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Regional Case Study

Isotope Analysis of ^{18}O and ^{2}H: A Coastal Confined Aquifer Case Study

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Abstract
In 2023, groundwater quality in Semarang declined due to excessive extraction, leading to land subsidence and reduced groundwater availability. Prolonged dry seasons caused drought in ten villages across five sub-districts. This study aims to investigate geological conditions, groundwater flow patterns, and the spatial distribution of pH, TDS, hardness, electrical conductivity, and major ions (Na^+, Ca^{2+}, Cl^-, and HCO_3^-). Additionally, it seeks to interpret groundwater evolution through Gibbs diagram analysis and identify groundwater origins using stable isotopes (^{18}O and ^{2}H). The methodology involves stable isotope analysis to trace groundwater sources and evaluate d-excess values, which are linked to drought conditions and recharge mechanisms. Water chemistry analysis was performed to characterize ion concentrations, while the Gibbs diagram was used to identify the dominant geochemical processes influencing groundwater. The study area comprises claystone, marl, sandstone, volcanic breccia, and alluvium, with 60 sampling points spanning Upper and Lower Semarang. Water types identified include $NaHCO_3$, NaCl, $CaHCO_3$, $MgHCO_3$, and $NaSO_4$. $NaHCO_3$ was the most common, followed by NaCl and $CaHCO_3$. Isotope analysis revealed several points with d-excess <10 (e.g., SB-10L, SB-20L, SA-4, SA-8, SA-29), indicating groundwater recharge from modern rainfall, typically characterized by d-excess values >10.

Keywords: Chemical and physical characteristics; d-excess, drought; Semarang groundwater; stable isotopes

1. Introduction

Groundwater is a crucial component of the global freshwater supply, stored and transmitted through porous soil and rock beneath the Earth's surface. It serves as a primary source of water for domestic, agricultural, and industrial use, particularly in regions experiencing surface water scarcity. In Indonesia, groundwater availability is estimated at approximately 4.7 trillion cubic meters per year, distributed across 224 groundwater basins (Rejekiningrum, 2009). Significant shares are found in Java-Madura (24.9%), Sumatra (21.3%), Kalimantan (17.7%), Sulawesi (7.6%), Papua (4.6%), and other islands (23.9%) (Direktorat Geologi Tata Lingkungan, 2018). Despite this potential, rapid urbanization, population growth, and unsustainable extraction practices have placed increasing pressure on groundwater systems, especially in coastal urban centers.

Semarang City, located along the northern coast of Central Java, has been experiencing serious groundwater challenges, particularly in recent years. In 2023, reports indicated a substantial decline in groundwater quality due to excessive extraction, leading to land subsidence and increased vulnerability to seawater intrusion (Gusti, 2023), combined with land subsidence and seawater intrusion, has led to a decline in groundwater quality and quantity. These issues are exacerbated by global sea level rise (3–5 mm/year) and land subsidence, which in some areas reaches up to 9 cm/year (Gusti, 2023). In 2023, prolonged dry conditions caused water shortages in 10 urban villages across five districts, Tembalang, Banyumanik, Mijen, Ngaliyan, and Gunungpati, highlighting the growing vulnerability of urban water security in the region (Pemkot Semarang, 2023).

This situation reflects a broader phenomenon of hydrological drought, characterized by reduced river discharge and groundwater levels due to insufficient rainfall (Rosyidie, 2013). Such conditions not only reduce surface water availability but also hinder groundwater recharge, increasing the susceptibility of aquifers to degradation and overuse. In coastal urban environments like Semarang, understanding the dynamics of groundwater recharge, flow, and quality under drought conditions is critical for ensuring sustainable water management.

To address this, scientific approaches combining hydrochemical and isotopic analyses have proven effective in characterizing groundwater systems. The Gibbs diagram, which relates total dissolved solids (TDS) to ionic ratios, helps to identify dominant geochemical processes such as precipitation influence, evaporation, or rock–water interaction (Marandi & Shand, 2018). Stable isotope ratios of oxygen-18 (^{18}O) and deuterium (^{2}H) are widely used to trace groundwater sources and recharge pathways (Setiawan et al., 2020). Furthermore, the deuterium excess (d-excess) parameter offers additional insight into the origin and evaporation history of precipitation, aiding in the interpretation of groundwater–atmosphere interactions (Bershaw, 2018).

Previous studies have examined the hydrogeology of Semarang, but a comprehensive understanding of the geochemical evolution and recharge mechanisms of its confined aquifers—especially during drought, remains limited. In particular, there is a lack of integrated studies combining stable isotope techniques and hydrochemical analysis to assess groundwater origins, mixing processes, and vulnerability to seawater intrusion or evaporation. To address this gap, the present study investigates the physical, chemical, and isotopic characteristics of groundwater in Semarang using two key approaches: (1) the Gibbs diagram to identify dominant hydrochemical processes (e.g., precipitation, evaporation, rock-water interaction), and (2) stable isotope analysis of $\delta^{18}O$ and $\delta^{2}H$ to trace groundwater sources and evaluate deuterium excess (d-excess) values. The integration of these methods provides a robust framework for understanding the spatial variability of groundwater recharge and salinization processes under drought-prone conditions. Ultimately, this study aims to contribute to improved groundwater management in Semarang by identifying critical zones affected by seawater intrusion, high mineralization, or shallow recharge, and offering data-driven recommendations for sustainable well utilization during dry seasons.

