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HYDROGEOLOGICAL AND HYDROCHEMICAL STUDIES OF AQUIFERS SYSTEM FOR THE BENEFIT OF SUSTAINABILITY IN THE WALINI URBAN AREA, WEST JAVA, INDONESIA

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Abstract: A combined iso-potentiometric mapping and hydrochemistry study was conducted in the Walini urban area to assess the quality and suitability of groundwater for domestic and other purposes regarding Walini's urban development. The direction of groundwater flow is northeast-southwest, based on observations from 22 water tables between 2022 and 2023. Groundwater samples obtained from dug wells, bore wells, and springs were analysed to determine physicochemical parameters (EC and pH) and concentrations of major ions. The result indicates that the groundwater is freshwater. It contains calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), and chloride (Cl^-) in balancing levels. Piper diagram shows the groundwater was classified into calcium-magnesium-bicarbonate-chloride as dominant water facies. Gibbs diagrams reflect that the groundwater is hydrochemically controlled by lithology. Compared to the World Health Organisation's (WHO) water quality standards, the water is appropriate for drinking and other domestic uses supporting urban development. However, compared to the shallow (4-20 m), the water quality of the deep (beyond 104 m) and middle unconfined aquifers (between 35 m and 73 m) is higher. This is because shallow aquifers are vulnerable to urbanisation. If current trends continue, appropriate management strategies for groundwater protection in the Walini would be critical for sustainability.

Keywords: Groundwater quality, hydrogeochemistry, planning, urban, Walini.

Introduction

West Java, Indonesia's most populous province is located on the western side of Java Island (Figure 1). As of 2021, the population is expected to be 48.78 million people (BPS, 2022). It accounts for 17% of the total population of Indonesia. Even so, West Java has a high economic disparity. An effort to overcome this economic disparity is by developing the concept of development on a territorial basis (Noviyanti *et al.*, 2020). According to the Indonesia Presidential Regulation (Perpres), there are four priority territories for development in West Java. They are: (1) Bandung Basin area (Perpres No. 45, 2018), (2) Bodebekkarpur Metropolitan area (Perpres No. 60, 2020), (3) Rebana area (Perpres No. 87, 2021), and (4) south of West Java (Perpres No. 87, 2021). The current research area is located on the periphery of the Bandung Basin urban development area.

Bandung Basin comprises five urban districts with 85 subdistricts (Perpres No. 45, 2018). One of these urban subdistricts is the Cikalong Wetan urban area, also known as the Walini urban area. The rapid development around the Bandung Basin area has increased the demand for clean water. Approximately, 70% of the clean water demand in Bandung Basin is estimated to be fulfilled from groundwater (Harnandi & Herawan, 2009). Until recently, groundwater withdrawal through dug wells pumping has undergone many failures, especially during the peak of the dry season. The situation is getting worse in the hilly areas and an area with factories due to water table depletion by excessive pumping (Akpan *et al.*, 2013). Comprising a drilled well and a submersible pump is one of the solutions. It may penetrate deeper to 50 m or 60 m and withdraw water even more, but it costs too much for most people in the area. A single private firm, wealthy people, or some communities who can afford to pay for the expensive installation of a drilled well and submersible pump usually have more profound and sufficient groundwater access. There is always a correlation between groundwater and people's welfare, at least in the case of Southeast Asia (Jacoby, 2017).

Water quality is another issue in Southeast Asia (Chatterjee & Chowdhury, 2020), especially in densely populated areas such as West Java. The groundwater quality is determined by the rainwater chemical properties, soil mineralogy and geochemistry, sediment matrix mineralogy and geochemistry, and the residence time between water, soil, and aquifer materials (Chatterjee & Chowdhury, 2020). The quality of groundwater has also been deteriorating due to human activities through changes in land use, intervention in natural flow patterns, and water pollution from housing, industry, and agriculture (Deshmukh, 2013; Rao *et al.*, 2022a). Changes in land use due to the development of urban areas have reduced the ability of the land to absorb rainwater, which means diminished groundwater infiltration and increased storm water and flood. Moreover, reducing groundwater reserves may cause deeper groundwater levels and land subsidence (Harnandi & Herawan, 2009).

As Walini has recently developed as an urban area, the objectives of this study were to investigate the hydrogeology and hydrogeochemical characteristics of aquifers in Walini and to assess the water quality and its suitability for domestic and supporting further urban development in the area. The findings will show how far the impact of the present urban development on the groundwater quality

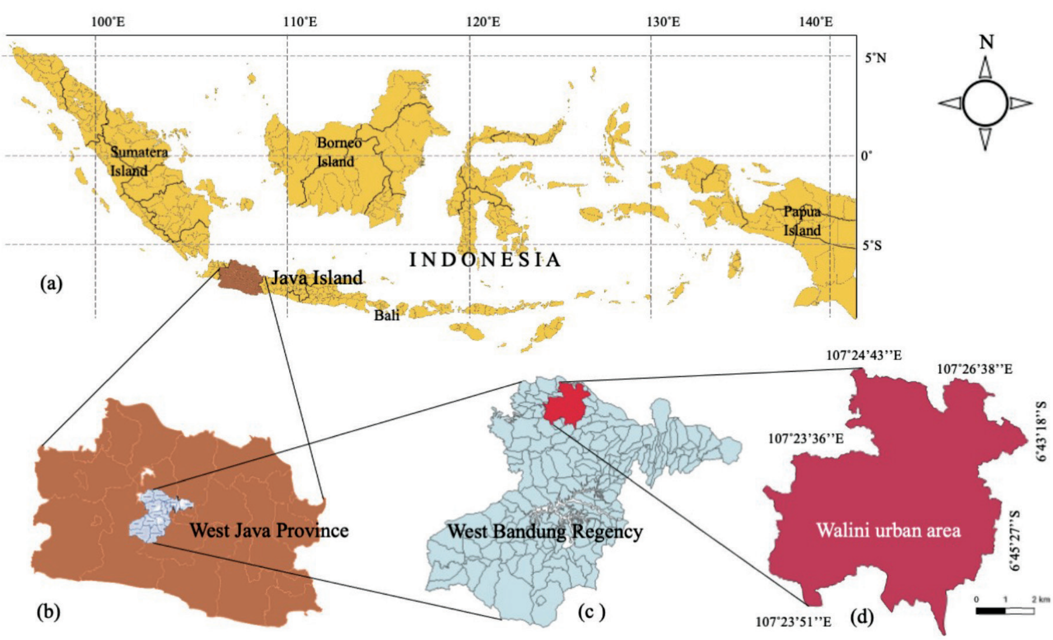

Figure 1: (a) Position of West Java Province in Indonesia, (b) position of West Bandung Regency in West Java Province, (c) location of Walini urban area, respectively in West Bandung Regency, and (d) geographic coordinates of Walini urban area

