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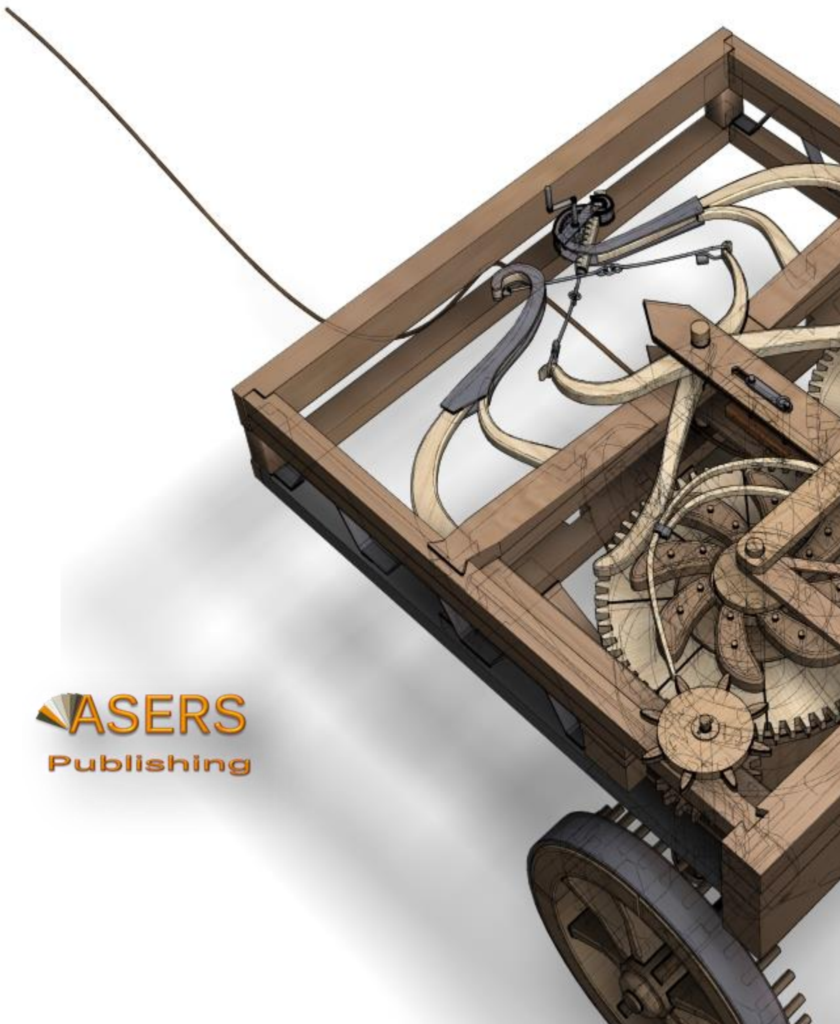

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Journal of Environmental Management and Tourism

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Identifying Karst Aquifer Recharge Area Using Environmental Stable Isotopes and Hydrochemical Data: A Case Study in Nusa Penida Island

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Abstract: Identifying the recharge area of karst aquifers is scientifically challenging due to the complexity of karst groundwater flow characteristics. It is essential to identify the recharge zones to conserve the groundwater resources contained within these aquifers. This paper proposes a combined methods for identifying recharge area of karst aquifers on Nusa Penida Island using stable isotopes (18O and 2H) and a hydrogeochemical approach. Based on the analysis of δ18O and δ2H values and their spatial distribution, it is possible to retrace karst aquifer recharge areas using average isotope elevations. In the meantime, groundwater facies will be determined in the karst region of Nusa Penida using the hydrogeochemical approach with the Piper diagram. According to the calculation of water stable isotope results, the average elevation of the groundwater recharge area at the study site is between 62 - 450 meters. If applied to the location of the study, the recharge area is almost entirely distributed across Nusa Penida. In addition, based on the hydrogeochemical analysis, the groundwater type at the study site can be divided into three categories: Na-Cl, mixed, and Mg-HCO3. The water types indicate that the groundwater in Nusa Penida comes from a combination of old water stored from its internal geological formations and mix with modern rainwater.

Keywords*:* recharge; karst; isotopes; hydrogeochemical; aquifer; facies.
JEL Classification: Q25; L65; Q57; R11.

Introduction

Nusa Penida is a district in Klungkung Regency, Bali Province, which has an area of 202.84 km^2 with a population of 63,468 people (Harmayani, *et al.* 2017). The sub-district includes three island groups, namely Nusa Penida (191.462 km^2), Nusa Lembongan (8.6875 km^2), and Nusa Ceningan (2.6875 km^2). Nusa Penida is a dry area with a hilly topography dominated by karst rocks in almost all parts of the island with slopes between 15% and 45% and consists of dry valleys filled with water during the rainy season only (Sudipa, *et al.* 2020). The Bali-Penida River Basin consists of 391 watersheds with an area of 5,617.04 km^2, making the potential for surface water on Nusa Penida Island quite large on Nusa Ceningan and Nusa Lembongan Islands there is no surface water potential. Nusa Penida has a negative karst morphology (valleys between the protrusions of hills), forming a river flow pattern that parallels the direction of direct flow to the open sea. In addition, the condition of the riverbed is composed of limestone formations with very high permeability (porous), causing water to seep directly and be wasted (Harmayani, Konsukartha, and Arsana 2017). In addition to surface water sources, Nusa Penida also has nine springs that can be utilized as raw water, including Penida (Sakti) Spring, Guyangan Spring, Seganing Spring, Tembeling Spring, Tabuanan Spring, Antapan Spring, Wates Spring, Angkel Spring, and Toya Pakeh Spring. Of these nine springs, two are already managed by the government in the form of a Drinking Water Supply System (SPAM), namely Penida Spring (200 lt/s) and Guyangan Spring (178 lt/s). The calculation of the water carrying capacity in Nusa Penida shows that the status of the water holding capacity in Nusa Penida is surplus (Harmayani, Konsukartha and Arsana 2017). This means that the potential water resources are sufficient for drinking water needs on Nusa Penida Island, but the problem of water scarcity also occurs on this island.

Karst is a special type of landscape that is formed by the dissolution of soluble rocks, including limestone and dolomite. Karst regions contain aquifers that are capable of providing large supplies of water. Karst aquifers commonly occur in limestone, and rarely in dolomite. Regarding porosity and hydraulic permeability, they are highly heterogeneous and often characterized by rapid groundwater flow. Karst aquifers are significant freshwater resources in many world regions. Their management demands a quantitative understanding of their hydrologic functioning to preserve water supplies, assess contaminants, and establish management strategies. In light of future climate change-related precipitation patterns, which will affect the transport of water and solutes through karst hydrogeological systems and strongly influence water availability for different uses, this is becoming increasingly important. Water scarcity is a growing issue in many karst areas (Chen, *et al.* 2018; Hartmann, *et al.* 2014). As the primary drinking water supply in many nations, these aquifers are incredibly susceptible to anthropogenic influences and the effects of climate change, necessitating a very specialized preservation strategy. The biggest issue for tiny islands, particularly karst islands, is water scarcity. Well-developed karst aquifers, with sluggish infiltration through the rock matrix and quick flow through conduits and fractures, are productive groundwater systems with high heterogeneity and anisotropy (Iacurto, at al, 2020). Consequently, identifying recharge areas and karst aquifer hydrogeological properties related to the significant type of groundwater discharge is crucial for sustainable groundwater management because karst aquifers are a substantial source of fresh water for humans (Sappa, *et al.* 2018; Shi *et al.* 2019).

