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Isotope Analysis of Coastal Groundwater in Padang City: Implications for Recharge and Salinization

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Abstract - The development of Padang City in the coastal area is potentially faced with seawater intrusion. This study was conducted to determine the characteristics of shallow groundwater on the coast of the city using stable oxygen -18 (^{18}O) and hydrogen -2 (^{2}H) or deuterium isotopes, which are abundant in the nature. The isotopic analysis revealed variations in groundwater isotopic composition, indicating the possibility of diverse recharge sources. Although this study was primarily focused on salinity identification, the isotopic data provided preliminary insights into the influence of local meteoric recharge. Water samples were taken at several locations 5 m below the ground surface, and one sample of seawater was collected at an elevation of 0 m, which comes directly from sea water. On the average, they were located 270 m from the sea. The spectrometry of these water samples produced isotope ratios expressed per thousand or mil, which were then plotted on a graph illustrating the relative abundances of oxygen (^{18}O) and deuterium (^{2}H). Analyses of the stable ^{18}O and ^{2}H isotopes found two water samples close to the local meteoric water line (LMWL) and one sample interacting or mixing with seawater. The mixing effect is likely the product of evaporation and interaction between water and oxide minerals that compose the aquifer lithology, i.e. loose (sand) deposits. Based on the electrical conductivity, these samples had brackish water.

Keywords: coastal, deuterium, intrusion, isotope, meteoric, Padang City

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Introduction

Padang City, the capital of West Sumatra Province, Indonesia, has developed on the western coast of Sumatra Island, bordered by the Indian Ocean to the west and volcanic hills, the Bukit Barisan, to the east. In general, the city development centre is located 13 to 15 km from the coastline. Continued urban development, including the expansion of settlement areas (Ni'mah and Lenonb, 2017) and the increasing population has led to an increase in groundwater extraction for daily domestic needs (Vogelbacher *et al.*, 2019).

Groundwater characteristics are significantly influenced by geological features that determine their capacity for storage and flow (Manga and Wang, 2007; Acworth, 2019; Febriarta *et al.*, 2022). Figure 1 illustrates the distribution of unconsolidated deposits that form an aquifer lithology along the coastline. Based on regional geology, the Padang coastal area is situated on surficial deposits (Kastowo *et al.*, 1996; PSG,

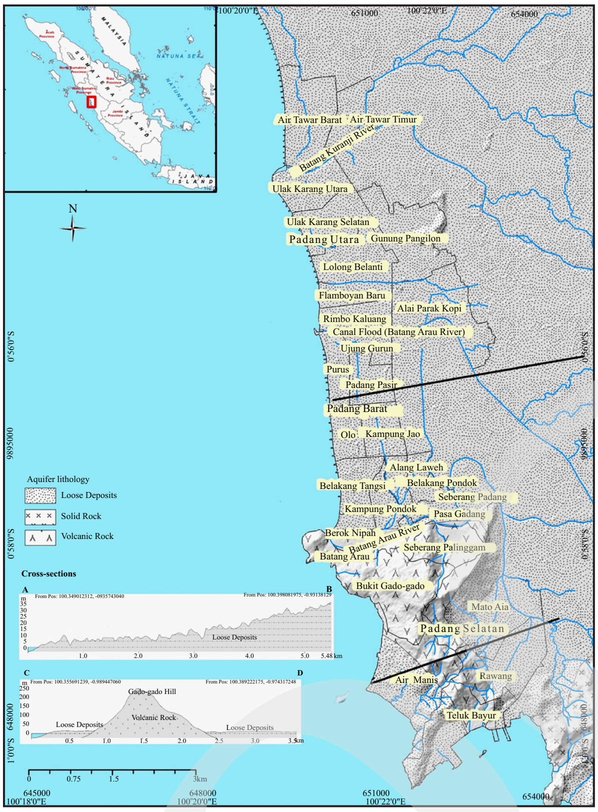

Figure 1. Researched location is on the coast of Padang City, whose aquifer is lithologically composed of loose sediments like sand (Source: PATGTL, 2015a).

