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Research Article

Seawater intrusion assessment and prediction of sea-freshwater interface in Parangtritis coastal aquifer, South of Yogyakarta Special Province, Indonesia

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Abstract

The Parangtritis area is a tourist destination in Yogyakarta, Indonesia, consisting of dunes and plains. One of the essential parameters in tourist areas is the provision of water sources. The increase in tourist visits and the development of tourism facilities in this area have increased groundwater utilization. Therefore, this study aimed to assess the potential of seawater intrusion in the Parangtritis Beach area and its surroundings, Indonesia. The research was carried out by surveying, field measurements, and groundwater samples to test major ions in the laboratory. Indications of seawater intrusion are based on TDS values, Cl^-, Simpson ratio, Sodium Chloride ratio, BEX, and groundwater type. The results showed that the research area had a shallow groundwater level with groundwater flow relative to the south-southwest and composed of unconfined aquifers. Only two water samples indicate seawater intrusion from Parangwedang spring and its southern place based on the geochemical analysis. However, this spring was formed due to geological structure related to geothermal manifestation and not due to seawater intrusion. It has a lateral flow to the south and is mixed with shallow groundwater, thereby increasing the chloride concentration in the groundwater. The sea-freshwater interface has a depth from 52 meters to 284 meters from sea level, where the farther from the coastline, the more profound.

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Introduction

The coastal area is an area prone to groundwater pollution due to the meeting area between the plains and the ocean. All water, both surface water and groundwater, will be discharged in this area. Therefore, all pollutants carried by the water media will end up in the coastal zone. However, because of its strategic location for transportation and tourism, many big cities worldwide are located in coastal areas with densely populated (Kantamaneni et al., 2017). The large population and economic activities in the coastal region have led to an increase in water use. Most of the big cities in coastal areas still use groundwater as a source of water needs (Hamed et al., 2018). Excess groundwater pumping in coastal areas will disrupt the sea-freshwater interface, which triggers seawater intrusion (Azonsi et al., 2003). The seawater intrusion mechanism consists of vertical upconing and lateral encroachment (Javadi et al., 2015). Over-pumping in coastal areas causes a vertical upconing of seawater. Reducing groundwater recharge will impact groundwater flow rates and a lateral enrichment of seawater in the aquifer (Kouzana et al., 2007). Besides, it can also be triggered by sea-level rise due to global climate change. Changes in global sea level, particularly sea-level rise, can affect the sea-freshwater interface position (Werner et al., 2013). The sea-level rise impact simulation indicates a change in the sea-freshwater interface towards the land to several hundred meters (Meyer et al., 2019).

In general, the factors that control the occurrence of seawater intrusion include geology, tidal activity, climate change, sea-level rise, and human-induced factors (Prusty and Farooq, 2020). Seawater intrusion will disturb the fulfilment of clean water for the community, economic and agricultural activities (Demirel, 2004). The spread of seawater intrusion is influenced by natural geology, hydraulic gradient, groundwater extraction discharge, and groundwater recharge (Choudhury et al., 2001). Methods for measuring and instrumentation used in monitoring seawater intrusion in the wells are pressure distribution, groundwater velocity, geology, and solute concentration distribution (Costall et al., 2020). Seawater intrusion assessments can be carried out in several ways, namely directly or indirectly (Prusty and Farooq, 2020). The direct method can be conducted using the geochemical analysis of groundwater (Hairoma et al., 2016; Gopinath et al., 2019) and isotope (Han et al., 2011; Putra et al., 2021). The indirect method is conducted by geophysical techniques (Rao et al., 2011; Vann et al., 2020) and numerical modeling (Wilopo et al., 2018; Guo et al., 2019; Costall et al., 2020).

Parangtritis Beach is one of the main tourist objects in the south of Yogyakarta City, Indonesia, and belongs to the Bantul Regency. In 2019, this coastal area had 177 hotels with 1,407 rooms and was visited by 2,808,134 tourists, both local and international (BPS of Bantul Regency, 2020). Water consumption in this area still relies on groundwater sources by making dug wells and boreholes. With the number of tourist visits and existing tourist facilities, the need for water will also increase. Therefore groundwater extraction will also increase. It can lead to seawater intrusion. Therefore, this study evaluated seawater intrusion potential in the Parangtritis coastal area based on groundwater geochemistry data and predicted the sea-freshwater interface position.

Materials and Methods

The research area is a coastal plain that belongs to the Parangtritis Beach area, Yogyakarta Special Region, Indonesia, as shown in Figure 1. The Parangtritis coastal area is bordered by the Opak river in the west and north, while in the eastern and northern parts, it is bordered by the southern mountains. The morphology in this area is in the form of coastal plains and dunes that extend east-west. This area comprises volcanic young Merapi volcanic deposits and alluvium.

