour.

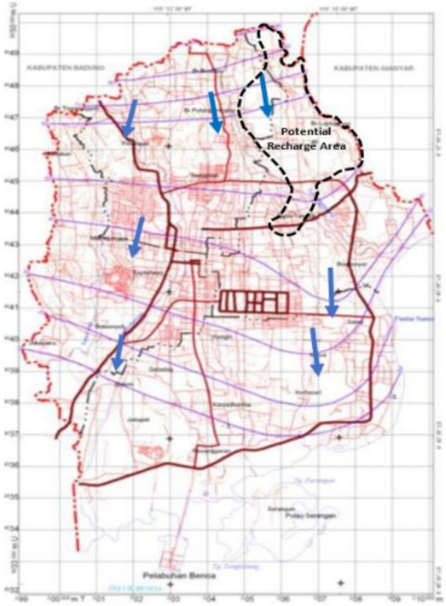

Fig. 9a. The groundwater movement map of Denpasar Aquifer

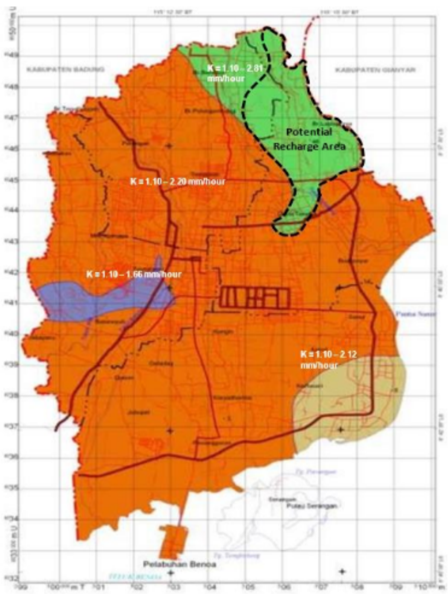

Fig. 9b. Hydraulic conductivity map of Denpasar aquifer

Conclusion

The present study examines the origin of groundwater in the plains of Denpasar by employing the analysis of ^{18}O and ^{2}H. The stable isotopic composition of precipitation and groundwater is analyzed to generate an extensive isotope database for preliminarily assessing the hydrologic characteristics of the basin. LMWL of precipitation in Denpasar is represented by $\delta D = 8{,}5839 \text{ x } \delta^{18}O + 19{,}876$. The analysis of the ^{18}O and ^{2}H isotopes, indicates that the groundwater in the aquifer of Denpasar plains originates and is highly dependent on local meteoric water (rainwater) or is a local recharge. From the analysis of deuterium and oxygen-18 isotope composition, groundwater genesis in Denpasar can also be determined. Based on its genesis, groundwater in Denpasar is grouped into three (A, B, and C). Based on the stable isotope composition, the lower (depleted) composition is located in the North and Northeast areas of Denpasar where the elevation, groundwater level and hydraulic conductivity are higher than the Southwest and South Denpasar areas. This corresponds to the elevation effect where the isotope composition will become more depleted at higher elevations and conversely, at lower elevations, the isotope composition will be more enriched. The spatial analysis of oxygen-18 isotope composition with Kriging interpolation also shows the North and Northeast areas of Denpasar with a more depleted ^{18}O and ^{2}H isotope composition with a higher elevation are precisely the recharge areas in the Denpasar aquifer.

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