2018), namely the Alluvium Deposits (Qal) consisting of silt, sand, and gravel, commonly found in coastal plains, including swamp deposits in the north and east of Padang. This formation extends along the coast at varying elevations from 5 to 15 m asl. The southern coast is a combination of hilly morphology with alternating andesite layers (QTa - Andesite Formation; old volcanic andesite and tuff) and lowland geologically composed of the same Alluvium Deposits as the central and northern coasts (Qal; unconsolidated deposits, *i.e.* boulders, gravel, sand, clay, and peat) (PSG, 2018). Based on the rock formations, groundwater is found within an intergranular aquifer system (intergranular pore spaces).

Padang serves as a discharge area for the Padang-Pariaman Groundwater Basin (PATGTL, 2018), with groundwater flow directions towards the southwest-south (flow network) (Permen ESDM, 2017). Morphologically, the discharge zone originates from the foothills of the volcanic Bukit Barisan mountain range. Sand is the dominant unconsolidated sediment composing the aquifer lithology, resulting in a highly productive aquifer with extensive distribution, moderate to high transmissivity, and a discharge potential exceeding 10 l/sec. (PATGTL, 2015b). Generally, the city coastal area features an unconfined aquifer. This characteristic implies that the groundwater is recharged from areas located at a considerable distance from the discharge zone or at higher elevations (Foppen *et al.*, 2020).

Generally, unconfined aquifers can be identified as groundwater basins with significant recharge or where multiple groundwater flows from distant recharge zones converge regionally (Gross *et al.* 2019; Purnama *et al.*, 2019). However, urban infiltration potential is categorized as having critical (poor) conditions, found in 18 % of the area (Guvil *et al.*, 2019). Additionally, shallow groundwater with high water movement is potentially susceptible to quality degradation. Based on these conditions, it is crucial to identify the groundwater characteristics in the coastal area of Padang City.

For long-term preservation and protection, groundwater management units based on local groundwater basins are necessary to facilitate monitoring and evaluation (Sobeih *et al*., 2017; Bastani and Harter, 2020). Gross *et al*. (2019) stated that identifying the sources of groundwater supply or recharge is the first step in groundwater management. Stable isotope analysis can help indicate the origin (Kharisma *et al*., 2015; Wijatna *et al*., 2019; Febriarta *et al.,* 2022; Poetra *et al*., 2023). The stable isotope ratios of oxygen (^{18}O) and hydrogen, namely deuterium (^{2}H), illustrate the isotopic similarity or relative proximity of groundwater to rainwater within the hydrological cycle (Talabi, 2013; Benaafi *et al*., 2022). Therefore, this study focuses on mapping the shared hydrochemical characteristics between groundwater and rainwater as potential sources using two stable isotopes: oxygen (^{18}O) and deuterium (^{2}H). This research aims to identify the origin of groundwater and groundwater recharge areas in the coastal city of Padang.

Scientific advancements in isotope hydrology have demonstrated the high effectiveness of stable isotope analyses of oxygen (^{18}O) and deuterium (^{2}H) in understanding coastal groundwater dynamics (Kendall and McDonnell, 1999). Previous studies have successfully identified seawater intrusion and mixing processes in various coastal regions (Talabi, 2013; Benaafi *et al.*, 2022). However, this research offers a novel aspect by focusing on the Padang City coast, which has specific geological and hydrological conditions, namely a loose sediment aquifer with critical infiltration potential (Guvil *et al.,* 2019). Furthermore, this study emphasizes the identification of specific hydrochemical characteristics through isotope ratios between groundwater and precipitation as potential sources, in areas with critical infiltration conditions. This research will also examine the influence of interactions between water and oxide minerals in the aquifer lithology on the isotopic composition of groundwater. Another novel aspect is that this study will identify the influence of interactions between water and oxide minerals present in the aquifer lithology on the isotopic composition of groundwater.