and will be beneficial to improve groundwater management for sustainable development in the Walini urban area.

Materials and Methods

Study Area

Walini urban area is located between latitude 6°41’59” and 6°46’55” S and longitude 107°22’59” and 107°28’02” E. It is a part of the Cikalong Wetan subdistrict in the West Bandung district. Walini covers approximately 45.4 square kilometre and is home to 69,617 people, resulting in a low population density of 1,533 people per square kilometre.

Walini’s urban area has grown in the last 10 years. The Walini urban area is more often used than the official government administrative term “the Cikalong Wetan urban area”. This is due to the well-known “Walini Tea” brand, which is produced by PT Perkebunan Nusantara VIII, a firm that manages the tea plantation in the study area (Mumpuni, 2015). Walini occupies the lower to a higher plain of Bandung Basin, ranging from 367 m to 711 m above sea level. Low to high relief and hilly topography describe the morphometry. The lowest slope is 0%, but the highest is 91%, with steeper slopes ranging from 8% to 36% dominating (Figure 2).

The weather is hot and humid, but it is steady. The temperature ranges from 24°C to 27°C. The climate was governed by two seasons in which May to October is the dry season and November to April is the wet season. An evaluation of daily accumulated precipitation (combined microwave-IR) estimations with gauge calibration across land held by LAPAN in Walini from 2012 to 2021 shows the average yearly rainfall in the last decade is 2,976 mm with an average relative humidity of 89% (LAPAN, 2022).

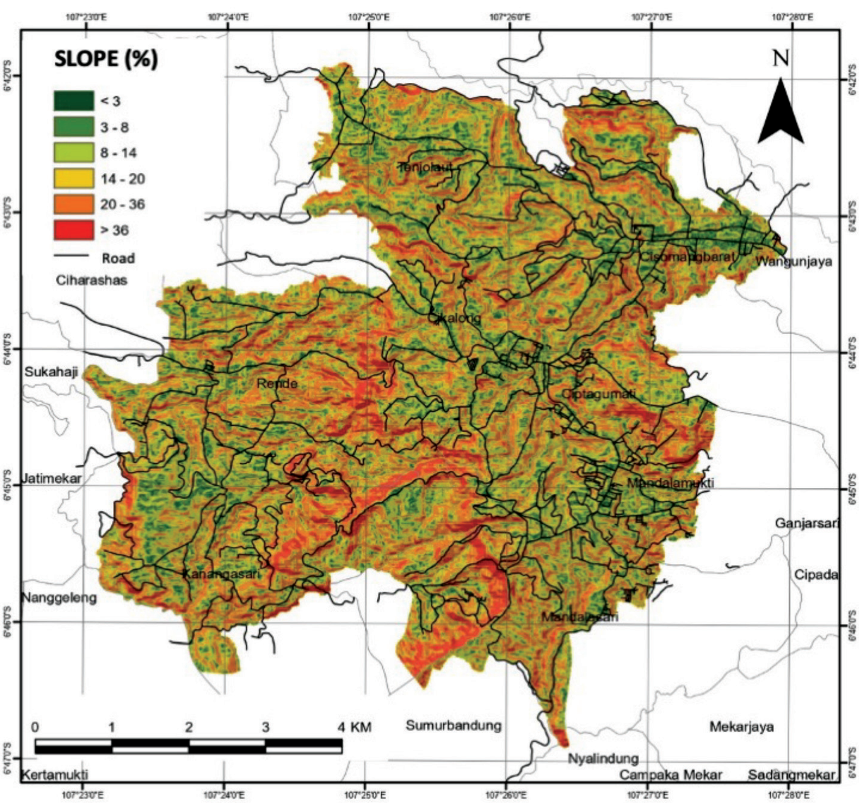

Figure 2: Slope map of Walini urban area

Hydrogeology and Geological Setting

According to Buana *et al.* (2018), the Walini urban area is overlain by two Neogene to Quaternary lithostratigraphic units comprising the Cantayan Formation (Late Miocene) and Young Volcanic products (Pleistocene) as shown in Figure 3. Stratigraphically represents deep marine (the Cantayan Formation) and non-marine depositional environment (Martodjojo, 1984). A quarter of the study area is covered by interbedded clayey sandstone and claystone of the Cantayan Formation (claystone member-Mttc). The claystone bed is thicker than the bedded sandstone. The claystone is highly jointed and brittle. This unit is unconformably overlain by greyish brown breccia of Young Volcanic products (Qob). The relatively fresh breccia comprises andesite fragments in granule to pebble size with a course to fine sand and tuff matrix (Sudjatmiko, 1972; Adam, 2022). The volcanic breccia unit covers the rest of the study area. The thickness varies between 4 m to 15 m. The area is controlled by less exposure to structures. The apparent structural feature in the area is a normal fault. Trending relatively east-west follows the general trend of the Miocene-Pliocene basement structure of Java (Buana *et al.*, 2018).