2. Methods

The study, conducted from July to August 2023, focused on multiple locations across Semarang City. spanning Gunungpati, Banyumanik, Mijen, Tembalang, South Semarang, Ngaliyan, Gajahmungkur, Candisari, Pedurungan, and Jatibarang. The research methodology involved extensive fieldwork to gather data on lithology types, geological structures, landforms, and hydrogeological conditions within the study area. Sixty groundwater samples were collected directly from bore wells owned by companies and residents in these locations. These samples underwent analysis to characterize groundwater, utilizing ^{18}O and ^{2}H isotopic data alongside chemical assessments of water quality at each research site.

2.1 Study Area

The study area, the city of Semarang, is located in the central part of Java Island, Indonesia. It serves as the capital of Central Java province and is bordered by the Java Sea to the north, Demak Regency to the east, Semarang Regency to the south, and Kendal Regency to the west. Semarang is positioned astronomically between 6°50' – 7°10' South Latitude and 109°35' – 110°50' East Longitude.

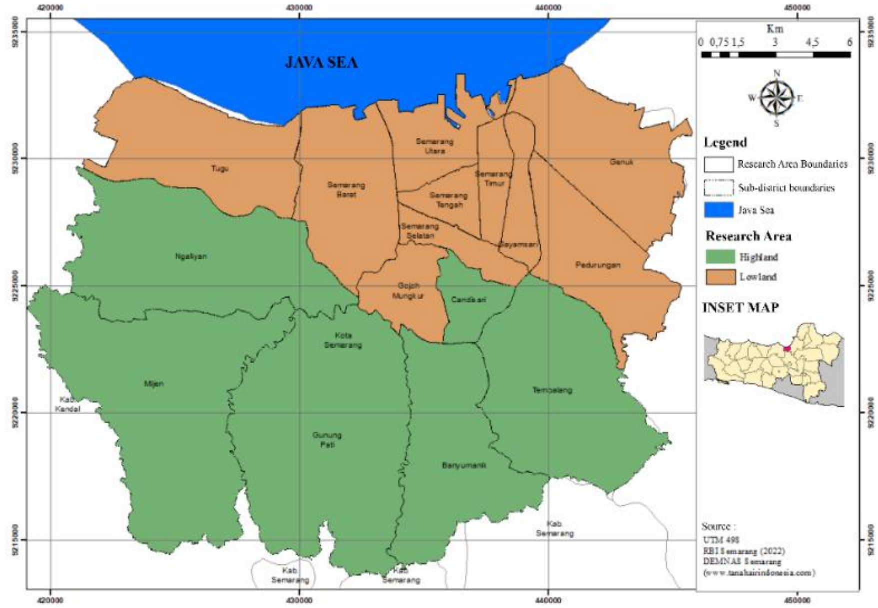

Figure 1. Research area

2.2. Preparation and Data Collection

Data collection in this study involved multiple steps. First, secondary data such as regional geological and hydrogeological maps, RBI maps, Digital Elevation Model (DEM), and borehole distribution maps were gathered to understand the study area's geological, geomorphological, and hydrogeological characteristics. Field observations were conducted to record lithology, morphology, and land use. Additionally, groundwater samples were collected directly from boreholes for chemical and isotopic analysis ($\delta^{18}O$ and $\delta^{2}H$). 60 sample points were selected from boreholes in the Semarang area. These collected data were used to analyze groundwater characteristics, including the geochemistry and isotopic content, to understand the groundwater's source and evolution.

2.3. Data Processing

The data processing stage involved multiple steps to achieve the research objectives. Geological data processing was carried out to determine the distribution of lithology and morphology using geological and geomorphological data, which were analyzed with supporting software. The groundwater table (MAT) data were processed through interpolation using the Kriging method. This process began with preparing an Excel file containing the coordinates (x, y) and MAT values, which were then processed using ArcGIS software to generate spatial representations of groundwater levels.

Physical and chemical data, including pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Hardness, were processed for each sample. The interpolation method using minimum curvature was applied, as it produced the smallest root mean square (RMS) value. This approach facilitated the generation of interpolated pH, TDS, EC, and Hardness distributions across the study area.

The Gibbs diagram was plotted by creating a scatter plot where the ratio of sodium/(calcium + sodium) was represented on the x-axis, while total dissolved solids (salinity) were plotted on the y-axis. This diagram was utilized to analyze groundwater evolution and understand the processes influencing groundwater quality over time and distance.

Isotopic data processing was conducted to analyze the isotopic composition of groundwater using $\delta^{18}O$ and $\delta^{2}H$ values. This analysis utilized the Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) equations to determine whether the groundwater originated from local or global precipitation sources. For instance, using the GMWL equation ($\delta D = 8\ \delta^{18}O + 10$), with a $\delta^{18}O$ value of -5.798, the resulting δD was calculated as -36.816. Similarly, the LMWL equation ($\delta D = 8.55\ \delta^{18}O + 16.76$) yielded a δD value of -32.816. Additionally, d-excess values were calculated to assess the influence of evaporation on the groundwater samples. The d-excess, determined by the formula d-excess = $\delta^2H - 8\ \delta^{18}O$, resulted in a value of 10.108, based on a δ^2H value of -36.280. These analyses provided valuable insights into the origin of the groundwater and its potential interactions with atmospheric and surface water sources.