In the study of karst aquifers, the use of environmental tracers can be viewed as an efficient strategy that permits an integrated inquiry in order to carry out suitable water resource management (Liebundgut, *et al.* 2009). Since the 1950s, the isotope tracer approach has been applied to hydrology; however, it is limited to the study of isotope tracing. Late in the 1960s, hydrological studies used isotopes considerably (Carucci, *et al.* 2012; Ma, *et al.* 2009; Ma, *et al.* 2003; Qian, *et al.* 2013). Hydrogen and oxygen stable isotopes are essential to comprehending hydrological processes (Zhang and Wang 2016; Ala-aho *et al.* 2018; Wang *et al.* 2016; Zhang and Wang 2016; Gat and Gonfiantini 1981). In recent years, technological advancements in hydrogen and oxygen isotope testing and a drop in testing costs have made extensive isotope application viable. Isotopes offer particular advantages in the study of groundwater production and supply mechanisms. Hydrogen and oxygen isotopes are exploited in international groundwater research (Abdalla, *et al.* 2018; Babaye *et al.* 2018; Boronina, *et al.* 2005; Hofmann, *et al.* 2020; Khaska *et al.* 2013; Love *et al.* 1994; Majumder *et al.* 2011; Mohammadzadeh *et al.* 2020; Pu *et al.* 2013; Richards *et al.* 2018; Sprenger, *et al.* 2014; Wei *et al.* 2014). The ^{18}O and ^{2}H data from groundwater are commonly utilized to gather information about the operation of the karst systems (Sappa, Vitale, and Ferranti 2018), to designate critical recharge regions of these aquifers, and to define the protection zones for the main springs (Zuppi and Sacchi 2004). The isotopic compositions of oxygen and hydrogen in water that meteoric processes have altered are valuable tracers for detecting the origin and migration of groundwater because they are largely unaffected by rock–water interactions at low temperatures (Sidle 1998). Hence, oxygen and hydrogen isotopes (^{18}O and ^{2}H) can be utilized to determine the source and course of groundwater and surface water. Similar systematic isotopic fractionation occurs in stable hydrogen and oxygen due to their similar behavior in the hydrologic cycle (González-Trinidad, *et al.* 2017). This widespread behavior results in covariation between stable hydrogen and oxygen isotope contents (González-Trinidad *et al.* 2017), which Craig (1961) refers to as the Global Meteoric Water Line (GMWL) connection. Residence periods and water flow pathways of oxygen-18 and deuterium have been widely used in catchment studies (Adomako *et al.* 2010; Ardana *et al.* 2022) to determine groundwater recharge. In addition to hydro isotopes, many researchers have focused on understanding the karst hydrogeology mechanisms using various tools, including hydrochemistry, analysis of geomorphological structures, hydrological dynamics of karst flow, and estimation of the mean rate and spatial distribution of recharge areas (Andreo *et al.* 2008).

Identifying the various sources and areas of recharge, flowpaths, and surface–ground water interactions in karst systems is important for proper water resource management. Furthermore, spring conservation must be planned, implemented, and supervised to prevent a drop in discharge and water quality. The spring, where groundwater leaves and the recharge, or catchment, region are conserved. Conservation at the spring exit protects water from contamination. In contrast, protection at the recharge area reintroduces as much surface water flow as possible into the ground to create a groundwater reserve. Since Nusa Penida Island is a geologically protected karst ecosystem, Penida Spring and Guyangan Spring must be conserved. Based on the problem that has been described, the primary goal of this study is to identify the hydrogeological processes in the Nusa Penida Island, in order to understand possible origins and mechanisms of groundwater and spring hydrochemical and sources of recharge (recharge area). These processes have been determined through the use of the stable isotopes ^{18}O and ^{2}H and determinations of major ions concentrations.

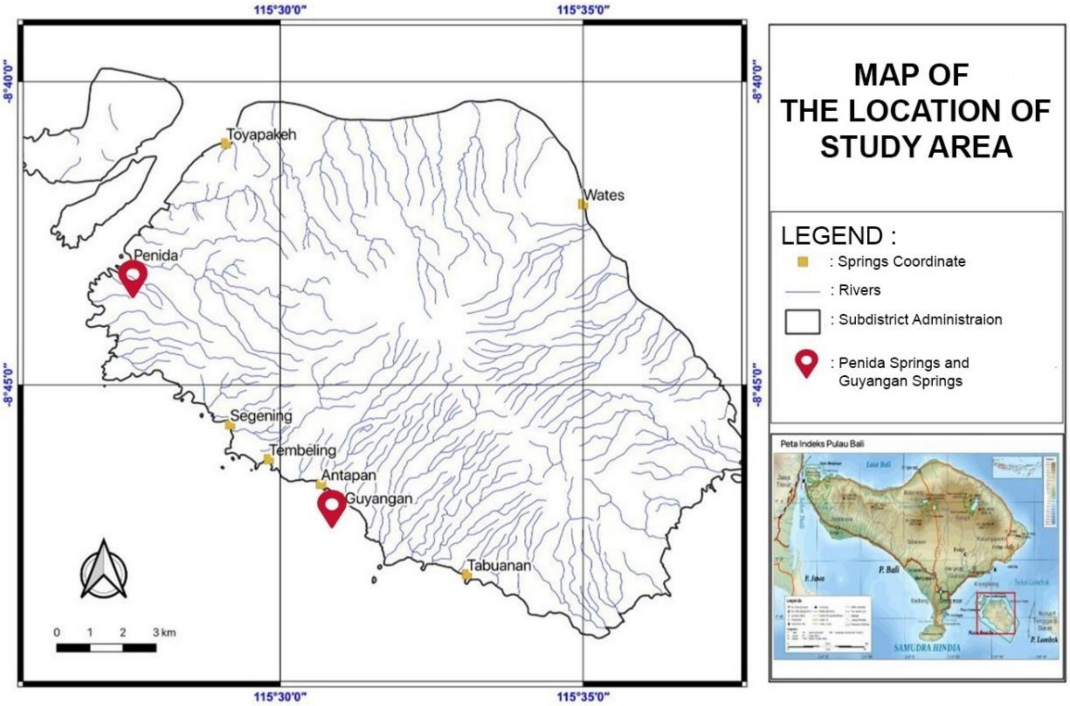
1 Material and Methods

This research is a quantitative descriptive method conducted with observation methods and measurements. Tests in the field and laboratory to obtain measured data or phenomena related to aquifer characteristics and groundwater recharge areas in karst areas on Nusa Penida Island. Primary data was collected in the form of an inventory of 10 spring points which are found in the region of Nusa Penida to measure hydrochemical and isotopes ratio. In addition, secondary data collection was also carried out in hydrogeological maps, geological maps, administrative maps of Nusa Penida, watershed maps, spring location maps, and annual rainfall data. 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). This study's primary element data collection was carried out using the ion chromatography (IC) testing method, which was analyzed using the Metrohm 930 Compact IC Flex instrument. Furthermore, the main element analysis results were plotted into a Piper Diagram. This Piper diagram is a conventional analysis method to determine the type/facies of water.

2. Study Area

The research was conducted on Nusa Penida Island, which is geographically located at coordinates 08°40'18,9"-08°50'10,8" sl and 115°26'47.6" -115°37'41.8" el. The area of Nusa Penida is two-thirds of the size of Klungkung Regency. Nusa Penida sub-district, with an area of 202,84 km^2, is bordered by the Badung Strait to the north and west, the Lombok Strait to the east, and the Indonesian Ocean to the south. Nusa Penida has a karst topography (undulating hills with rocks consisting of limestone). The land slope in Nusa Penida exceeds 40%, where this area is hilly. While land with a slope of 0 - 2% covers only 106,775 ha (18.94%), and a slope of 2 - 15% covers 124,051 ha (22.01%) (Badan Pusat Statistik Kabupaten Klungkung 2021) respectively, shown in Figure 1. The climate type in the Nusa Penida Island area is tropical, characterized by high temperature, humidity, and seasonal rainfall. Based on the Schmidt and Fergusson climate classification, the study area belongs to climate type F, indicated by an average of 4 wet months with rainfall of 1376 mm/year and an average dry month of 55 days/year. Such climatic conditions affect land use, which is more utilized for plantation land compared to rice fields. The average air temperature on Nusa Penida Island is around 26°C with an air humidity of 82%, fluctuating between the rainy and dry seasons (Sedana 2016).