Walini is very dependent on groundwater since the river in the nearby area is very limited. Hydrogeologically, the study area comprises two main unconfined aquifer horizons of volcanic breccia interbedded between clayey sandstone and claystone (PATGTL, 2020; Adam, 2022). They are arranged as multistorey layers (Buana *et al.*, 2018). Tuff breccia aquifer is distributed at a depth of 8 m to 20 m. Meanwhile, sandstone intercalated with claystone is found at depths ranging from 20 m to 73 m and 104 m to 134 m (Figure 4). The extraction of groundwater resources in this area involves using open-dug wells, drilled wells, and springs.

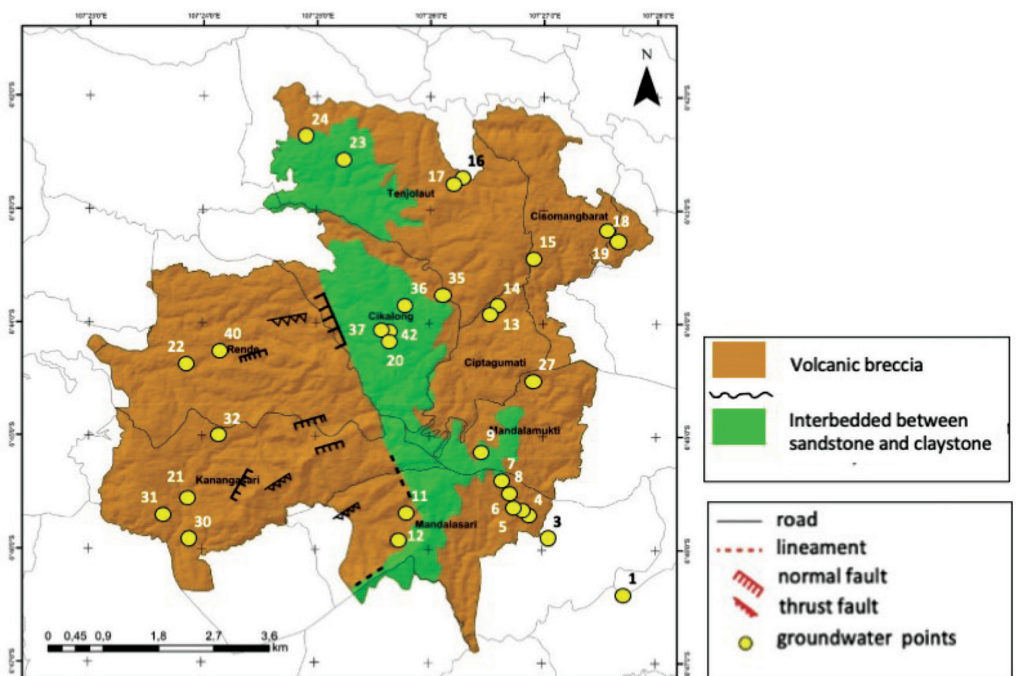

Figure 3: Generalised geological map of the Walini urban area including the hydrogeology sampling points

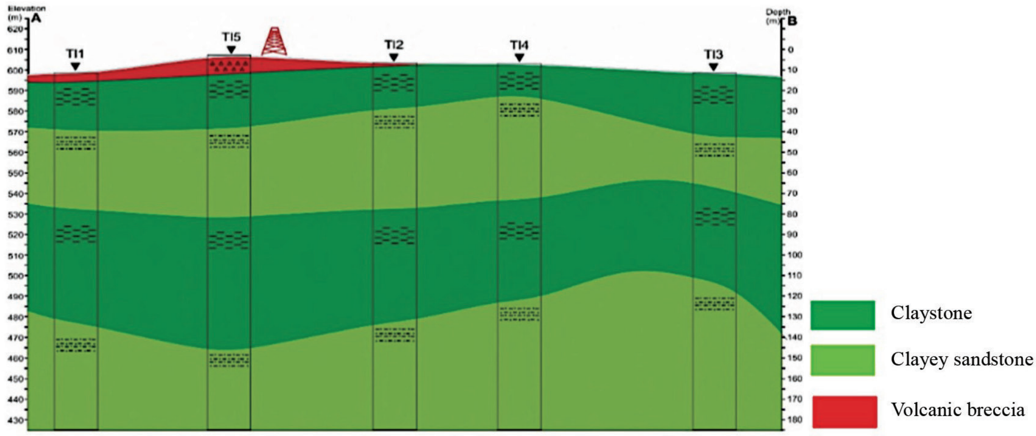

Figure 4: Cross-section of resistivity measurement result in site 23 of Tenjo Laut subdistrict (PATGTL, 2020)

Methodology

Extensive field surveys have successfully mapped eight springs around the study area, including measurements on the water table from 22 dug wells (Table 1). Water samples were obtained between 2022 and 2023 from two dug wells, three bore wells, and three springs as physicochemical data. The maximum distance between the two adjacent sampling sites was kept at less than two km but depended on accessibility.

Water level measurements were taken in each of the wells using a 50 m water level flat tape. The water level is measured manually in each well based on a mark at the end of the tape as a reference point. The distance from a specific point on the ground surface is also determined. The samples were collected in new one L polyethylene bottles pre-washed with HNO_3 and rinsed three times with the groundwater sample before collecting the sample. Then, the samples were labelled accordingly. After sampling, portable instruments were immediately used for in situ electrical conductivity (EC) and pH measurement. All samples and measurements were collected during the dry-wet seasonal transition (October 2021).

The samples were then analysed immediately following the standard water quality method within less than 48 hours after sampling at the laboratory of the Center for Groundwater and Environmental Geology, Geological Agency, and Ministry of Energy and Mineral Resources, Republic of Indonesia. The ions of calcium (Ca^{2+}), sodium (Na^{+}), magnesium (Mg^{2+}), and potassium (K^{+}) were analysed using the Dionex ICS-1500 Ion Chromatography System. As for SO_4^{2-} ion, it was determined using Varian Cary 100 UV-Visible Spectrophotometers. Meanwhile, Cl^- and HCO_3^- were measured with argentometric and alkalinity titration, respectively.