3. Result and Discussion

3.1. Geological Condition

The lithology in the study area includes alluvium, sandstone, marl, claystone, andesite breccia, and andesite, comprising formations like the Kerek Formation, Kalibeng Formation, Damar Formation, Kaligetas Formation, Gajahmungkur Volcanic Rock, Kaligesik Volcanic Rock, and Alluvium (Figure 2). The claystone of the Kerek Formation is characterized by interbedded clay, marl, tuffaceous sandstone, and limestone, formed from the Early to Late Miocene, featuring laminations and moderate to high weathering. The marl of the Kalibeng Formation comprises massive marl with tuffaceous sandstone and limestone nodules, dating from the Late Miocene to Pliocene, displaying greenish-gray to black color and low weathering. The sandstone of the Damar Formation contains tuffaceous sandstone, conglomerate, and volcanic breccia, mainly non-marine, found near the Damar River, with brown color, moderate sorting, and low weathering. The volcanic breccia of the Kaligetas Formation includes lava flows, tuffs, and tuffaceous sandstone formed from fragmented volcanic material, displaying a massive texture with poor sorting and angular grains. The andesite of the Gajahmungkur and Kaligesik Volcanoes has moderate to high weathering, gray to brownish-gray, hypohyaline texture, and aphanitic granularity. The alluvial unit consists of coastal, river, and lake deposits, including clay, silt, sand, gravel, cobbles, and boulders, with varying thicknesses.

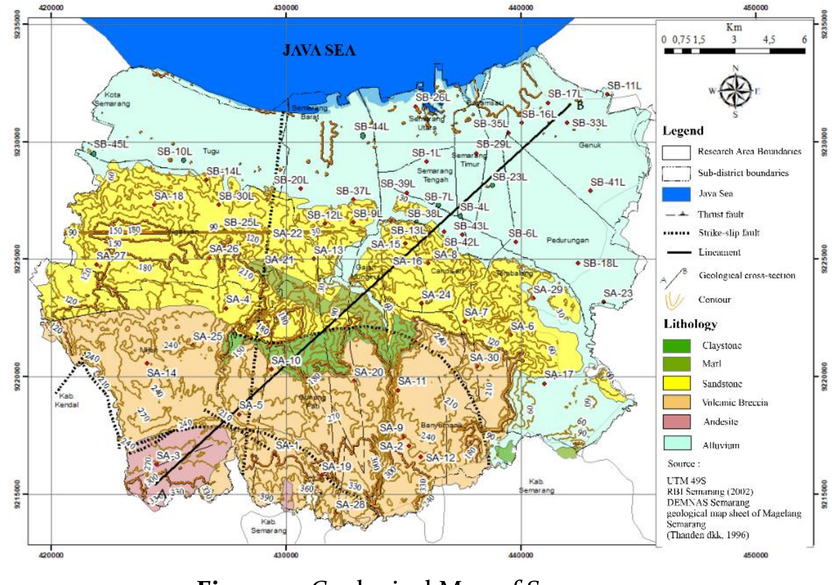

Figure 2. Geological Map of Semarang
Source: (Thanden dkk, 1996)

3.2 Aquifer System

The study area is divided into two Groundwater Basins (GWB): GWB Semarang-Demak, located in the northern part, which has groundwater flow patterns directed southwest-northeast and northwest-southeast, and GWB Ungaran, situated in the southern part, which exhibits similar groundwater flow patterns. These differences in groundwater flow direction are linked to the geological structures in the study area, which influence the local hydrogeological conditions. Additionally, the presence of rivers affects the groundwater flow patterns in the region (Rahayuningtyas, 2023).

The study area is 60 groundwater sample points from confined aquifers distributed throughout Semarang City. Based on observations, there are three types of aquifers, according to Said and Sukrisno (1988): aquifers with intergranular flow; aquifers where flow occurs through fractures, faults, and channels; and aquifers where flow occurs through fractures and cavities. The distribution of samples according to aquifer types can be seen in Figure 3.

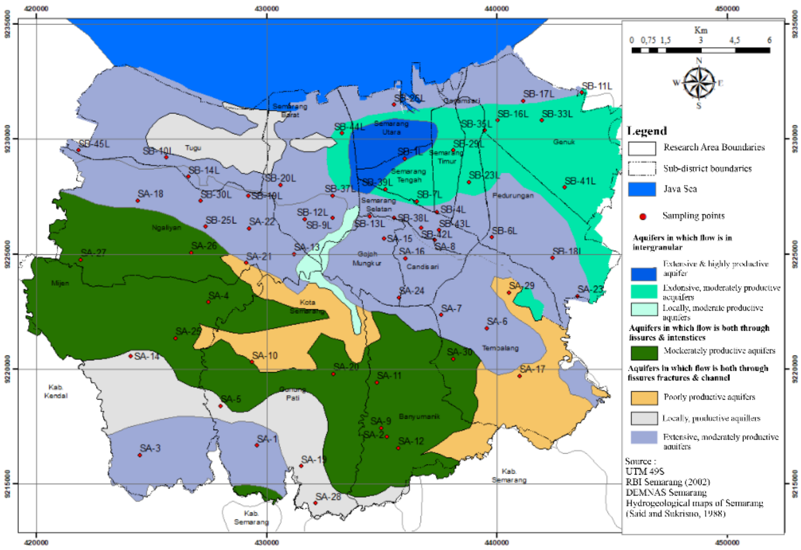

Figure 3. Aquifer Map in Semarang Jawa Tengah

3.3 Physical and Chemical Parameters of Groundwater

The laboratory tests aimed to determine groundwater's physical and chemical characteristics in the study area, resulting in several maps illustrating these characteristics (Figure 4). The data was interpolated using the minimum curvature method, which is preferred for its conservative nature. The generated map shows that most of Semarang has safe TDS levels, under 1000 mg/l, except for the northern region, which exhibits higher salinity levels, likely due to seawater intrusion from the Java Sea (Figure 4c). The study sampled 60 points, finding that eastern and western parts exhibit predominantly primary (pH 7.7 to 8.2) and neutral (pH 7.2 to 7.7) conditions (Suharyadi, 1994). Acidic pH values (below 7.2) were identified in the northern and central areas (Figure 4d). The dominant medium hardness was noted in the north and some southern regions, with tough water in northern plots near Mranggen (Figure 4b). Most of Semarang falls into the good category (250-750 µS/cm), with excellent EC primarily in the western area. Some regions, like Mranggen, Pedurungan, and Genuk, exhibit moderate EC (750-2000 µS/cm), with small areas in the north having poor to very poor EC, likely due to proximity to the sea (Figure 4a).