Figure 1 The location of study area



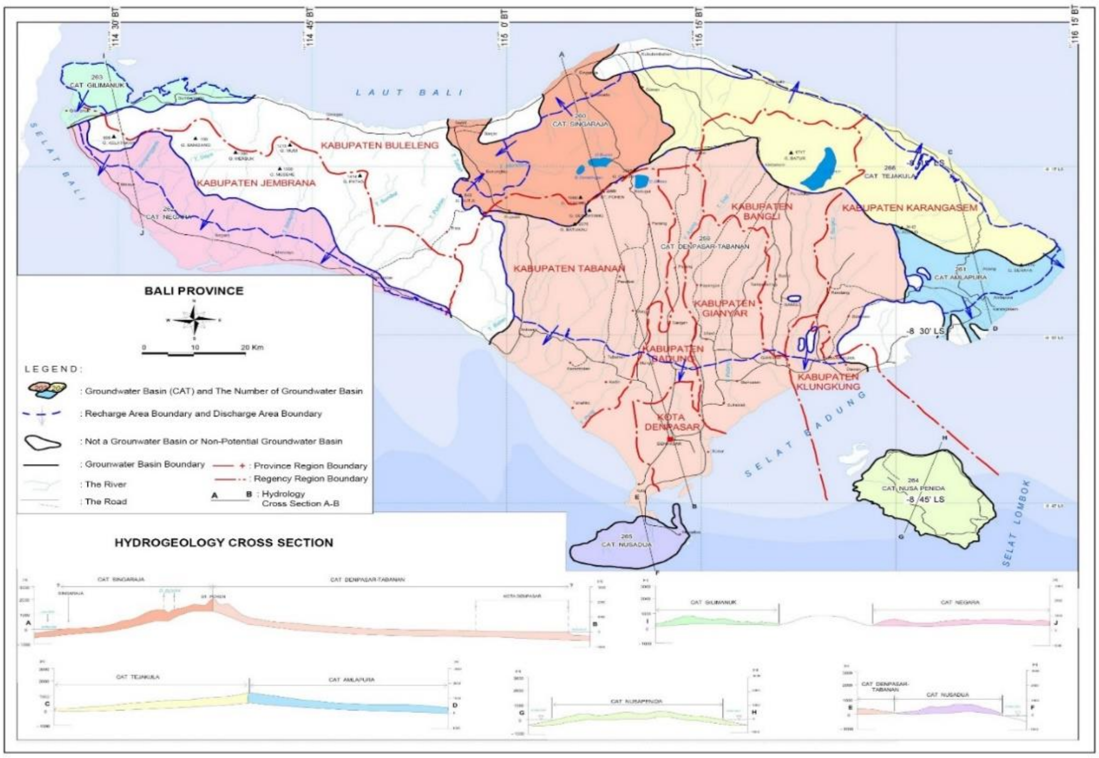
3. Geological and Hydrogeological Setting

The study area is located on Nusa Penida Island. Nusa Penida is located in the Nusa Penida groundwater basin. The Nusa Penida groundwater basin (CAT) is located in the southeast of Bali Province (Figure 2), located in Klungkung Regency, with an area of approximately 202,84 Km^2. This basin only has shallow groundwater potential in unconfined aquifers of roughly 79 million m^3/year. The topographic elevation of this basin is between 0 - 500 m.a.s.l, with a trellis river flow pattern, which is in the direction of the slope (Figure 3), thus forming morphological units of plains and undulating hills. Based on the lithological composition of rocks and their permeabilities, Nusa Penida Island consists of folded strata (Figure 4). This basin has a primary lithology (Figure 5) that functions as an aquifer in the form of mainly reef limestone from the South Formation, with medium-high graduation. With this geological condition, CAT Nusa Penida only has 1 (one) type of aquifer (Figure 5), namely aquifers with flow through faults, fractures and channels, with locally productive aquifer productivity, with groundwater flow limited to the zone of faults, fractures and dissolution channels, the groundwater table or piezometric height is generally deep. Nusa Penida has nine springs (Figure 6) that can be utilized as raw water, of these nine springs, two are already managed by the government in the form of a Drinking Water Supply System (SPAM), namely Penida Spring (200 lt/s) and Guyangan Spring (178 lt/s).

4. Research Method

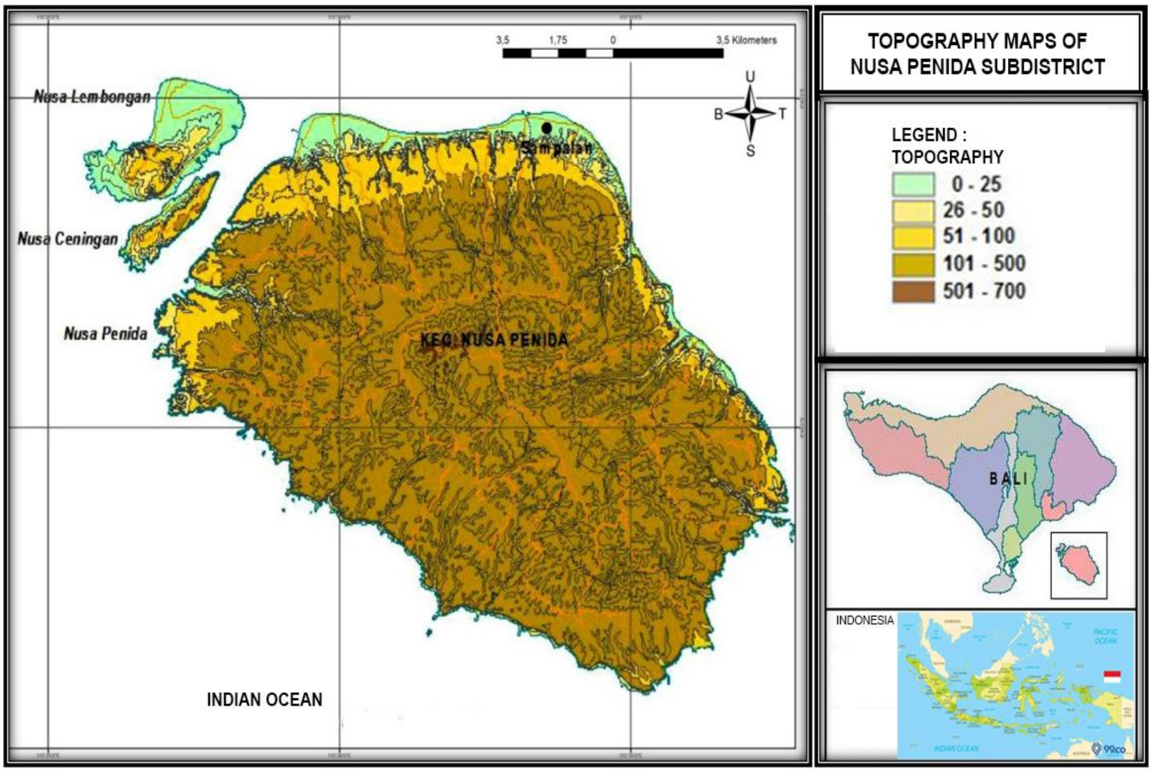
Determination of recharge areas in karst areas in Nusa Penida is based on hydrogeochemical and hydro isotope analysis. Based on the results of hydro isotope analysis, the ^{2}H and ^{18}O ratio values of groundwater, springs, and rainwater are obtained, and the Local Meteoric Water Line (LMWL) equation will be obtained. LMWL is an equation that describes the relationship between isotopic compositions of precipitation and altitude. LMWL is very useful in determining groundwater genesis and a function of elevation to determine the origin or location of groundwater and groundwater recharge areas. Meanwhile, based on the results of hydro isotope analysis, the major ion composition of groundwater will be obtained to determine the groundwater facies group.