The Piper and Gibbs diagrams represented the hydrogeochemical analyses. The Piper diagram is a graphical representation of water ion composition and consists of two triangles and one rhombus (Piper, 1944; Nematollahi *et al.*, 2016; Abbasnia *et al.*, 2019). In this diagram, ion values are converted into a percentage. Cations are described in the bottom-left triangle, whereas anions are described in the bottom-right triangle. The diamond (rhombus) shape at the top consists of all ions from both triangles. The Piper diagram helps indicate the geochemical type of water (Piper, 1944; Nematollahi *et al.*, 2016; Rao *et al.*, 2024). It can also analyse the mixing process between groundwater and water from other sources in the study area (Purnama, 2019). While, understanding the variables controlling ion generation in groundwater can be done with the help of the Gibbs diagram

Table 1: Location of some water samples and water table measurements

Sample No.	Location Name	Geographic Coordinates		Elevation (m)	Water Table (m)	Aquifer Layer	Well or Spring
		Latitude (S)	Longitude (E)				
1	Kraton	6°46’25.92”	107°27’43.94”	684	-	Silty clay-sand	Spring
2	Mandalasari 1	6°45’51.19”	107°27’01.76”	590	15	Silty clay-sand	Well
3	Mandalasari 2	6°45’44.04”	107°26’55.19”	595	25	Silty clay-sand	Well
4	Mandalasari 3	6°45’41.56”	107°26’52.76”	622	20	Silty clay-sand	Well
5	Mandalasari 4	6°45’40.65”	107°26’52.65”	626	20	Silty clay-sand	Well
6	Mandalasari 5	6°45’27.76”	107°26’44.69”	639	15	Silty clay-sand	Well
7	Mandalasari 6	6°45’27.77”	107°26’46.02”	638	25	Silty clay-sand	Well
8	Mandalasari 7	6°42’41.13”	107°26’18.89”	588	-	Silty clay-sand	Spring
9	Warung Domba	6°45’08.66”	107°26’38.12”	651	15	Silty clay-sand	Well
10	Ciptagumati 1	6°43’50.71”	107°26’35.70”	631	9	Silty clay-sand	Well
11	Ciptagumati 2	6°43’49.71”	107°26’38.23”	631	11	Silty clay-sand	Well
12	Cisomang Barat 1	6°43’22.87”	107°26’53.35”	674	13	Silty clay-sand	Well
13	Cisomang Barat 2	6°42’41.13”	107°26’18.89”	633	30	Silty clay-sand	Well
14	Cisomang Barat 3	6°42’42.87”	107°26’18.95”	623	8	Silty clay-sand	Well
15	Cisomang Barat 4	6°43’10.90”	107°27’37.49”	682	15	Silty clay-sand	Well
16	Cisomang Barat 5	6°43’12.36”	107°27’33.53”	682	17	Silty clay-sand	Well
17	Rende 1	6°44’16.94”	107°25’08.03”	568	-	Breccia	Spring
18	Rende 2	6°44’09.53”	107°23’50.37”	443	22	Silty clay-sand	Well
19	Tenjo Laut 1	6°42’31.69”	107°25’18.17”	593	21	Silty clay-sand	Well
20	Tenjo Laut 2	6°42’19.03”	107°24’49.56”	566	14	Silty clay-sand	Well
21	Cibulakan	6°44’31.98”	107°26’57.46”	624	-	Silty clay-sand	Spring
22	Kanangasari 1	6°45’56.93”	107°23’52.31”	394	-	Breccia	Spring
23	Kanangasari 2	6°45’41.93”	107°23’43.77”	421	15	Silty clay-sand	Well
24	Cicariu	6°45’04.12”	107°23’56.59”	457	-	Silty clay-sand	Spring
25	Cikalong 1	6°44’15.32”	107°25’47.35”	637	25	Silty clay-sand	Well
26	Cikalong 2	6°44’00.87”	107°25’55.12”	632	15	Silty clay-sand	Well
27	Cikalong 3	6°44’04.46”	107°25’53.32”	633	14	Silty clay-sand	Well
28	Cikalong 4	6°44’01.35”	107°25’43.96”	636	17	Silty clay-sand	Well
29	Cikalong 5	6°44’11.52”	107°25’46.16”	635	20	Silty clay-sand	Well
30	Cikalong 6	6°44’15.32”	107°25’47.35”	569	-	Silty clay-sand	Spring
31	Mama Rende	6°44’07.35”	107°24’26.48”	479	-	Silty clay-sand	Spring

(Li *et al.*, 2020). ($Na^+ + K^+$)/($Na^+ + Ca^{2+} + K^+$) and Cl^-/($Cl^- + HCO_3^-$) for cations and anions were calculated to create the Gibbs diagram. Following that, the calculated cations and anions ratios were plotted individually on a linear scale while TDS concentrations were presented on a logarithmic scale. The parameters controlling the ions generation in water were determined by locating the areas, where the projected values in the Gibbs diagram fell (Ogbozige & Toko, 2020).

Results and Discussion

Groundwater Flow Results

The observed water table data were interpolated as a contour. The water table map, which captures the groundwater flow for the Walini urban area is shown in Figure 5. The shallower subsurface aquifer is shown on the map in the southwestern part, including the Mandalasari, Rende, and Kanangasari communities. Cisomang Barat, in the northeastern section has a localised peak value of 680 m. The topographic slope is oriented NE-SW.

The direction of groundwater flow is perpendicular to the groundwater contour. Groundwater contour lines on a map can be drawn by extrapolating the height of the points of dug wells and producing the direction of groundwater flow. Interpolation of the water level results in the flow trend towards the southwest, which is parallel to the topographic slope. It explains how the topographic gradient between the higher elevated recharge points and the low-lying areas provides the dominant driving force that causes the water to flow downslope into low-lying areas.