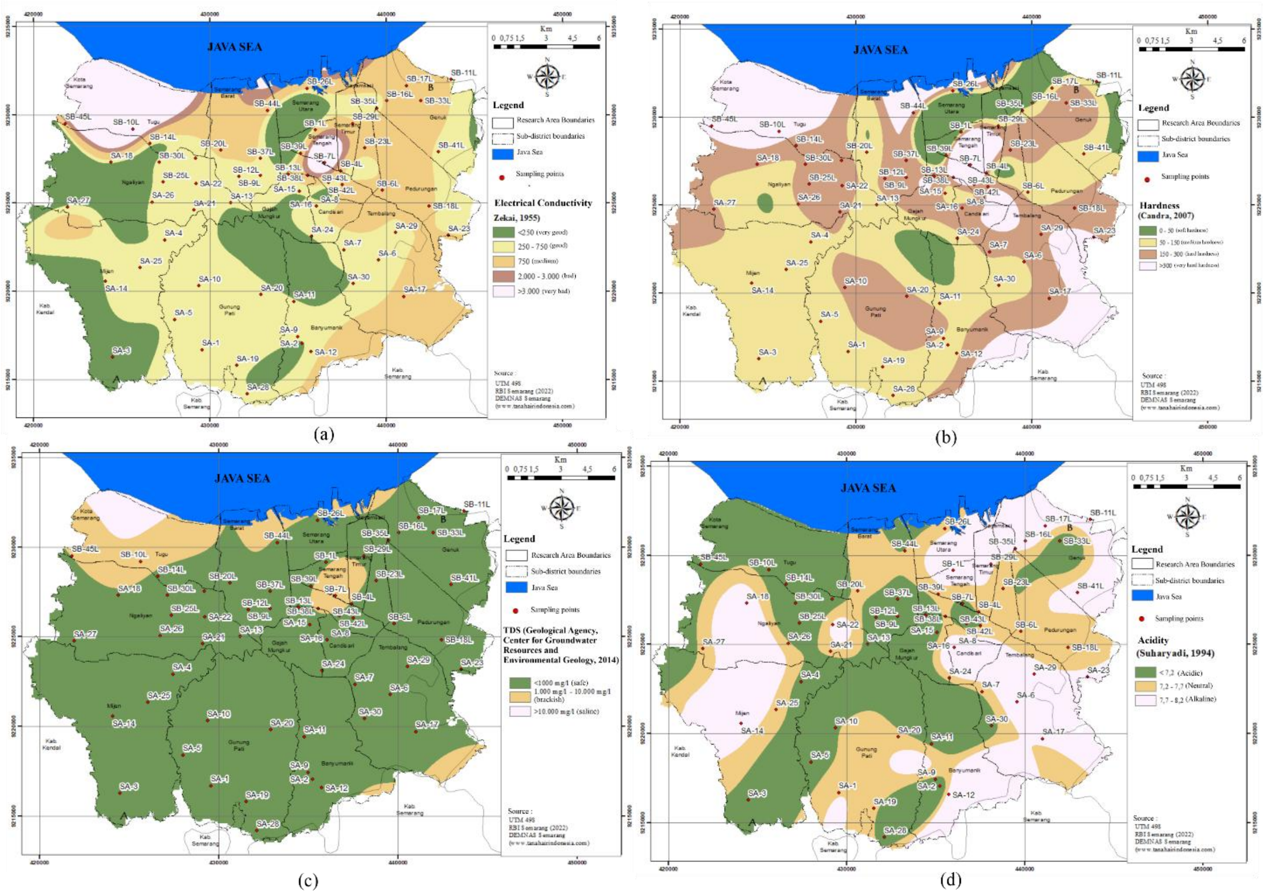

Figure 4. Physical and chemical properties interpolation map in Semarang City

3.4 Correlation of Physical and Chemical Groundwater Content Between Lowland and Highland of Semarang

The groundwater study in Semarang examines the correlation between its physical and chemical content, comparing Highland and Lowland areas using bar charts. Effendi (2003) attributes high Total Dissolved Solids (TDS) in seawater to various chemical compounds, leading to elevated salinity and electrical conductivity. The Geological Agency and the Groundwater Center set a TDS limit of 1000 mg/l in 2014, with Upper Semarang samples within this limit, while Lower Semarang samples (SB-7, SB-10, SB-38, SB-45) exceed it due to prolonged water travel, rock dissolution, and potential industrial pollution (Lestari et al., 2021). Aisyah (2017) notes that high TDS in groundwater stems from organic and inorganic compounds, sediments, and solid waste influenced by pH. Boreholes deeper than 10 meters exhibit a stable pH (6-9), unlike rainwater (pH 5.6-5.8), which is affected by atmospheric CO2 (Satriawan, 2018; Anam et al.., 2022).