Figure 2. Nusa Penida groundwater basin



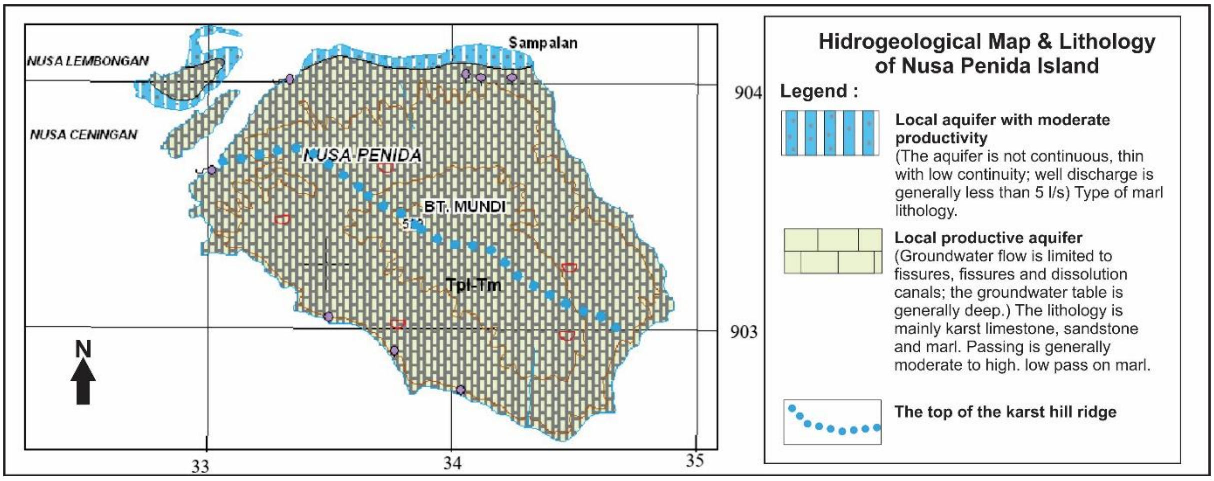
Source: Mudiana and Setiadi 2008

Figure 3. Topography and river flow patern on Nusa Penida groundwater basin



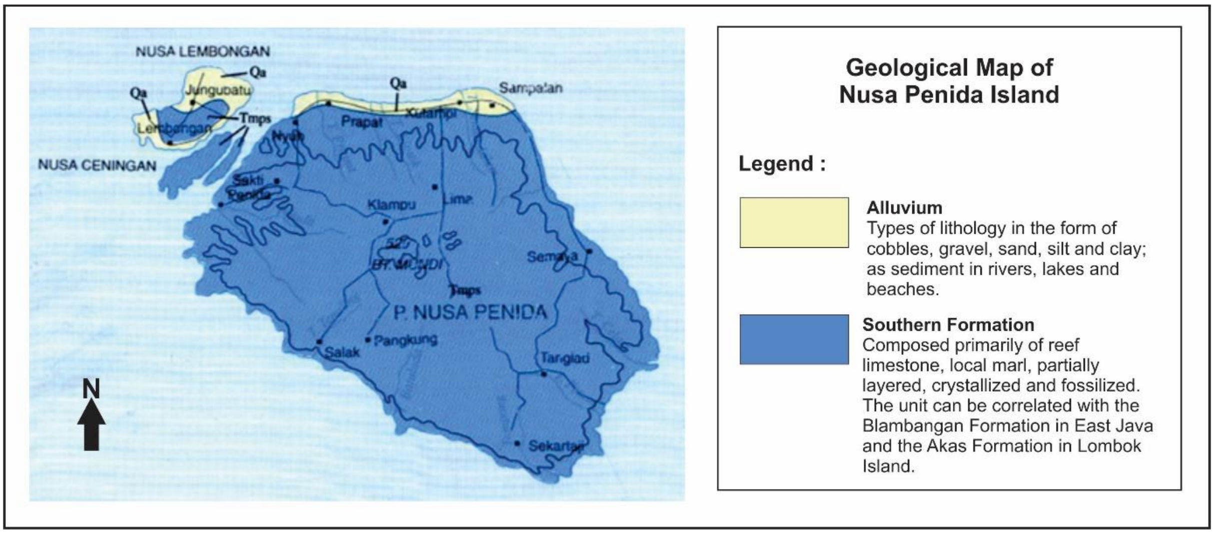
Source: Sudipa, 2020

Figure 4. Lithological composition on Nusa Penida groundwater basin



Source: Purbo-Hadiwidjojo, *et al.* 1998

Figure 5. Hydrogeological map on Nusa Penida groundwater basin



Source: Sudadi *et al.* 1986

5. Hydrogeochemical

Hydrogeochemical analysis was obtained based on data from direct measurements in the field, including measurements of water's physicochemical properties in the form of temperature, color, turbidity, acidity (pH), electrical conductivity (DHL), ion content (HCO_3^-, NO_3^-, and NO_2). In addition, groundwater sampling was also conducted for hydrochemical analysis of major ions (Setiawan, *et al.* 2018). According to Ford and Williams (1992), karst areas can be viewed as a system consisting of two integrated components, namely the hydrogeological sub-system and the hydrochemical sub-system, so that certain hydrochemical characteristics will reflect certain groundwater flow characteristics or mechanisms. According to Matthes (1981) in (Suganda, 2021), the chemical composition of groundwater (hydrogeochemistry) in an area is highly dependent on the interaction between air (CO_2), water (H_2O), and rock (in this case, limestone or $CaCO_3$). In karstification, water acts as a dissolving agent for carbonate rocks through reactions (Kehew 2001):

$$CaCO_{3(S)} + CO_{2(g)} + H_2O_{(l)} = Ca^{2+}_{(l)} + 2HCO^-_{3(l)} \quad 5.1$$

According to Ford and Williams (1992), to determine the level of interaction between water and CO_2 it is important to know the amount of CO_2 (Pco2) which can theoretically be calculated from the hydrochemical analysis of water samples through the equation:

$$Pco_2 = \frac{(HCO_3^-)\,(H^+)}{K_1\, K_{CO_2}} \quad 5.2$$

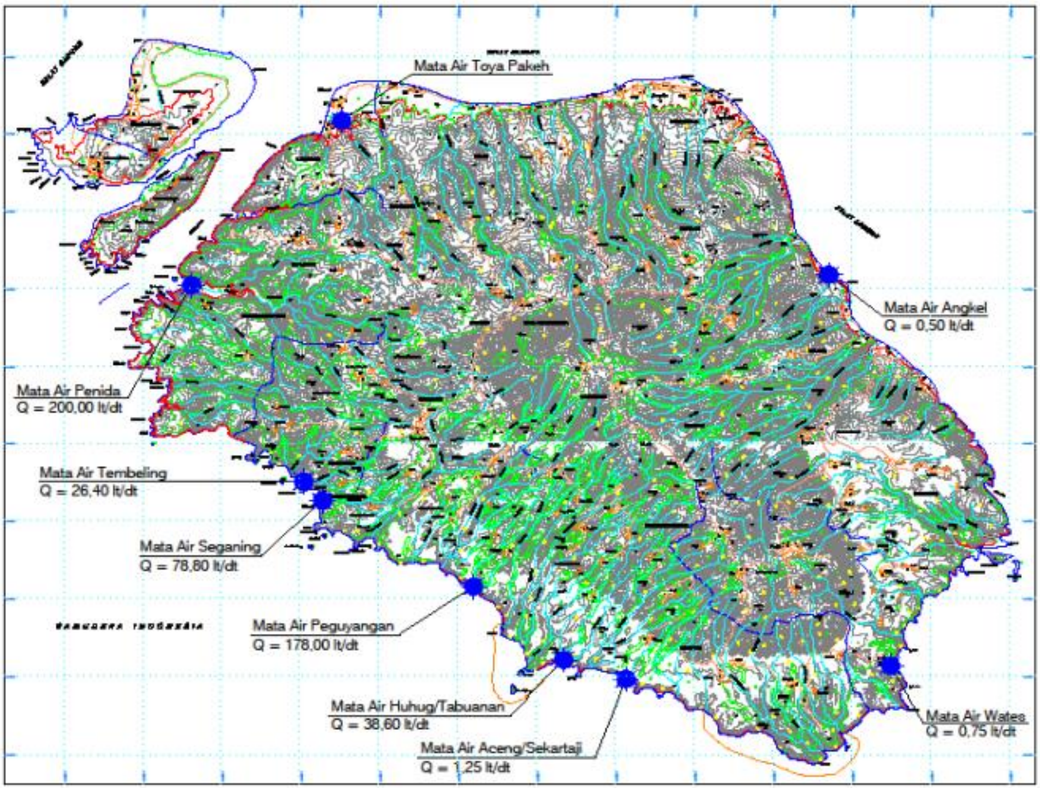
$$\text{Log } Pco_2 = \log\,(HCO_3^-) - pH + pKCO_2 + pK_1 \quad 5.3$$

The chemical reaction between water and carbonate rock ($CaCO_3$) is a reversible partial equilibrium reaction between dissolution and precipitation. To determine the level of water saturation in dissolving $CaCO_3$ the saturation index parameter for $CaCO_3$ minerals $CaCO_3$ ($SI_{calcite}$) is used, which is formulated as follows (Domenico, 1990 in Setiawan *et al.* 2018):

$$SI_{kalsit}=\text{Log}\ \frac{\left(Ca^{2+}\right)\left(HCO_3^{-}\right)K_2}{\left(H^{+}\right)K_{CaCO_3}} \qquad 5.4$$

A solution is in equilibrium concerning $CaCO_3$ if the $SI_{calcite} = 0$, which means that the dissolution process of $CaCO_3$ has stopped. A negative calcite value indicates that the solution is undersaturated concerning $CaCO_3$, so water can still dissolve $CaCO_3$. A positive calcite value means that the solution is supersaturated concerning $CaCO_3$, so that $CaCO_3$ will be precipitated. According to Ford and Williams (1992), due to the difficulty of measurement in the field, the $SI_{calcite}$ value generally has an error rate of ± 0.1 - 0.2. According to Kehew (2001), the nature of groundwater flow in karst areas is divided into diffusion flow (slow flow) through pore media or dense fracture networks and flow through cavity networks (fast flow). Groundwater flowing through the cavity network is more difficult to reach saturated conditions for calcite.