The influence of precipitation supported the above fact. According to the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia, the average monthly rain of 247.97 mm and 2,976 mm in a year is considered medium humid. As rain is the primary source of recharge, it will drop in the hilly area and the seepage will flow to low-lying areas. Moreover, the annual precipitation data shows that the northeast areas received more rain than others (Figure 6). The precipitation

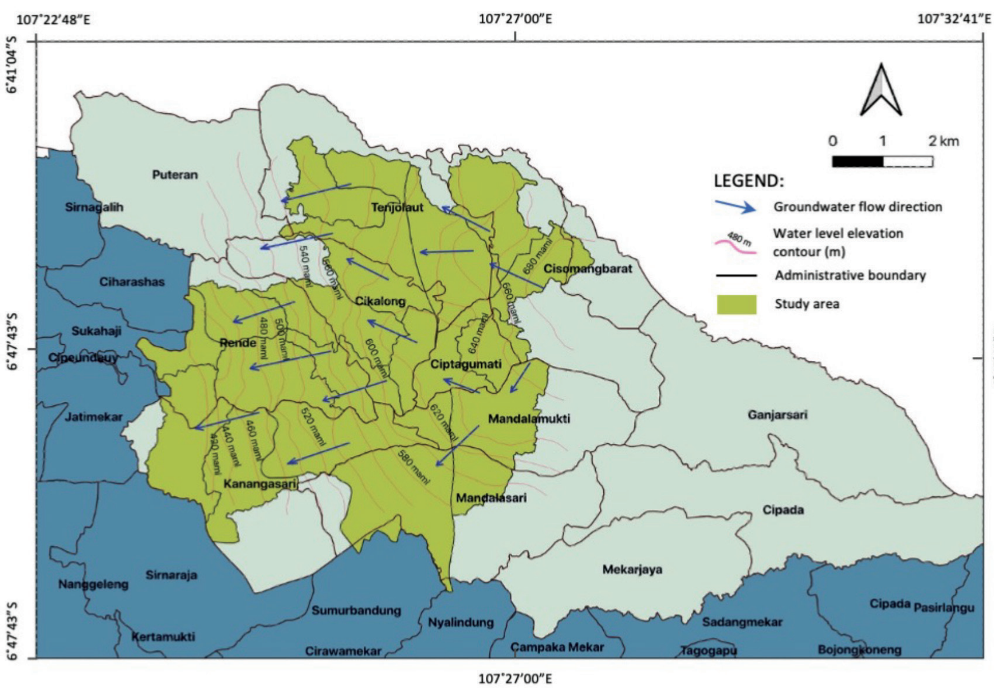

Figure 5: Water table contour map of the study area showing the groundwater flow direction

rate gradually lowered in the southwestern part, which is a tally to the groundwater flow trend.

Physiochemical Parameters

The physiochemical data of the sample analysis is given in Table 2. The pH of the aquifer spring samples ranges from 6.76 to 7.83 while the pH of the dug well samples is below 6.5. In comparison, the groundwater pH of the well bore samples is slightly higher up to eight. This slightly acidic pH value is due to dug wells in the study area, primarily around the housing complex. Thus, human domestic activities commonly as dishes, clothes washing, or septic tanks might pollute the unconfined aquifer. However, compared to the WHO (2004) water quality standards, the groundwater of the study area is neutral.

The observed EC values range from 105 µS/cm to 188 µS/cm for springs, slightly lower (73 µS/cm to 93 µS/cm) for dug wells, and somewhat higher from samples from bore wells. These values are considered low salinity. Electrical conductivity (EC) indicates the ability of water to conduct electric currents (Rao *et al.*, 2012a). This is due to the number of salts or free ions in the groundwater. The higher the salt or free ions amount, the higher the EC value. In contrast, pure water is not a good conductor of electric current (low salinity). According to WHO (2004), the EC values of the samples do not exceed the drinking water limit.

Hydrochemistry

The concentration of the hydrochemical parameters of the water samples was observed during the dry-wet season transition in October 2021. In general, the water contains calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) in balancing levels. However, the order of abundance of cations is still Ca > Mg > Na. Younger (2007) mentioned some possible causes of this concentration's order are rainwater enrichment, weathering, and ion exchange from minerals such as anorthite plagioclase ($CaAl_2Si_2O_8$), hornblende [$Ca_2(Mg, Fe, Al)_5(Al, Si)_8O_{22}(OH)_2$], or biotite [$K(Mg, Fe)_3(AlSi_3O_{10})(F, OH)$]. The longer the groundwater residence time within the aquifer, the longer the cation exchange time. In this case, the higher value of Ca and Mg cations are due to the chemical weathering of volcanic breccia,

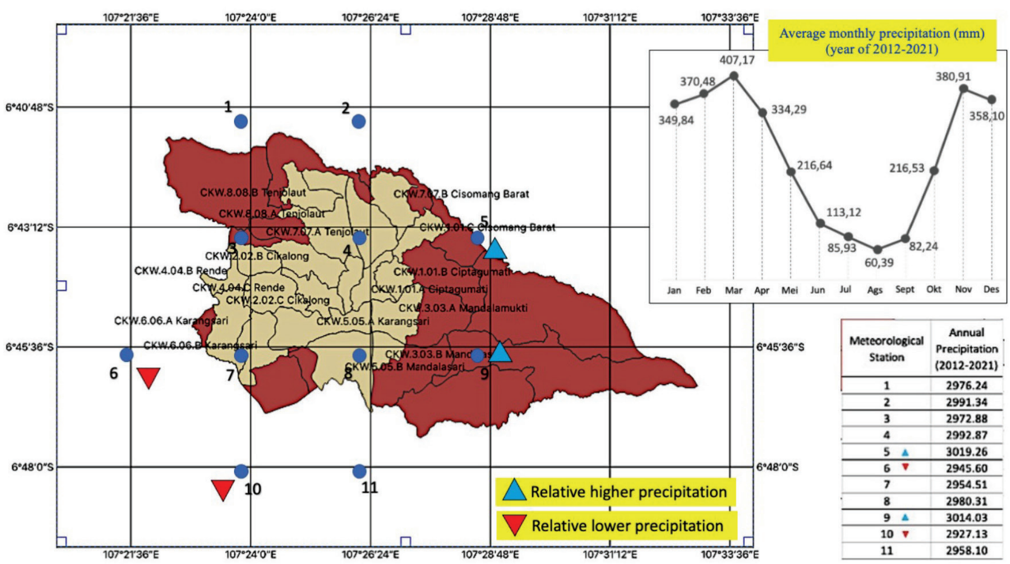

Figure 6: Average monthly precipitation in the last decade shows two different seasons—dry (May-October) and wet (November-April). Meteorological stations around the study area show a trend of higher precipitation in the north-eastern part