The primary focus of this research is to identify the potential for seawater intrusion and shallow groundwater resources in the coastal area of Padang City. This issue is approached theoretically through the concept of isotope hydrology, which utilizes natural variations of stable isotopes oxygen (^{18}O) and deuterium (^{2}H) to trace the origin and interactions of groundwater (Clark and Fritz, 1997). This approach enables the differentiation between groundwater originating from local precipitation (meteoric water) and seawater, as well as the understanding of mixing processes that occur. The specific study object is the isotopic characteristics of shallow groundwater at a depth of 5 m below the ground surface, compared to seawater as an endmember. Specifically, this research identifies the isotopic characteristics of shallow groundwater and compare groundwater with seawater as an endmember to determine the existence of seawater intrusion.

Data and Methodology

Water Sampling

The researched area is the coastal area of Padang, which is the city centre and administratively belongs to Padang Utara (north), Padang Barat (middle), and Padang Selatan (south) Districts. Three water sampling points were determined based on the presence of hydrological features, *i.e.* rivers, that create barriers for groundwater flows to the discharge zone or the sea (Younger, 2007). The coastal city is traversed by several major rivers, forming three large groundwater areas: the northern part is flanked by Lubuk Menturun and Batang Kuranji Rivers; the middle one by the Batang Arau River and its tributary, the East Flood Canal; and the southern part is fenced by Bukit Gado-Gado, a volcanic hill. Figure 2 and Table 1 show the water sampling locations (coordinates were recorded with a global positioning system (GPS). Spatial coordinates are referenced using the UTM Zone 47S projection. Three groundwater and one seawater samples (50 ml each) were

Figure 2. Map of the water sampling points (GW: Groundwater, S1:Seawater).

Table 1. Water Sampling Locations

No	X	Y	Z (masl)	ID	Location	Water Type
1	652475	9890774	4	GW1	Air Manis, South Padang	Groundwater
2	650527	9895363	4	GW2	Olo, West Padang	Groundwater
3	649694	9900573	5	GW3	Air Tawar Barat, North Padang	Groundwater
4	650309	9896210	0	S1	Purus, West Padang	Seawater

collected and stored in an airtight bottle for the stable isotope analysis. Here, the seawater sample is a reference for the isotope ratio of the freshwater samples.

Water samples for isotopic analysis were collected using clean, tightly sealed HDPE bottles to prevent evaporation and contamination. Bottles were rinsed multiple times with the water to be sampled prior to filling. Samples were filled to the brim to minimize headspace and to reduce evaporation. For groundwater, sampling was conducted after purging the well for a sufficient period to ensure the collected water represented aquifer conditions. Samples were stored in a cool, dark place to prevent changes in isotopic composition. and then shipped to the laboratory for analysis as soon as possible.

Correlation Analysis between Electrical Conductivity and Salinity

Electrical conductivity measures the ability of water to conduct electricity (Fetter, 2014). Dissolved ions of the salt compound in water also have the ability to conduct electricity quickly. Therefore, this correlation can be used to indicate salinity (Ma *et al.*, 2017; Cahyadi, 2019; Febriarta and Widyastuti, 2020; Hounsinou, 2020). The electrical conductivity used for this purpose is presented in ranges of values in Table 2.

Table 2. Correlation between Electrical Conductivity and Salinity

No	Electrical Conductivity (µS/cm)	Salinity
1	< 1,500	Freshwater
2	>1,500 - ≤ 5,000	Slightly brackish
3	>5,000 - ≤ 15,000	Brackish
4	> 15,000 - ≤ 50,000	Saline
5	> 50,000	Brine

Estimating the Elevation of Recharge Point

Identifying the recharge point means estimating the elevation at which rain falls and seeps into the ground. For this purpose, a logarithmic-linear equation was used as it identifies the equation of an unknown variable or variable value. For the isotopic characteristics, this research did not take any rainwater samples, but used a reference from Haryono *et al*. (2022). The coordinates, locations, and isotope ratio are presented in Table 3.

Table 3. Rainwater Isotopes of Tapaktuan, Aceh Selatan Regency

X	Y	Z (masl)	ID	Location	δ 18O
312281	346728	6	R1	Ujung Pandang Asahan	-4.839
317439	346774	526	R2	Pondok Gunong Pulo	-11.146

The $\delta\ ^{18}O$ and elevation (Z) obtained were processed with a logarithmic-linear approach. As a result, the equation y= -79.118x - 374.89 was obtained (Figure 3). To calculate the elevation of the recharge point (*y*), the *x* was substituted with the $\delta\ ^{18}O$ value measured from field-derived data.