Figure 6. Distribution map of springs in Nusa Penida Island



Source: Harmayani, Konsukartha, and Arsana 2017

6. Hydro Isotopes

The hydro isotope method is used as a comparison to the review of groundwater dynamics from a hydrogeological aspect, especially about the origin of groundwater. Natural isotopes are isotopes of chemical elements that occur naturally in nature. The most important natural isotopes in hydrology are isotopes of the atoms that form the water molecule itself, namely isotopes of hydrogen atoms: ^{1}H; ^{2}H (deuterium, D); ^{3}H (tritium, T), and isotopes of oxygen atoms (^{16}O, ^{17}O, ^{18}O). The abundance of hydrogen isotopes in nature is about ^{1}H = 99,985%, ^{2}H (D) = 0,015%, and ^{3}H (T) (radioactive) < 0,001%. Whereas the abundance of oxygen isotopes is: ^{16}O= 99,63%, ^{17}O = 0,0375%, and ^{18}O = 0,1995% (International Atomic Energy Agency 1981). From the abundance of these isotopes, it can be seen that the most dominant water molecules are: $H_2{}^{16}O$ (mass-18), $HD^{16}O$ (mass-19), and $H_2{}^{18}O$ (mass-20). In applications, the abundance of these molecules in water is not measured absolutely, but the relative abundance to a standard is measured.

The relative abundance of $HD^{16}O$ molecules is called the relative abundance of deuterium (δD), and the relative abundance of $H_2{}^{18}O$ is called the relative abundance of oxygen-18 (^{18}O). The deuterium relative abundance and oxygen-18 relative abundance in water are measured relative to an international standard Standard Mean Ocean Water (SMOW), with the following formula (Eriksson 1983):

The relative abundance of deuterium is written as δD, with the formula:

$$\delta_D = \left(\frac{R_{D(sample)}}{R_{D(standard)}} - 1\right) x\ 1000\% \qquad 6.1$$

The relative abundance of oxygen-18 is written as ^{18}O, with the formula:

$$^{18}O = \left(\frac{R_{O\text{-}18(sample)}}{R_{O\text{-}18(standard)}} - 1\right) x\ 1000\% \qquad 6.2$$

Rainwater that falls and seeps into the soil, as long as it does not evaporate, the isotopic composition of ^2H and ^{18}O does not change. In the hydrological cycle, the degree of change in the composition of ^2H and ^{18}O isotopes in fractionation is influenced by the air temperature where the fractionation occurs. In nature, differences in air temperature can occur due to differences in geographical parameters such as altitude, latitude, and distance from the coast. The ^2H and ^{18}O composition of precipitation occurring at different locations will have different isotopic compositions. When plotted on the coordinates δ^2H against $\delta^{18}O$, these varying isotope compositions lie on a straight line called the Local Meteoric Water Line (LMWL). The relationship between the abundance of deuterium (δD) and oxygen-18 ($\delta^{18}O$) of a water sample has been proven by experts to be linear and written with the equation; $\delta D = A\ \delta^{18}O + B$. The relationship is obtained as an example for rainwater obtained from 91 earth stations worldwide: $\delta D = 8\ \delta^{18}O + 10$ and is called the Global Meteoric Water Line (GMWL) (Craig 1961).

Validation of hydro isotope data analysis

a.For LMWL based on rainwater isotopes, the higher the elevation, the ratio of O and H isotopes will be depleted (poor) with a greater value and vice versa low elevation isotope ratio values are enriched (rich), the value is getting smaller. If it is appropriate, it is said to be valid.

b.Groundwater flow direction (gravity concept). The recharge area has the highest position or level, meaning groundwater will flow from the highest to the lowest. Hence, it is necessary to describe the groundwater flow pattern.

c. Position of spring isotope values. If it is on the LMWL, then the spring comes from rainwater, and if it is outside the LMWL line (above or below it), then it is estimated that there is a source of the spring that is in a higher place than the spring. Furthermore, it is necessary to examine the approximate recharge location and, if the source location is found, test the water in the hypothetical recharge location again to equate the O and H isotope variations with the O and H isotopes of the spring as well as hydrochemical testing.

7. Result and Discussion

7.1. Hydrogeochemical Analysis (Major Ions)

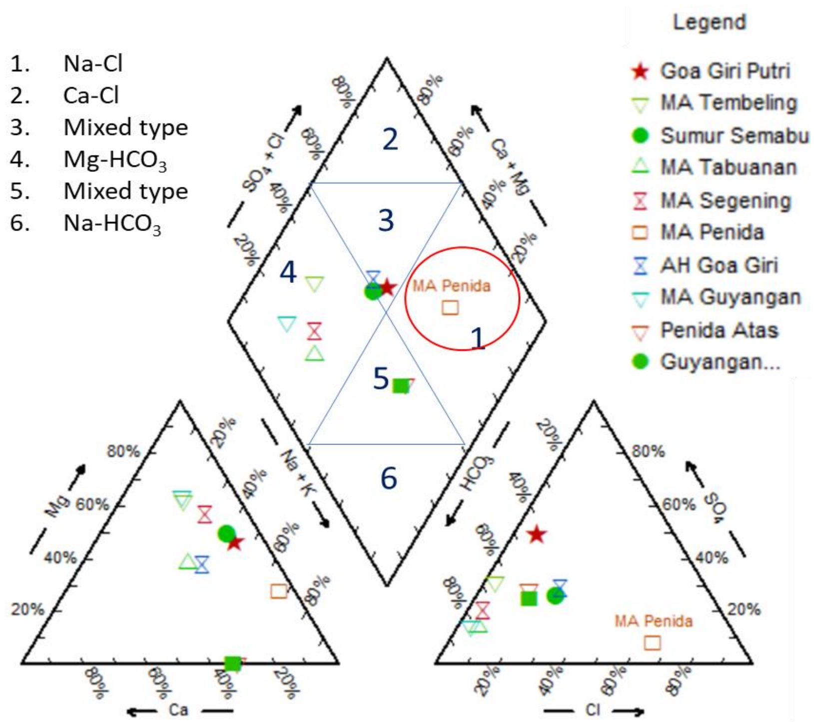
Water found in nature contains a certain number of dissolved elements, including major, rare, and trace elements. These elements are present in the form of ions and dissolved metals that make up the chemical composition of water. This study's primary element data was collected using the ion chromatography (IC) testing method in the Hydrogeology and Hydrogeochemistry Laboratory Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology (ITB). Water samples from the field were prepared using cellulose membrane filter paper measuring 0.2 μm and 25 mm in diameter. The filtered samples were then put into a small bottle (vial) of approximately 10 ml and then analyzed using the Metrohm 930 Compact IC Flex instrument. The main element analysis results of groundwater and surface water samples are shown in Table 1.

The main element analysis results obtained from the ion chromatography test were further analyzed using a piper diagram plot. Piper diagram is a conventional analytical method to determine the type/facies of water. Based on the diagram (Figure 8), the groundwater type at the study site can generally be divided into three types: Na-Cl, mixed type, and $Mg\text{-}HCO_3$. The mixed type water, which consists of rainwater samples from Goa Giri, Goa Giri Putri spring, and water from Semabu Hotel boring well, shows no ions (cations or anions) that dominate the chemical composition of the water. Rainwater samples around Penida spring and Guyangan spring also offer a mixed type. The samples from Tembeling spring, Segening spring, Guyangan Spring, and Tabuanan Spring are $Mg\text{-}HCO_3$ type water. The magnesium and bicarbonate content in these water samples is thought to come from the dissolution of the limestone from which the springs flow. The water sample from Penida spring (Sakti) differs from the other springs, namely the Na-Cl type. Na-Cl-type water is generally found in quite old water or located close to the sea. Penida spring, as it is known, is located on the coast of Crystal Bay. The water from this spring is collected in an area resembling a dam so that the water from this dam does not flow freely like other springs in Nusa Penida. This is why Penida spring water has a Na-Cl type that characterizes the interaction with seawater.