Table 2: Physiochemical characteristics of water samples concentration of major ions in groundwater

Sample No.*	Location Name	EC (µS/cm)	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	K^{+} (mg/L)	CO_3^{2-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)
1	Kraton	188	7.83	27.6	8.1	8.19	3.543	129.3	0	8.4	0
9	Warung domba	93	5.39	8.7	4.6	0.842	4.483	30.5	0	15	0
12	Mandalasari 1	n.a	8.00	n.a	n.a	n.a	n.a	57.34	0	17	81
19	Tenjo Laut 1	73	6.22	11.5	2.5	2.166	2.901	34.6	0	9.9	1.3
21	Cibulakan	105	6.76	24.5	3.3	5.902	3.06	94.7	0	6.9	0.1
22	Kanangasari 1	168	6.79	7.8	18.1	10.827	1.521	122.5	0	6.7	1.4
23	Tenjo Laut 2	696	7.27	60.64	21.48	n.a	n.a	292.81	0	68.4	46
32	Cipada	397	7.58	39.87	14.34	n.a	n.a	193.59	0	23.09	17
	(WHO, 2004) standard		6.5-8.5	75-200	50-150	200	12	150-300		200-600	200-400

*Samples no. 1, 21, and 22 are from springs; no. 9 and 19 are from dug wells; and no. 12, 23, and 32 are from bore wells.

as Andesite, the fragment of breccia is rich in plagioclase, hornblende, and biotite phenocrysts (Kuno, 1968; Purwanto *et al.*, 2021).

In general, the weathering dissolution path of Ca^{2+} is earlier than followed by Mg^{2+} and Na^{+} (Rao *et al*., 2012). So, due to calcium from lithology being dissolved first, it is normal to have more Ca^{2+} and Mg^{2+} and then Na^{+} and K^{+}. The zero CO_3^{2-} concentration in groundwater samples tally to the pH condition (ranges from 6.76 to 8) of water in Walini. This is because the CO_3^{2-} concentration only appears in water with a pH above 8.4 (Marghade *et al*., 2011).

In the study area, sodium (Na^{+}) concentration ranges from 0.842 mg/L to 10.827 mg/L, which is considered very low. The higher Na^{+} concentrations are all from spring groundwater samples. According to Younger (2007), it most probably comes from weathering rock-forming minerals such as sodium plagioclase ($NaAlSi_3O_8$) from andesite fragments of breccia or interbedded claystone. In addition, there is a possibility that groundwater in springs has a longer path than groundwater in dug wells, resulting in the enrichment of Na elements through the cation exchange mechanism. Cation exchange occurs when groundwater passes through a clay layer (Rao *et al.,* 2012; Kshetrimayum, 2015; Ravindra *et al*., 2023). The clay layer will absorb Ca ions in the water and Na ions in the clay layer will be released into the water. This process certainly takes a relatively long time. This can also be seen from the EC value of spring water which is higher than that of dug wells.

The potassium (K^{+}) concentration in the study area is also low and varies between 1.521 mg/L and 4.483 mg/L. Potassium in groundwater is usually derived from rainwater, weathering of silicate minerals in igneous or metamorphic rocks, and fertiliser or other anthropogenic activities (Deshmukh, 2013; Das *et al*., 2023). However, the medium to high rate of rainwater and anthropogenic activities are the two primary sources in the case of this study area, as the samples were taken within a radius of 100 m of housing and populated places.

The anions in the groundwater samples of the study area, from the most dominant one are bicarbonate (HCO_3^-), followed by chloride (Cl^-) and sulphate (SO_4^{2-}). In the study area, (HCO_3^-) ranges between 94.7 mg/L to 129.3 mg/L for springs and much lower for dug wells at 30.5 mg/L to 34.6 mg/L. The primary source of (HCO_3^-) is the dissolution of minerals like calcite and dolomite (Marghade *et al*., 2011). However, these sources are absent in the study area as CO_3^{2-} is undetectable in all water samples. The HCO_3^- here can result from the diffusion of CO_2 in the water. It is an indication of the local groundwater system of an unconfined aquifer.

Compared to bicarbonate, Cl^-, and SO_4^{2-} concentrations are negligible in the groundwater from dug wells and springs. They vary from 6.7 mg/L to 15 mg/L and 0.1 mg/L to 1.4 mg/L, respectively. Although the Cl^- concentration in groundwater is deficient, it shows the highest in the water sample from the Warung Domba site (sample No. 9). Practically, Cl^- concentration comes from domestic effluents such as fertiliser, septic tanks, and leachates from waste. Indeed, the site is located near a complex of food courts, making it possible for such domestic contamination (Shekhar & Sarkar, 2013). Another reason for the high amount of its opposite to the low Cl^- and SO_4^{2-} is due to the seasons, where bicarbonate was high during the wet season, but Cl^- and SO_4^{2-} could increase during the dry season (Abbasnia *et al*., 2019).