Hydrogen ($^{18}0$) and Deuterium (^{2}H) Isotope Analysis

The isotopic composition of a compound can be altered due to evaporation, condensation, freezing, chemical reactions, or biological processes, collectively known as isotopic fractionation. For instance, hydrogen (H) atoms in groundwater derived from rainwater infiltration are generally located close to the local meteoric water line, except when the groundwater undergoes changes, such as oxygen ^{18}O exchange with

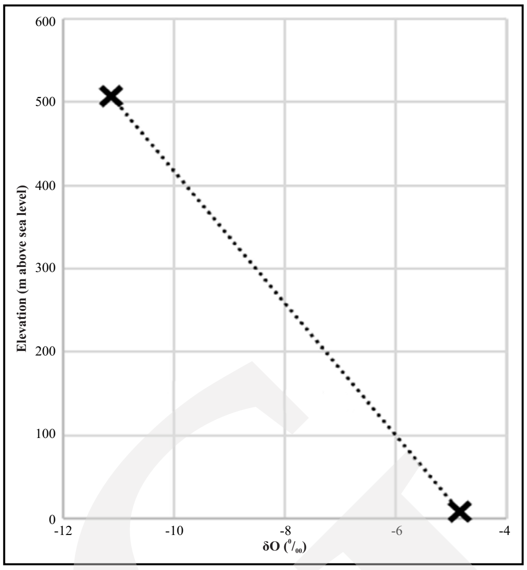

Figure 3. Interpolation between the elevation of the rainwater sampling point and the $\delta^{18}O$ value.

O (Singhal and Gupta, 2010; Wati *et al*., 2020). On the contrary, due to the mixing of atoms or evaporation, the ^{18}O and ^{2}H correlation graph deviates or is situated away from the LMWL (Clark, 2015).

The water samples were analyzed using a mass spectrometer, which is a tool or instrument that can determine the chemical structure of organic molecules based on their atomic mass and fragmentation pattern. Isotopic fractionation in every phase of the hydrological cycle results in unique isotopic compositions. The abundance, or deviation, of stable isotope ratio relative to Standard Mean Ocean Water (SMOW) is expressed in delta (δ) per mil or parts per thousand (‰) (White, 2015). First, the molecular concentration was converted into $^{2}H/^{1}H$ and $^{18}O/^{16}O$ values, then $\delta^{2}H$ and $\delta^{18}O$ were calculated according to SMOW using the formulas below (Polonia *et al*., 2016; White, 2015).

Relative abundance of oxygen-18 (^{18}O), denoted by $\delta^{18}O$:

$$\delta^{18}O\left(\frac{RO-18\ (water\ \text{sample})}{RO\ (SMOW)}-1\right)x1000‰ \quad \ldots\ldots\ldots\ (1)$$

Relative abundance of deuterium (^{2}H), denoted by $\delta^{2}H$:

$$\delta H \left(\frac{RD - 18 \; (water \text{ sample})}{RD \; (SMOW)} - 1 \right) x1000 ‰ \text{ .... (2)}$$

RD and RO-18 are the relative abundances of the composition ratios $^2H/^1H$ dan $^{18}O/^{16}O$. Stable isotope tests for $\delta^{18}O$ dan δ^2H were obtained from the laboratory of the Centre for Groundwater and Environmental Geology (Geology Agency, Indonesia Ministry of Energy and Mineral Resources). Furthermore, the origin of the groundwater was analyzed using a graphical correlation by plotting the relative abundances of $\delta^{18}O$ dan δ^2H against the LMWL (Setiawan *et al.*, 2018; Seizarwati, 2019; Satrio *et al*., 2020). Furthermore, the rainfall values were plotted in relation to The Global Meteoric Water Line (GMWL), defined by the equation $\delta^2H= 8\delta^{18}O + 10$ (Craig, 1961). In general, the distance between the sample points and the LMWL indicates the degree of similarity between the water samples and the water source (*i.e.* rain). For instance, a sample point close to the LMWL means the analyzed groundwater comes from rainwater with a local hydrological cycle. In this research, the LMWL of Riau δD= 7.60dO+10.5, LMWL of Langkat δD= 8.052dO+14.162, LMWL of Danau Toba δD= 7.74dO+7.82, and LMWL of Tapaktuan (Aceh Selatan, Indonesia) δD= 9.2207dO+23.448 (Haryono *et al*., 2022) were used as the local meteoric reference, because it has the same characteristic as the studied area, which is on the western coast of Sumatra Island.