Table 1. Chromatography Ion Analysis Results (main ions)

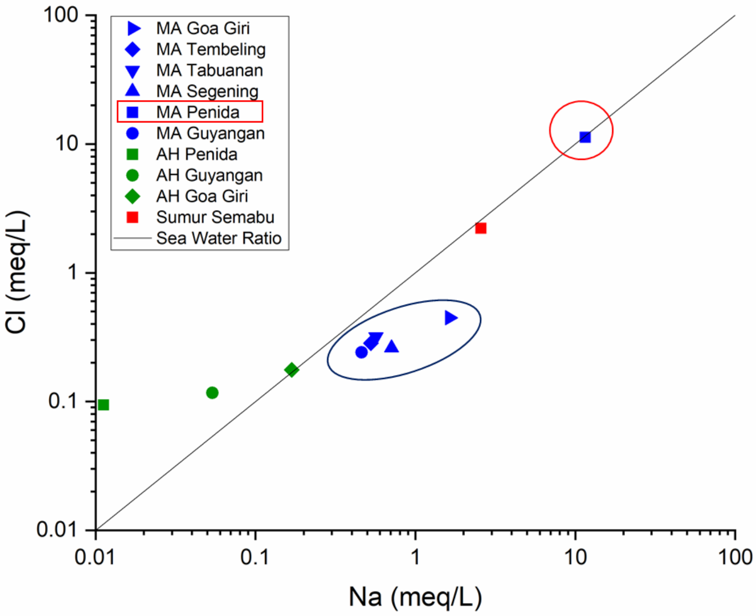
No	Sample ID	Na^+ (ppm)	K^+ (ppm)	Ca^{2+} (ppm)	Mg^{2+} (ppm)	Cl^- (ppm)	SO_4^{2-} (ppm)	HCO_3^- (ppm)
1	Goa Giri Putri	37.56	9.08	7.92	23.51	15.85	133.5	149.4
2	MA Tembeling	12.11	6.33	11.6	25.11	10.06	97.88	262.9
3	Semabu well	59.07	11.52	14.81	42.46	78.32	109.1	257.3
4	MA Tabuanan	13.02	8.03	12.71	10.57	11.27	29.59	212.6
5	MA Segening	16.31	14.95	10.01	25.37	9.28	45.99	211.4
6	MA Penida	265.4	16.5	16.01	59.63	400.3	64.16	289.4
7	AH Goa Giri	3.877	1.78	2.69	2.55	6.26	9.51	19.52
8	MA Guyangan	10.58	6.70	11.64	25.43	8.56	33.76	252.3
9	Penida Atas (precipitation water)	0.258	0.35	0.18		3.33	7.76	19.52
10	Guyangan Atas (precipitation water)	1.234	0.39	0.63		4.14	7.83	23.18

Figure 7. Piper Diagram Analysis of Major Ion Data



Further analysis of the Penida spring samples was conducted using a bivariate plot of sodium (Na+) against chloride (Cl-). This cross-plot was used to see the tendency of the chemical composition of the water toward possible interaction with seawater. It is known that seawater is composed of predominantly sodium and chloride ions. The bivariate plot of spring and rainwater samples in Nusa Penida is shown in Figure 9. The black line in the figure is the seawater ratio based on a 1:1 ratio between sodium and chloride composition. Based on the diagram, it can be seen that the spring water samples from Penida/Crystal Bay fall right on the seawater ratio line. Samples that fall precisely on the sequence indicate a seawater influence on the water sample. The other spring samples tended not to fall on the seawater ratio line, indicating a difference with the Penida spring.

Figure 8. Bivariat Na-Cl Diagram



7.2. Water Stable Isotope Analysis ($\delta^{18}O$ and δ^2H)

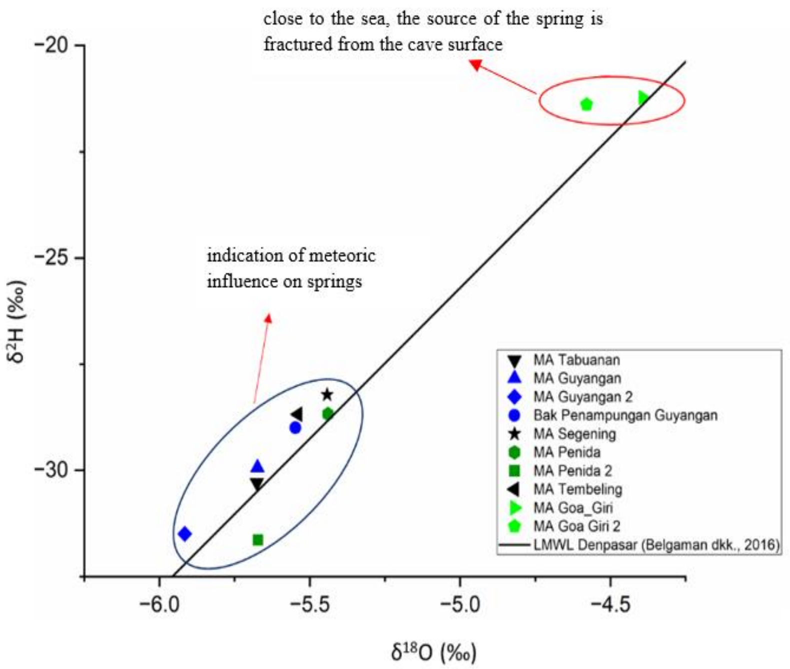
The stable isotopes present in water with the greatest abundance are $\delta^{18}O$ (oxygen-18) and δ^2H (deuterium). These two types of isotopes are the main constituent components of water composition in nature. Oxygen-18 and deuterium in this study were analyzed using the Picarro L2130-i Analyzer instrument with the Cavity Ring Down Spectrometer (CRDS) method in testing method in the Hydrogeology and Hydrogeochemistry Laboratory Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology (ITB).

The sample required for stable isotope water analysis is 1.9 ml with prior filtration using a 0.2 µm membrane filter. The basic principle of isotope analysis is the fractionation of heavy and light isotopes, which are then sent to the vaporizer to produce steam from the water sample at 110°C. The steam produced from the evaporation process in the vaporizer then flows into the analyzer for further fractionation of $\delta^{18}O$ (oxygen-18) and δ^2H (deuterium) isotopes.

Table 2. Water Stable Isotope Analysis Result

Sample	$\delta^{18}O$ (‰)	δ^2H (‰)
MA Tabuanan	-5.676	-30.285
MA Guyangan	-5.674	-29.933
MA Segening	-5.442	-28.220
MA Penida	-5.439	-28.672
MA Tembeling	-5.539	-28.679
MA Goa Giri	-4.393	-21.223
Reservoir Guyangan	-5.548	-28.997
MA Guyangan 2	-5.916	-31.491
MA Penida 2	-5.672	-31.635
MA Goa Giri 2	-4.579	-21.386

Figure 9. Bivariat plot of water stable isotope



The laboratory analysis data for water-stable isotope parameters can be seen in Table 2. Water stable isotope analysis was conducted using a bivariate plot of oxygen-18 against deuterium (Figure 11). The black line on the diagram is the Denpasar local meteoric water line based on Belgaman, *et al.* 2016. This line determines the process in water samples relative to rainwater conditions. Based on the plot, it can be seen that all samples are relatively around the meteoric water line. This indicates the influence of meteoric/rainwater on the water composition of the spring samples. The water samples from Goa Giri spring have heavier oxygen-18 and deuterium isotope ratios than the other spring samples. This may occur because Goa Giri spring is located close to the sea. The spring at Goa Giri is a fracture whose source is thought to come from the surface interacting directly with rainwater. In addition, the location of Goa Giri spring, which is very close to the sea, causes the fractionation of heavier isotope ratios to fall first compared to lighter isotope ratios.