Water hardness, caused by Ca^{2+}, Mg^{2+}, and other metal ions (Effendi, 2003), varies within acceptable limits for drinking water, with some exceptions like SB-7L (1368.0 mg/L) at Plaza Simpang Lima. Alluvial deposits contribute to hardness (Putranto et al., 2024). Electrical conductivity (EC), influencing water's saltiness, is higher in Lower Semarang, possibly due to seawater intrusion, correlating positively with TDS (Ruseffandi et al., 2020)

3.5. Gibbs Diagram

The chemical composition of natural groundwater in Semarang reflects complex geological and environmental processes (Freeze and Cherry, 1979). Groundwater chemistry typically evolves from a bicarbonate (HCO_3) dominated type to a chloride (Cl) type with increasing salinity, evidenced by a $Na/(Na^+ + Ca^{2+})$ ratio predominantly > 0.5 and low Total Dissolved Solids (TDS) values (<1000 mg/L)

(Chebotarev, 1955; Liu et al., 2016). This evolution suggests that weathering and ion exchange processes significantly shape groundwater chemistry in the region's confined aquifers (Qian et al., 2023). Samples from coastal areas, such as SB-45, SB-10, SB-7, and SB-38, exhibit higher TDS concentrations and $Cl^-/(Cl^- + HCO_3^-)$ ratios > 0.5, indicating influence from evaporation and seawater intrusion (Barica, 1972; Sarwade et al., 2006).in coastal plains (Sarwade et al., 2006). According to research, the four samples are located in coastal areas with high TDS values, so the evaporation process has influenced these four samples. In the study area, there are only four samples, namely SB-45, SB-10, SB-7, and SB-38, which have $Cl^-/(Cl^- + HCO_3^-)$ ratio values > 0.5, so besides these samples are freshwater and not affected by the mixing with seawater (Figure 5).

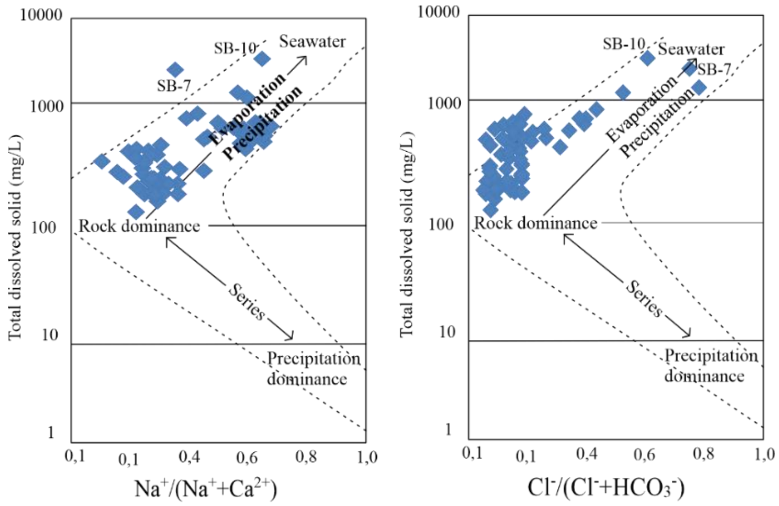

Figure 5. Gibbs Diagram in research area

In the Gibbs diagram, the ratios $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/(Cl^- + HCO_3^-)$ are used to compare the abundance of Na, Ca, Cl, and HCO3 in the study areas of Semarang Bawah (Lower Semarang) and Semarang Atas (Upper Semarang). The diagram comparing Na+ content between Semarang Bawah and Semarang Atas (Figure 10) shows that Na+ content in Semarang Bawah is higher than Semarang Atas. 11 samples in Semarang Atas have values < 200 mg/L, whereas in Semarang Bawah, there are five samples with values > 200 mg/L, namely SB-7L, SB-10L, SB-38L, and SB-45L. This is because Semarang Bawah, a coastal area, contains a significant amount of halite, a dominant source of Na+ and Cl– in groundwater; the molar ratio varies spatially due to cation exchange (Wayland et al., 2003).

The comparison of Ca^{2+} content between Semarang Atas and Semarang Bawah (Figure 10) shows that in Semarang Bawah, the tendency of Ca^{2+} values is higher than in Semarang Atas. All samples in Semarang Atas have values < 100, while in Semarang Bawah, samples such as SB-7L and SB-33L have very high Ca^{2+} contents. The high Ca^{2+} content in Semarang Bawah is likely due to dissolution from carbonate rocks (Fadly et al., 2015). Although Semarang Atas also has carbonate sandstone lithology, the dissolution intensity differs between Semarang Atas and Semarang Bawah, where weathering in Semarang Bawah is more intensive, resulting in higher dissolved Ca^{2+}.

A bar diagram comparing Cl-content between Semarang Atas and Semarang Bawah (Figure 10) shows that Cl-content tends to be higher in Semarang Bawah than in Semarang Atas. This could be because these samples are located in coastal areas, where seawater intrusion is a significant cause of high chloride content in groundwater. Seawater containing salts (including chloride) can enter freshwater aquifers, significantly if the groundwater level declines due to over-pumping (Anam et al., 2022).

HCO_3^- concentrations show spatial variation due to carbonate rocks in the recharge area. A comparison of HCO_3^- chemical content in Semarang Atas and Semarang Bawah (Figure 10) indicates relatively similar values between the two regions. HCO_3^- is also an indicator that the groundwater is freshwater. This can occur due to rocks containing carbonate minerals, such as carbonate sandstone. Additionally, bicarbonate content is formed from the weathering of silicate minerals, which then reacts with water to form bicarbonate (Fadly et al., 2015).