Result and Discussion

Isotope Results

Four water samples were collected at varying elevations from 0 to 5 m asl. on the coast of Padang City, and oxygen-18 (^{18}O) and hydrogen or deuterium (^2H) were used for their stable isotope analyses. GW1 was 345 m from the shoreline, GW2 179 m, and GW3 168 m. In addition, the isotope composition of the seawater sample (S1) was also tested as a reference for analyzing the effects of seawater. As presented in Table 4, the measured $\delta^{18}O$ dan δ^2H showed very small deviation values, indicating statistically sound results to be further used in the plotting analysis.

Electrical Conductivity And Salinity

Electrical conductivity correlates with the degree of salinity that can aid in assessing water quality (Gaikwad *et al*., 2020). Table 4 shows electrical conductivity ranging in values from 348 to 844 µS/cm, which, according to the EC-salinity correlation in (Suherman, 2007; Febriarta and Widyastuti, 2020), is classified as freshwater. In comparison, the seawater sample (S1) had an EC of 30,300 µS/cm. The EC data consistently reflects salinity levels, validating the use of EC as a water quality indicator. GW1, located in the southern segment of the coast, had the highest EC of 844 µS/cm. This might result from the morphology of the area that is bordered by a volcanic hill (Bukit Gado-Gado) to the east that is impermeable and has a small catchment (potentially low water recharge). Volcanic hills act as natural barriers, limiting groundwater recharge and leading to increased salinity in GW1. In contrast, GW2 in the middle segment had the smallest EC of 348 µS/cm, although it was the closest point to the coastline compared with other samples. The influx of freshwater from the flood control canal exerts a significant dilution effect, thereby reducing salinity in GW2. This condition was likely due

Table 4. Isotope Measurement Results on the Coast of Padang City

No	ID	Location	Water Sample	EC (µS/cm)	δ ^{18}O	δ ^{2}H	SD ^{18}O	SD ^{2}H
1	GW1	Air Manis, South Padang	Groundwater	844	-7.914	-50.170	0.258	0.524
2	GW2	Olo, West Padang	Groundwater	348	-9.366	-60.389	0.249	0.507
3	GW3	Air Tawar Barat, North Padang	Groundwater	538	-7.826	-48.945	0.250	0.502
4	S1	Purus, West Padang	Seawater	30.300	-1.200	-8.356	0.214	0.488

(Source: Data analysis, 2022)

to the influence of freshwater movement in the flood canal towards the nearby estuary, diluting the dissolved salt ions. The satellite image (see Figure 2) shows a lighter hue of the seawater around S1, indicating a potential mixture of seawater and freshwater-which is associated with a turbid colour representing mud from erosion in the watershed (He *et al*., 2022).

Elevation of the Recharge Point

The elevation is expressed in meters above sea level (m asl.). Interpolation was conducted between the elevation of the rainwater sampling point and the $\delta^{18}O$ value (see Figure 3) to obtain an equation to approximate at which elevation rain fell and replenished the groundwater at each sample point. The assumption was that the $\delta^{18}O$ of the rainwater did not change when it reached the surface and was transported to the sample point (Haryono *et al.,* 2022). The $\delta^{18}O$ value is more commonly used to determine the origin of groundwater, because it is fractionated more than $\delta^{2}H$. Calculations showed that the recharge point ranged in elevation from 244 to 366 m asl. as summarized in Table 5.