7.3. Recharge Area Analysis

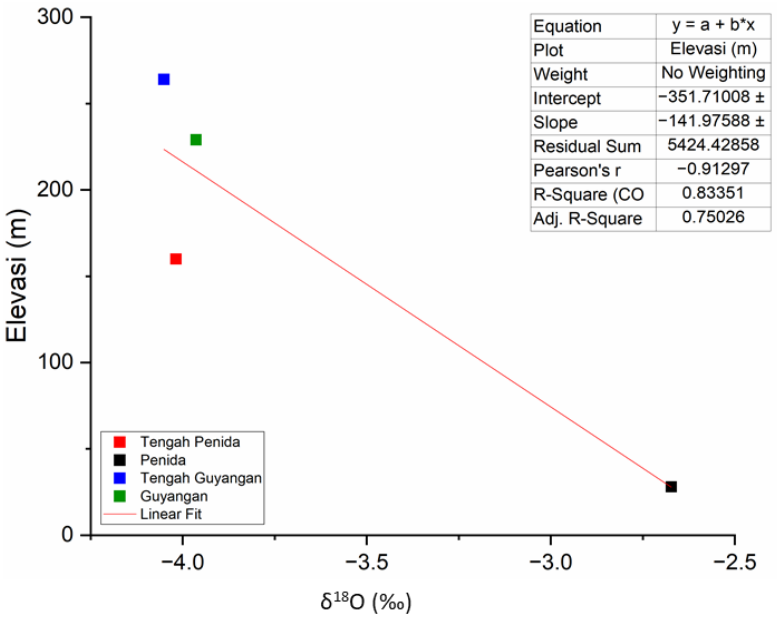
The water stable isotope approach ($\delta^{18}O$ and $\delta^{2}H$) was used in determining the recharge area in the Nusa Penida region. Water-stable isotopes will provide information on the processes that have taken place during water transportation to a location. Water-stable isotopes can also provide information about the water catchment area at that location. The results of laboratory analysis for rainwater stable isotope parameters around Penida and Guyangan springs and sampling elevations are shown in Table 3. The elevation of the catchment area can be determined based on the relationship between the ratio of oxygen-18 and deuterium isotopes to sampling elevation. A linear equation between the two values was determined based on this elevation and isotope data.

Table 3. Rainwater Stable Isotope Data and Sampling Elevation

Point of Rainfall	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Elevation (m)
Midle of Penida	-4.018	-15.259	160
Penida	-2.673	-1.882	28
Midle of Guyangan	-4.051	-15.732	264
Guyangan	-3.964	-14.86	229

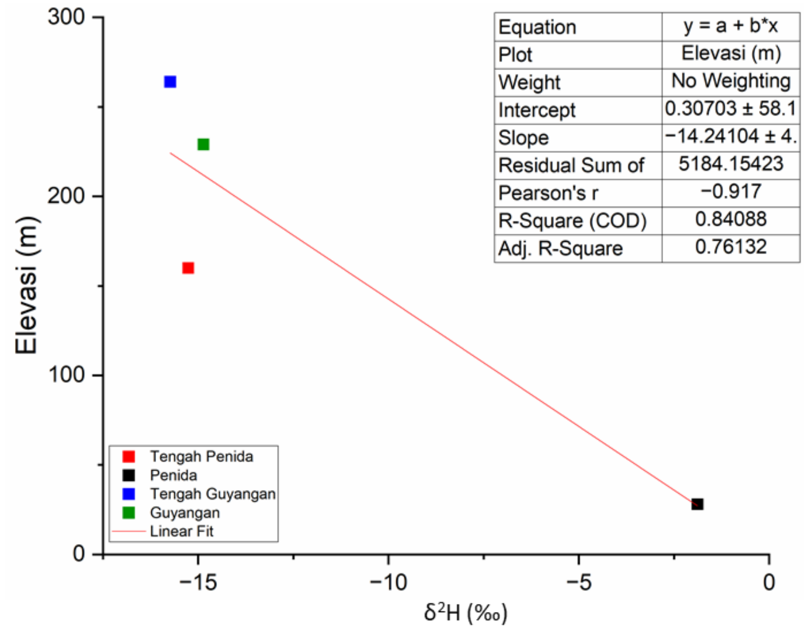
The cross plot between rainwater oxygen-18 isotopes and elevation is shown in Figure 12 with the linear equation E ($\delta^{18}O$) =-141.976 $\delta^{18}O$ - 351.71008.

Figure 10. Oxygen-18 correlation with elevation



In contrast, the plot between deuterium isotopes and elevation is shown in Figure 13 with the equation E (δ^2H) = -14.241 δ^2H + 0.307.

Figure 11. Deuterium correlation with elevation



These two equations will be used to calculate the recharge area elevation of the springs at the study site. The calculation table of the Nusa Penida catchment elevation for the Guyangan and Penida spring samples is shown in Table 4.

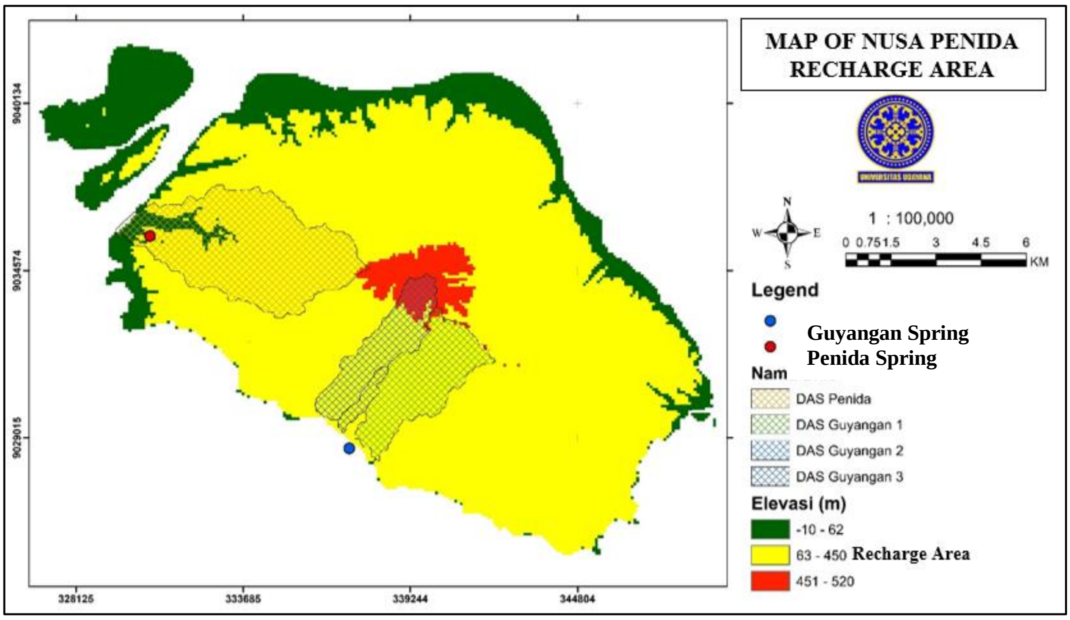
Based on the calculation results, it is known that, generally, the elevation of the recharge area for groundwater at the study site ranges between 62 m - 450 m. If applied to the research location, the recharge area is almost throughout Nusa Penida Island, with a relatively broad distribution. The recharge area can be seen on the elevation distribution map of this recharge area in Figure 14.

Table 4. Penida and Guyangan Springs Infiltration Area Elevation Calculation Table

Sample	Deuterium	Oxygen	Gradient	D intercept	O intercept	Correlation Factor of Topography	Elevation D	Elevation O
MA Penida	-28.672	-5.439	6	-27.87	-5.44	3.96	397.21	420.55
			6.1	-27.78	-5.29	4.51	395.86	399.70
			6.2	-27.66	-5.28	5.05	394.21	397.39
			6.3	-27.52	-5.26	5.60	392.15	394.49
			6.4	-27.33	-5.23	6.14	389.50	390.77
			6.5	-27.08	-5.19	6.68	385.96	385.80
			6.6	-26.73	-5.15	7.23	381.01	378.85
			6.7	-26.21	-5.07	7.77	373.59	368.42
			6.8	-25.34	-4.95	8.32	361.21	351.05
			6.9	-23.60	-4.70	8.86	336.46	316.29
			7	-18.39	-3.97	9.40	262.22	212.03
			7.1	-28.67	-5.44	9.95	408.62	420.55
			7.2	-39.25	-6.91	10.49	559.21	629.07
			7.3	-34.03	-6.17	11.03	484.96	524.81
			7.4	-32.29	-5.93	11.58	460.21	490.06
			7.5	-31.43	-5.81	12.12	447.84	472.68
			7.6	-30.90	-5.73	12.67	440.41	462.26
			7.7	-30.56	-5.68	13.21	435.46	455.31
			7.8	-30.31	-5.65	13.75	431.93	450.34
			7.9	-30.12	-5.62	14.30	429.28	446.62
			8	-29.98	-5.60	14.84	427.21	443.72
			average	-28.72	-5.43	max	409.26	419.56
						min	262.22	212.03
MA Guyangan	-29.9	-5.674	6	-26.92	-5.67	4.11	383.71	453.87
			6.1	-26.57	-5.12	4.68	378.64	375.52
			6.2	-26.13	-5.06	5.25	372.44	366.81
			6.3	-25.59	-4.98	5.81	364.69	355.93
			6.4	-24.89	-4.89	6.38	354.73	341.94
			6.5	-23.95	-4.75	6.95	341.44	323.28
			6.6	-22.65	-4.57	7.51	322.84	297.17
			6.7	-20.69	-4.29	8.08	294.94	257.99
			6.8	-17.42	-3.83	8.65	248.45	192.70