3.6. Water Type Based on Cation and Anion Content

The $NaHCO_3$ water type dominates many locations, identified by high bicarbonate levels, and is found in places like Queen City Mall, PT. HM Sampoerna Tbk, and Plaza Simpang Lima, as well as Gunungpati, Banyumanik, and Tembalang. The NaCl water type, characterized by high sodium and chloride levels, is detected at sites like RSIA Bunda, PT. Sandang Asia Maju Abadi, Masjid Agung JT, and PT. Kongo Indonesia, as well as in Karang Kidul, Plamongansari, and Jatibarang. The $CaHCO_3$ water type, noted for high calcium and bicarbonate levels, is common at PT. Sinar Pantja Djaja, PT. Sentra Agri Mulia Lestari, and PT. Prawita Jaya Baru, and in Banyumanik, Pongangan, and Kalipancur. The $MgHCO_3$ water type, with significant magnesium and bicarbonate levels, is recorded at PT. Permata Panca Buana, Bandeng Juwana Pamularsih, PT. Nufarindo, and in Karangrejo, Bringin, Podorejo, Plamongansari, and Sambiroto. The $NaSO_4$ water type, marked by high sulfate levels, is also found at PT. Charoen Pokphand. These variations in mineral content stem from the different sources of deep springs, influenced by factors such as water source, regional geology, human activity, and natural processes.

3.7. Stable Isotope

Stable isotope samples of ^{18}O and ^{2}H were collected from 60 confined aquifer points across Semarang City for this study. Analysis showed that the relationship between ^{18}O and ^{2}H in the groundwater of the study area can be described by the equation D(2H) = 6.3343x + 1.5669, which is parallel to the Global Meteoric Water Line (GMWL); a strong correlation is evident from the coefficient of determination (R2) of 0.8758 and the correlation coefficient (r) of 0.936, signifying a significant relationship between ^{18}O and ^{2}H content in the 60 analyzed samples (Figure 6).

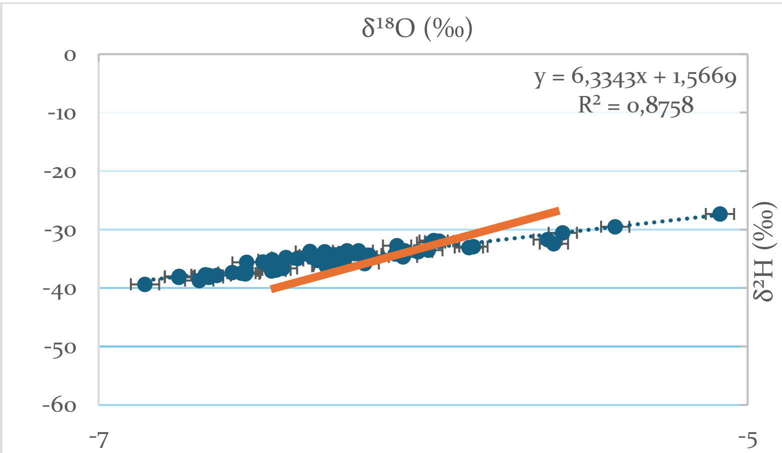

Figure 6. The linear relationship between ^{18}O and ^{2}H

The isotopes in the study area can be grouped based on stable isotope content (Sudaryanto and Lubis, 2011) as follows (Figure 7):

1. Group I has a ^{18}O value around -4.585‰ from SB-10 and SA-17 around -4.908‰. Groundwater in this group tends to have heavier oxygen content than other samples, indicating a dominant influence of saline water, with oxygen weight values close to -4‰. Groundwater type analysis shows that SB-10 is NaCl type, suggesting ancient salt influence rising through the soil layers due to higher Mg^{2+} content than Ca^{2+} (Suherman and Sudaryanto, 2009).
2. Group II has a ^{18}O value around -5.070 to -5.097‰ from SB-20 and SA-14. Groundwater in this group has moderate oxygen content with a slight saline water influence. Analysis indicates SB-20 and SA-14 are $NaHCO_3$ type, resulting from NaCl washing by $Ca(HCO_3)_2$ as freshwater, which

can occur during coastal formation when trapped seawater is continuously flushed by freshwater (Suherman and Sudaryanto, 2009).

3. Group III has an ^{18}O value ranging from -5.451 to -6.044‰, dispersed across almost all samples, indicating the groundwater originates locally.

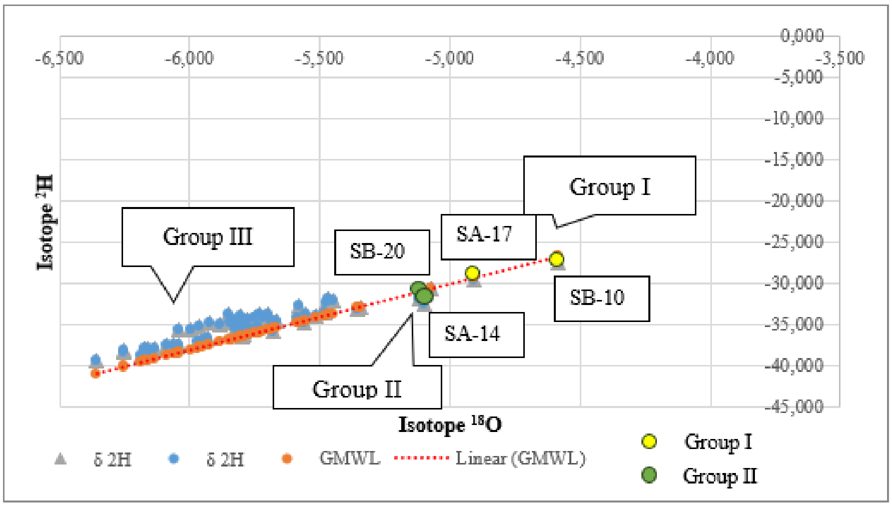

Figure 7. Grouping based on stable isotope content according to Sudaryanto and Lubis (2011) and the relationship with the global meteoric water line