Based on the estimated elevation (Figure 4), GW1 was recharged from a height of 251.23 m asl., which topographically points to the volcanic hill Bukit Gado-Gado in the south. The origin of groundwater at GW2 was estimated at 366.14 m asl. or around the foot slope of Bukit Barisan, the old volcanic hills traversing the middle of Sumatra Island. It was predicted that GW3 was replenished from an elevation of 244.27 m asl. Although it is nearly as high as the origin of GW1, the topographical condition indicates the foot slope of Bukit Barisan (instead of Bukit Gado-Gado). In conclusion, GW2 and GW3 have the same recharge area, *i.e*. the foot slope of the old volcanic hills, Bukit Barisan.

Hydrogen (^{18}0) and Deuterium (^{2}H) Isotope Analysis

Results showed that the groundwater samples had heterogeneous $\delta^{18}O$ and $\delta^{2}H$ (Figure 5) from -7.8 to -9.3 and from -48.9 to -60.3, respectively. Based on the $\delta^{18}O$ vs. $\delta^{2}H$ graph, the three groundwater samples were plotted very close. Graphical analysis revealed negative values: a more negative relative abundance indicates a farther recharge point. GW2 had the lowest $\delta^{18}O$ and $\delta^{2}H$ values, meaning the groundwater was replenished from the most distant point or a wide area (regional recharge), as confirmed by the relative abundance ratio. Based on the estimated elevation of the recharge site, it corresponds to the most distant elevation identified, 355.14 m asl. on the foot slope of the old volcanic hills. The negative relative abundance might also be caused by surface runoff or water flow in the flood canal, which is a tributary of the Batang Arau River with the main stream length of 24 km starting from Bukit Barisan. At low elevations, there is a potential for mixing between: groundwater originating from regional recharge (high elevations), local rainwater infiltrating into the soil, surface water from rivers or flood channels (*e.g.* Batang Arau River), and seawater with potential intrusion

The relative abundances of GW1, GW2, and GW3 were close to and on the LMWL of Tapaktuan, signifying isotopic similarity between the groundwater samples and rainwater. However, the isotope abundance ratio of GW1 was between that of GW2 and GW3, indicating a recharge area smaller than GW2 but larger than GW3. Estimations showed that GW1 originated at 251.23 m asl., and because it was located in an alluvial plain isolated by old volcanic hills, Bukit Gado-Gado, the recharge point was presumedly located at the hills.

Table 5. Estimated Elevation of the Groundwater Recharge Point

No	Z (masl)	ID	$\delta^{18}O$	Equation	Elevation	Recharge area
1	4	GW1	-7.914	-79.118 x -7.914 - 374.89	251.23	Volcanic hills (Gado-Gado hill)
2	4	GW2	-9.366	-79.118 x -9.366 - 374.89	366.14	Foot slope of old volcanic hills (Barisan Mountains)
3	5	GW3	-7.826	-79.118 x -7.826 - 374.89	244.27	