Sample	Deuterium	Oxygen	Gradient	D intercept	O intercept	Correlation Factor of Topography	Elevation D	Elevation O
			6.9	-10.89	-2.91	9.22	155.45	62.11
			7	8.70	-0.16	9.78		
			7.1	-29.93	-5.67	10.35	426.58	453.87
			7.2	-69.67	-11.19	10.92	992.41	1237.37
			7.3	-50.07	-8.43	11.49	713.42	845.62
			7.4	-43.54	-7.51	12.05	620.43	715.04
			7.5	-40.28	-7.05	12.62	573.93	649.74
			7.6	-38.32	-6.78	13.19	546.03	610.57
			7.7	-37.01	-6.59	13.76	527.43	584.45
			7.8	-36.08	-6.46	14.32	514.15	565.80
			7.9	-35.38	-6.36	14.89	504.18	551.81
			8	-34.84	-6.29	15.46	496.43	540.92
			average	-30.10	-5.65	max	428.99	450.14
						min	155.45	62.11

Figure 12. Nusa Penida Recharge Area



Based on the watershed analysis and hydrogeological analysis above, it is indicated that it is not possible for relatively large springs, such as Guyangan Spring and Penida Spring, to rely on water inputs from the catchment area alone. Although based on isotope analysis, it is known that the catchment area in Nusa Penida is spread over almost the entire area of Nusa Penida Island, the reliable discharge obtained is still much smaller to provide a relatively large discharge for Penida Spring and Guyangan Spring in particular. Considering the results of this analysis, it is reasonable to assume that the water source for these two springs is a mixture of rainwater and water from the subsurface stored in the limestone reservoirs/aquifers of Nusa Penida. There is also a possibility of groundwater flow in the aquifer beneath the Nusa Penida limestone formation from the southeastern part of Bali Island, which belongs to the Ulakan Formation.

Conclusion

This paper identifies aquifer recharge areas in a karst basin on Nusa Penida Island using the stable isotope ratios of hydrogen and oxygen combined with a hydrogeochemical approach. Based on the hydrogeochemical analysis, the groundwater type at the study site can generally be divided into three types: Na-Cl, mixed type, and Mg-HCO_3. Mixed-type water comprises rainwater samples from Goa Giri, Putri, Semabu Hotel boring well, and Penida spring. Furthermore, Tembeling spring, Segening spring, Guyangan Spring, and Tabuanan Spring are magnesium and bicarbonate (Mg-HCO_3) type water, which content in these water samples are thought to come from the dissolution of the limestone from which the springs flow. Na-Cl-type water is found in old water or near the sea at the Penida Spring. According to the calculation of water stable isotope results, it is known that, generally, the elevation of the recharge area for groundwater at the study site ranges between 62 m - 450 m. If applied to the research location, the recharge area is almost throughout Nusa Penida, with a relatively broad distribution. But it can be distinguished genesis of the Guyangan Spring and Penida Spring. The water source for Guyangan Spring and Penida Spring is likely a mixture of modern rainwater and water from the older groundwater that stored in the limestone reservoirs/aquifers of Nusa Penida, or it could be there is connection groundwater flow from the southeastern part of Bali Island with groundwater in Nusa Penida.

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Credit Authorship Contribution Statement

I Ketut Ariantana: Conceptualization, Investigation, Methodology, Project Administration, Formal Analysis, Writing – Original Draft, Funding Acquisition.
Made Sudiana Mahendra: Supervision.
I Wayan Nuarsa: Supervision.
I Wayan Sandi Adnyana: Supervision.
Lambok Hutasoit: Supervision.
Irwan Iskandar: Investigation and Supervision.
Mustiatin: Formal Analysis.
Putu Doddy Heka Ardana: Formal Analysis, Supervision, Validation, Writing - Review and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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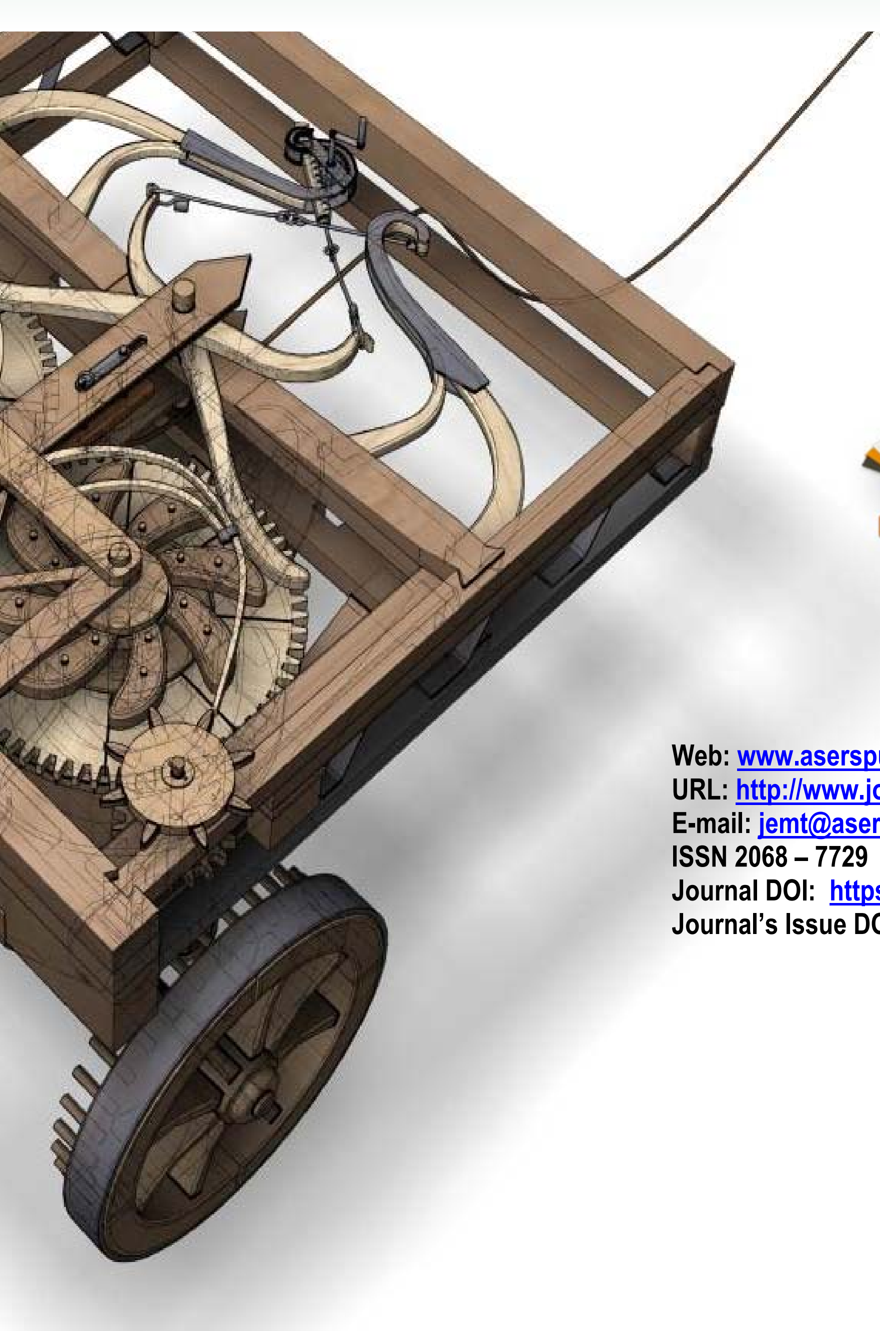

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