In this study area, d-excess values were calculated. The d-excess values help infer secondary processes forming atmospheric vapor composition in the natural evaporation and condensation cycle (Craig, 1961; Gat et al., 1994). Most borehole samples have d-excess values greater than 10, indicating deeper groundwater. Some samples with d-excess less than 10 are SA-4, SA-8, SA-14, SA-17, SA-21, SB-10L, and SB-20L, showing shallower drainage systems with high temperatures and low humidity, resulting in rainwater recharge influenced by evaporation during infiltration, especially at SB-10. The SB-10 point is more influenced by secondary evaporation, indicating lower rainfall in summer (Dansgaard, 1964).

If ^{18}O and ^{2}H values are moderate to high and the d-excess is less than 10, it indicates a relatively shallow groundwater system influenced by evaporation. A d-excess of less than 10 suggests evaporation, with a shallow slope, high temperature, and low humidity causing faster secondary evaporation, as seen in samples SA-4, SA-8, SA-14, SA-17, and SA-21 located on gentle slopes. Rainfall affected by evaporation shows 18O enrichment and d-excess reduction (Lin et al., 2008; Peng et al., 2007).

The groundwater in Semarang City is estimated to originate from modern rainwater and deep groundwater types, as indicated by scatter plots showing groundwater samples close to the GMWL (Global Meteoric Water Line). The d-excess analysis shows values greater than 10, suggesting that the groundwater in Semarang City comes from modern rainwater. However, research by Li et al. (2013) has limitations, preventing definitive conclusions about the groundwater's origin in the study area. The similarity of low d-excess values (<10) in nearby wells, such as SA-4, SA-8, and SA-29, along the lithological boundary indicates the possible influence of similar environmental conditions on the isotopic properties of groundwater in the region.

3.8. Comparison of Isotope Content Between the Lowland and Highland of Semarang

A cross-section was created to provide information on elevation, lithology, and isotopic content. This section was derived from an A-B cut on the geological map (Figure 11), and a geological cross-section was made, including isotopic content and chemical and physical groundwater properties (Figure 8).

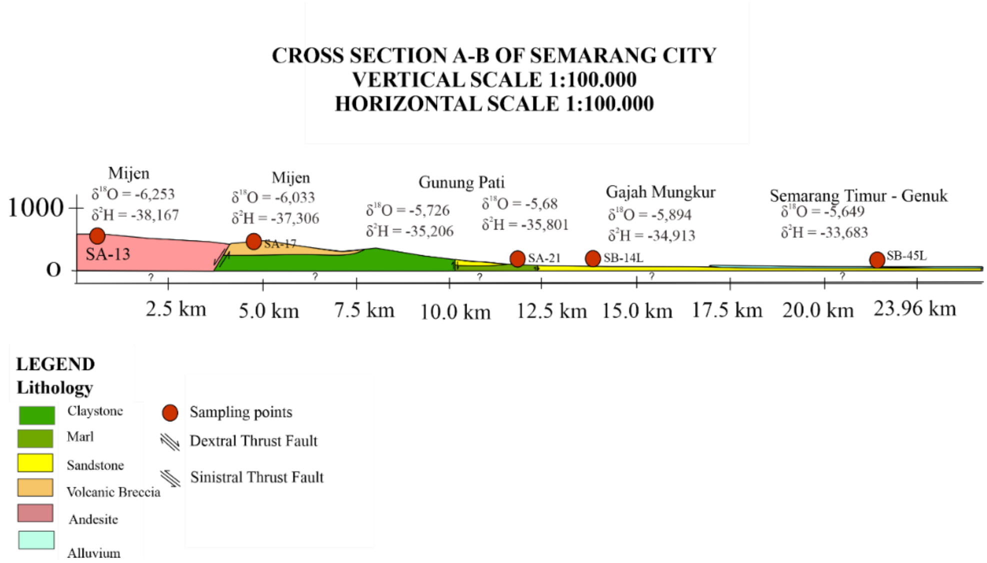

Figure 8. Cross section A-B of Semarang City

In this cross-section, the values of ^{18}O and ^{2}H increase as the elevation decreases. Higher values of ^{18}O and ^{2}H indicate a more significant influence from mixing and evaporation (Mook, 2006). The ^{2}H values decrease towards Lower Semarang, with Mijen having an average of -38.167 (andesite lithology) and East Semarang-Genuk having an average of -33.683 (alluvium lithology), indicating higher values. Similarly, ^{18}O values are higher in Lower Semarang, with Mijen averaging -6.253 and Lower Semarang averaging -5.649.

3.9. Relationship Between Lithology, TDS, EC, Water Type, and d-excess

The study conducted in Semarang City compared the values of Total Dissolved Solids (TDS), Electrical Conductivity (EC), water type according to Breuk (1991), d-excess, and lithology—locations such as PT. Sandang Asia Maju Abadi (SB-10L) and Plaza Simpang Lima (SB-7L) showed very high TDS, indicating significant mineralization, particularly from salt (NaCl). High EC measurements at the exact locations correlate directly with TDS samples with d-excess below 10, such as PT. Sandang Asia Maju Abadi (SB-10L) indicates higher evaporation processes, providing insights into the hydrological history and microclimate of the area (Nuryana et al., 2021).