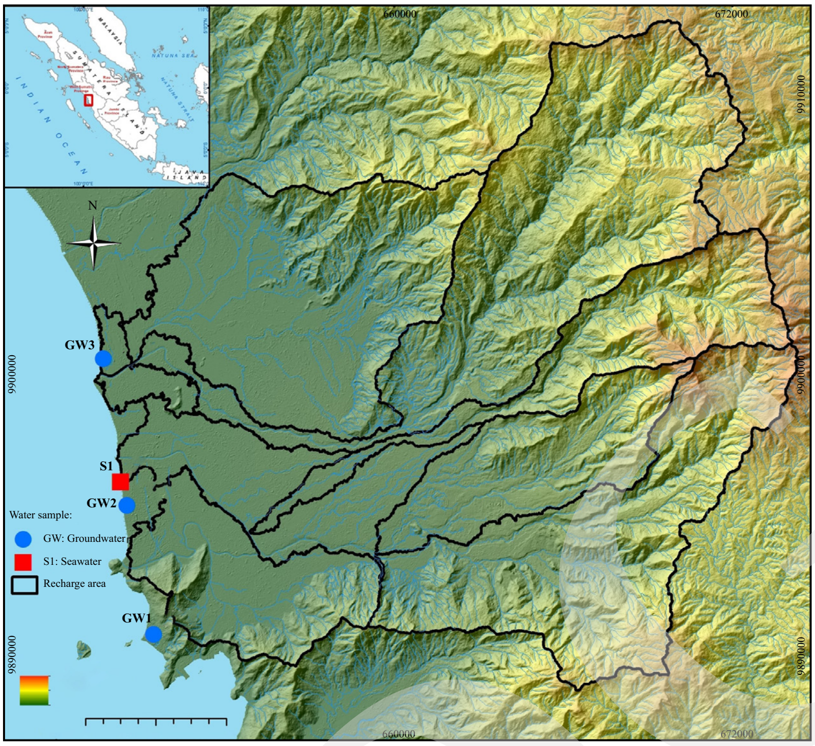

Figure 4. Delineation of Groundwater Recharge Areas: Gado-Gado Hill and Barisan Mountains.

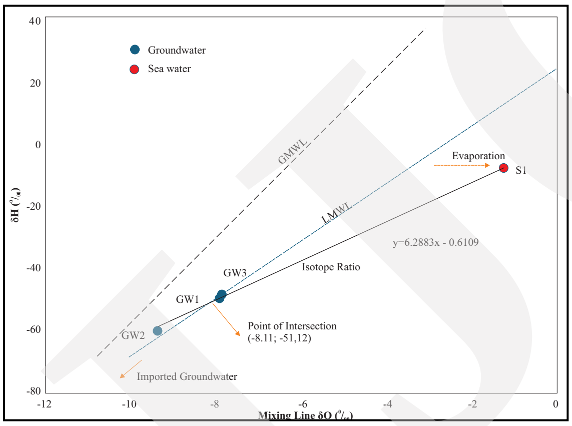

Figure 5. Isotope ratio plots showing the three groundwater samples close to or on the local meteoric water line.

The relative abundance of ^{18}O and ^{2}H in GW3 (northern coast) was the highest, indicating the smallest groundwater recharge area. Cross-section C-D (Figure 1) indicates that the GW3 area is situated in a low-lying region with shallow, unconsolidated deposits. This cross-section supports the potential influence of surface runoff and swamps on local recharge. In comparison, this area would be smaller than the recharge zone of GW1 or Gado-Gado Hill. It was located at the lowest elevation, 244.27 m asl., and topographically surrounded by surface flow in the south (a tributary of Batang Kuranji River) and swamps in the north. These groundwater characteristics were different from GW1, which was hemmed in by volcanic hills. Cross-section A-B (Figure 1) indicates that Gado-Gado Hill is composed of volcanic rocks, while the GW1 area is situated within an alluvial plain characterized by unconsolidated deposits. This cross-section demonstrates an elevation gradient from Gado-Gado Hill to the alluvial plain, supporting the potential for groundwater flow

Figure 5 shows an increase in the ratio value (positive) of the seawater sample (S1), representing the evaporation of surface water. Based on the trendline of the four water samples, derived from using the isotopic composition of the seawater sample, an equation or a mixing line was obtained, $\delta^2H = 6.2883\ \delta\ ^{18}O - 0.6109$. Moreover, this line intersected the LMWL at the coordinates of -8.11, -51.12. The intersection point was the initial isotopic composition of groundwater (fresh water) prior to mixing with seawater due to intrusion. As seen from the graph in Figure 5, the isotopic composition of GW3 correlated with the high electrical conductivity close to slightly brackish.

Conclusions

Groundwater on the coast of Padang City shares similar isotopic composition with rainwater (source) based on the analyses of two stable isotopes: oxygen-18 (^{18}O) and hydrogen or deuterium (^{2}H). Also, the groundwater in the southern and northern coastal areas has a narrow or local recharge area. In contrast, the one in the middle segment has the farthest replenishment point or, thus, a regional recharge area. Electrical conductivity (EC) analysis reveals variations in groundwater salinity along the coast of Padang City. Although all groundwater samples (GW1, GW2, GW3) fall under the category of fresh water based on EC values, significant differences exist among them. GW1 exhibits the highest salinity, potentially due to limited groundwater recharge by impermeable volcanic hills. GW2 shows the lowest salinity, presumably due to dilution effects from fresh water flow from flood control canals.

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