Piper's trilinear diagram helps to classify hydrogeological facies. The plot of chemical data on the Piper trilinear diagram (Figure 7) shows the dominant ion (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, and SO_4^{2-}). It clearly shows different hydrogeochemistry characteristics between dug wells and springs. A significant increase in the HCO_3^- and Mg^{2+} concentrations is observed in all spring samples. An increase of Mg^{2+} suggests that springs have a deeper groundwater system

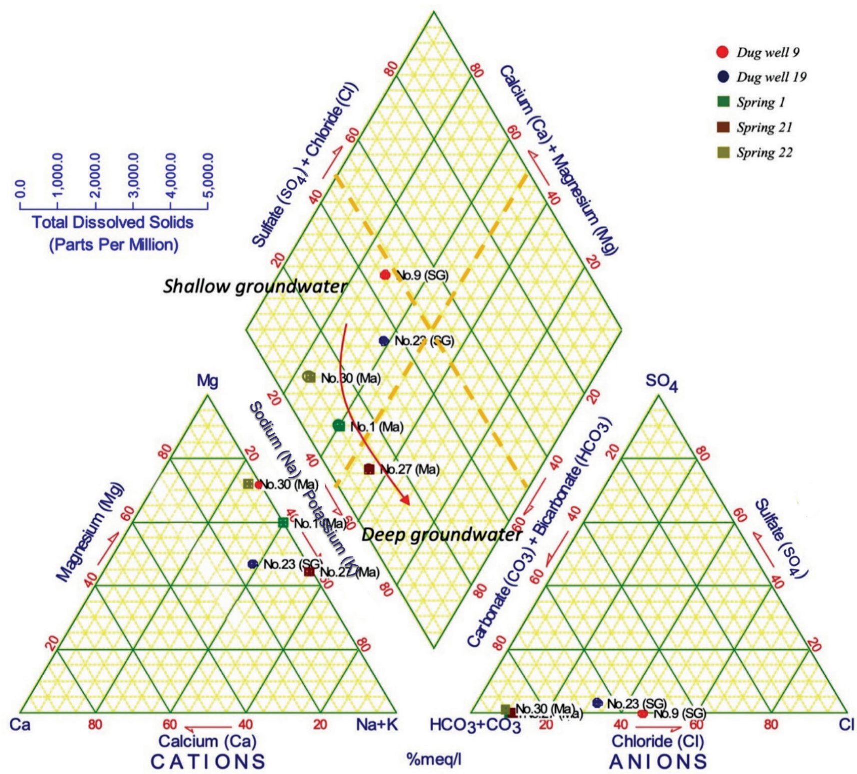

Figure 7: Piper diagram of the water samples showing the hydrogeochemical facies, variation of major ions, and relation to the groundwater depth zone

than dug wells, but both were still in the zone of the unconfined aquifer (shallow zone) due to the interaction between H_2O and CO_2, increasing HCO_3^-. Further, it highlights the dominance of (a) Ca–Mg–HCO_3–Cl, (b) Ca–Mg–HCO_3, (c) Ca–HCO_3, and (d) Ca–Mg–Na–HCO_3 in the water facies.

This finding confirms previous analysis that springs have a deeper groundwater system than dug wells. The system goes deeper to the southwest towards the lowland contour, as marked by the sample plotted in the Piper diagram. This means a shallower groundwater system depends on the surface or atmospheric conditions. Based on the bore wells data, the hydrochemistry composition of a much deeper unconfined aquifer is more or less the same as the shallow one, except for EC and sulphate.

Using Gibbs diagrams, the cation ratio (Na^+ + K^+)/(Na^+ + Ca^{2+} + K^+) and anion ratio Cl^-/(Cl^- + HCO_3^-) were plotted versus TDS to identify the influences of precipitation, lithology (rock-water interactions), and climatic (evaporation) processes in controlling groundwater chemistry (Figure 8). All groundwater samples, either from dug wells (o), springs (□), or bore wells (Δ) are plotted in the rock weathering dominance field. Factors affecting the groundwater chemistry, where the TDS is less than 1,000 mg/L, mean the groundwater quality falls into the freshwater category. The results suggest that rainwater reacts with the lithology to cause chemical weathering, which dissolves the minerals that compose the rocks in the area.

Water Quality and Usability Assessment

According to Rao *et al*. (2012b), the observed EC values from dug wells and springs, representing shallower aquifer systems are between 73 µS/cm and 188 µS/cm, as shown in Table 2. Meanwhile, the EC values of water samples from bore wells representing deeper aquifers show higher values between 397 µS/cm and 696 µS/cm. Compared to WHO (2004), EC values for drinking water standards are 200 µS/cm to 800 µS/cm, meaning that all groundwater samples belong to the excellent water class.

Evaluation of the acid-base balance of water is usually marked by the pH parameter (Meride & Ayenew, 2016). According to the WHO (2004) standard, the benchmark for pH in water is 6.5 to 8.5. The spring water is within the limit. Thus, the water is suitable for drinking and other public domestic purposes. Meanwhile, the water from dug wells was slightly acidic due to the shallow aquifer. When it is shallow, the water residence time in the aquifer is limited. The weathering dissolution path is also limited. This statement can be proven by EC data in the dug wells, where the low EC data in the dug wells indicate the water quality is suitable for drinking.