A pattern emerged from the study indicating that samples SB-4L, SB-38L, and SB-7L, located close to each other, exhibited high TDS and EC values. These samples share similar characteristics: high TDS and EC values, NaCl water type, and alluvium lithology (Table 1). This suggests a common geochemical source or mechanism influencing these locations (Rizqullah et al., 2015). The high TDS and EC values, coupled with the NaCl water type, indicate that the primary source of salinity is likely from evaporite mineral dissolution or interaction with salt-rich geological layers. Alluvial deposits, often found in lowland areas, might be influenced by seawater or brackish water (Sugeng, 2010).

Table 1. Sample with the same characteristic

Sample Number	Location	TDS	EC	Water Type (Breuk, 1991)	d-*excess*	Lithology
SB-7L	PLAZA SIMPANG LIMA	3404	5080	NaCl	11.61875	Alluvium
SB-4L	RSIA BUNDA	829	1238	NaCl	12.255	Alluvium
SB-10L	PT. SANDANG ASIA MAJU ABADI	4241	6330	NaCl	9.35475	Alluvium
SB-23L	MASJID AGUNG JT	691	1032	NaCl	13.0312	Alluvium
SB-38L	THAMRIN SQUARE	1276	1905	NaCl	11.90925	Alluvium

Sample Number	Location	TDS	EC	Water Type (Breuk, 1991)	d-*excess*	Lithology
SB-44L	PT. PROPAN RAYA	693	1034	NaCl	10.9038	Aluvium
SB-45L	PT. NUFARINDO	1154	1723	NaCl	11.65025	Aluvium

Some samples show high TDS and EC but d-excess >10, suggesting mineral dissolution or pollution rather than significant evaporation before groundwater infiltration (West et al., 2014). The graph (Figure 9) illustrates the relationship between TDS and ^{18}O values, showing groundwater origins predominantly as Meteoric Water, except for SB-10L, SB-20L (Brackish Waters), and SA-17 (Flushing Phase), indicating dilution of saltwater with freshwater (White, 1973).

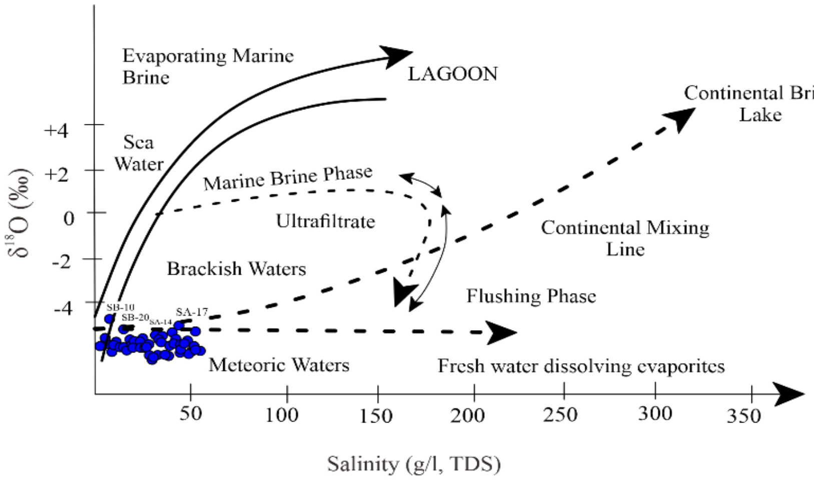

Figure 9. Classification of water based on isotopic content against TDS
Source: (White, 1973)

Groundwater in Semarang falls into categories: Meteoric Water (low to moderate TDS, δ18O indicating rainwater), Connate Water (trapped in geological formations with complex chemistry), and Brackish Water (high TDS indicating seawater influence). The flushing phase at SA-17 suggests groundwater cleansing by fresh infiltration, enhancing water quality (White, 1973). Groundwater with NaCl type can indicate connate water or intrusion, differentiated by d-excess values (Gat et al., 1996).

4. Conclusion

Based on the findings of this study conducted in Semarang City, it is evident that geological and hydrogeological conditions play crucial roles in shaping the characteristics of groundwater. The area exhibits diverse lithologies, including alluvium, sandstone, shale, claystone, andesite breccia. Hydrogeologically, complex groundwater flow patterns are observed and affected by natural geological processes and anthropogenic activities. The analysis using Gibbs diagrams reveals the influence of evaporation, precipitation, and rock weathering on groundwater composition. Samples categorized as Evaporation Precipitation and Sea Water show the dominant influences of evaporation and seawater intrusion, while those classified as Rock Dominance indicate significant contributions from rock weathering. Isotope analysis of ^{18}O and ^{2}H indicates distinct groups of groundwater samples, reflecting varying influences of saline water, freshwater, and local factors. According to White's classification (1973), most samples in Semarang City are categorized as Meteoric Water (rainwater), with some samples classified as Connate Water and Brackish Water, along with a flushing phase indicating purification by fresh water. It is recommended not to use boreholes at locations SA-4, SA-8, SA-14, SA-17, SA-21, SB-10L, and SB-20L due to their low d-excess values (<10), indicating susceptibility to evaporation processes and potential dryness during the dry season. Additionally, boreholes at SB-7L, SB-4L, SB-10L, SB-23L, SB-38L, SB-44L, and SB-45L are not advisable because of their high Total Dissolved Solids (TDS) and Electrical Conductivity (EC) levels, as well as NaCl water type, making them unsuitable for drinking water or irrigation purposes.

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