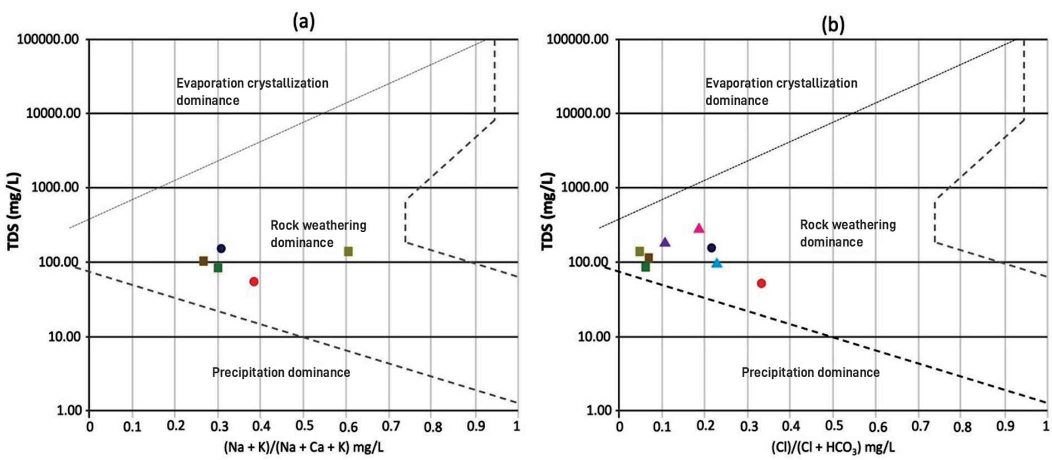

Figure 8: Gibbs diagram on TDS versus (a) major cations and (b) major anions

In the study area, both calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were far below the tolerance limit of 75 mg/L to 200 mg/L and 50 mg/L to 150 mg/L, respectively (WHO, 2004). Both Ca^{2+} and Mg^{2+} values here range from 2.5 mg/L to 27.6 mg/L. Thus, the water is considered safe to consume. Similarly, sodium (Na^{+}) and potassium (K^{+}) concentrations were also far below the tolerance limit of 200 mg/L and 12 mg/L, respectively. The concentration of Na^{+} in the study area is deficient and varies less than 11 mg/L, so, it is considered neglectable. Thus, the content of Na^{+} and K^{+} has no adverse health effects.

Bicarbonate concentration (HCO_3^{-}) is directly linked with the alkalinity of water. Alkalinity measures the water's ability to neutralise acids and is related to pH (Akpan *et al.*, 2013). Water with low alkalinity and high pH is usually corrosive. The alkalinity of the water in the study area is sourced entirely from the bicarbonate content. According to the WHO (2004), the standard limit of bicarbonate (HCO_3^{-}) is between 150 mg/L to 300 mg/L. Deeper groundwater system such as springs in the study area has an HCO_3^{-} concentration of 94.7 mg/L to 129.3 mg/L while the shallower one from dug wells has an HCO_3^{-} concentration of about 30 mg/L. In the study area, since the HCO_3^{-} concentration is followed by neutral pH and low EC, the water is safe and not corrosive.

Usually, a high concentration of chloride (Cl^{-}) and sulfate (SO_4^{2-}) comes from precipitation and is anthropogenic in origins such as fertiliser and recycled water from irrigation (Rao *et al.*, 2022b). The small amount of Cl^{-} here indicates the intensity of evapotranspiration in the study area (Younger, 2007). However, in the study area, both Cl^{-} and SO_4^{2-} not exceed the limit as regulated by the WHO. Thus, the water in the Walini urban area is appropriate for drinking and other domestic applications that support urban development.

Hydrogeology and Walini's Urban Development Plan

Recharge and discharge areas of a growing urban site of Walini have been delineated with the aid of elevation, water table data, and precipitation rate. The results show elevated topography in the northeast, which covers Cisomang Barat and Wangunjaya villages and tends to receive higher precipitation rates. The rain percolated as groundwater, thus flowing from NE to SW direction following a topography gradient. It makes Mandalasari, Kanangasari, and Rende subdistricts (discharge zone) in the south have sufficient groundwater resources in nature, so, they are the better option for future development.

The urban centre of Walini is currently in Ciptagumati village, which is precisely in the centre of the study area. It is also the capital of the Cikalong Wetan subdistrict. The recent urban growth moving southward to Mandalasari village was launched early by the tunnel construction of the Jakarta-Bandung high-speed train in the area, followed by the development of some housing complexes. Unfortunately, the water quality in Mandalasari has deteriorated since that time. Indeed, water samples from the shallow unconfined aquifer in the Mandalasari area are prone to being slightly polluted, despite being within the regulatory limit.

Compared to the World Health Organisation's (WHO) groundwater quality standards, groundwater in the Walini urban area is suitable for drinking and other domestic uses supporting urban development. On the other hand, compared to the shallow unconfined aquifer (4 m to 20 m), the water quality of the deep aquifers (beyond 104 m), and middle unconfined aquifers (between 35 m and 73 m) is higher. It follows the comprehensive classification of aquifer depth in the Greater Bandung area by Agustin *et al.* (2023).

As in the case of Mandalasari village, due to the vulnerability of shallow groundwater to urbanisation, the water has a slightly lower pH (acidic). If the current trends continue, appropriate management measures for Walini shallow groundwater protection will be important for long-term sustainability. Drastic water table drawdown happens, especially in some parts of the study area. Most likely because of excessive groundwater extraction from some factories nearby.

Conclusions

In the Walini urban area, groundwater is essential, providing as much as 80% of the people drinking water supply and domestic needs and ~20% to water the corps. The people dependence on groundwater affects the sustainability of the area. Therefore, groundwater data from field observations, hydrogeochemical techniques, and precipitation have been integrated to assess groundwater quality, including delineating the groundwater recharge and discharge flow.

The groundwater shows the order of major cations and anions is $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+} > HCO_3^{-} > Cl^{-} >$ which leads into four water facies: (a) $Ca–Mg–HCO_3–Cl$, (b) $Ca–Mg–HCO_3$, (c) $Ca–HCO_3$, and (d) $Ca–Mg–Na–HCO_3$. These ion distributions are caused by the influences of lithology or rock weathering (mineral dissolution, ion exchange, and mineral solubility). The hydrogeochemical signatures indicate that the groundwater is classified as freshwater.

The groundwater quality meets the standards of WHO (2004) for drinking and domestic purposes. However, the study reveals that good to excellent water quality comes from the middle (35 m to 73 m) and deep unconfined aquifers (at a depth of more than 104 m). Meanwhile, the shallow unconfined aquifer (4 m to 20 m) has lower water quality than the other two. This study recommends continuous monitoring of the groundwater quality in the area, as further urban development may increase the risk of water contamination, especially in the shallow groundwater. The study also reveals that the northeastern Walini urban area is more prone to groundwater recharge while the southwestern one is the discharge zone. Therefore, the existing pine-protected forest on the north must be preserved to support the Walini recharge zone. As a result, the growing development in the south (Mandalasari village) is secure from groundwater supplies as long as the water quality is monitored; hence, the water extraction rate needs to be controlled for sustainability.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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