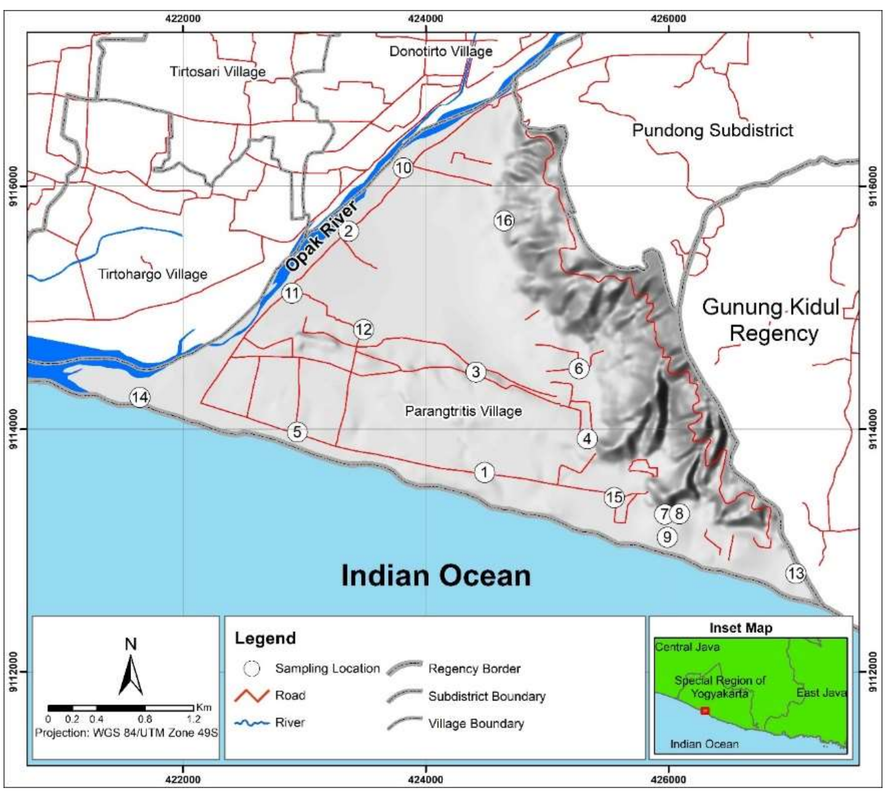

Figure 1. Research area (brown shading).

The Tertiary rocks from the Nglanggran and Wonosari formations were found in the mountainous region in the eastern part (Rahardjo et al., 1995). There was also an intrusion of igneous rocks in the Parangkusumo area, extending north and south following geological structure. The geological structure in this area is relatively complex and consists of strike-slip and normal faults, as shown in Figure 2 (Idral et al., 2003). Meanwhile, the aquifer is dominated by an unconfined aquifer that influences the Opak River flow. The research was conducted by field survey and chemical analysis of water samples. Field measurements were carried out on 15 dug wells and one spring as shown in Figure 1, including groundwater level, temperature, pH, total dissolved solids (TDS), and electrical conductivity (EC) using calibrated portable pH meters. The selection of measurement locations and water sampling was carried out randomly based on residential and tourist areas.

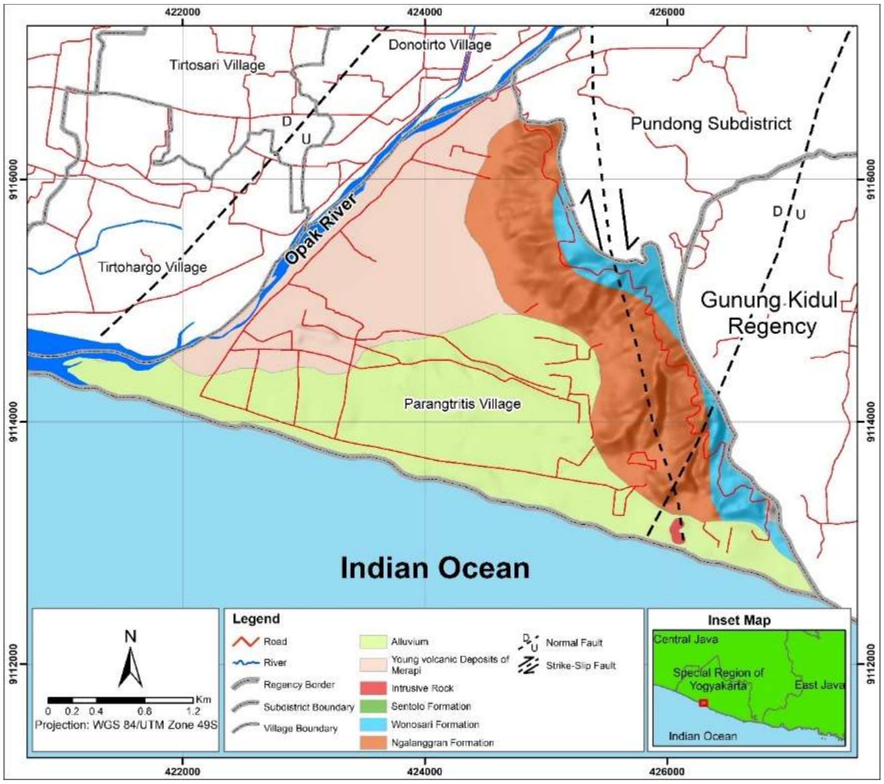

Figure 2. Geological Map of the research area.

Sixteen water samples with 500 ml were taken using polyethylene bottles washed with hydrochloric acid and distilled water. Then, rewash with water to be taken in the field, fill it until full, and put it in an icebox for testing in the laboratory. The water samples were analyzed for their major ion composition, including Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, and SO_4^{-} using the Ion Chromatographic Method (IC). Meanwhile, the HCO_3^{-} and CO_3^{2-} ions were carried out through the volumetric titration method.

The accuracy of the chemical analysis results is confirmed by the ionic error balance (RE), which is less than ± 5%. The chemical analysis results were used to analyze seawater intrusion indication based on the TDS, Cl^{-}, piper diagram, Simpson ratio, sodium chloride ratio, and base exchange indices (BEX). Freshwater has the maximum TDS content of 1000 mg/L, while concentrations between 1000 mg/L and 3,000 mg/L are categorized as slightly saline water, between 3,000 mg/L and 10,000 mg/L is moderately saline water, between 10,000 mg/L and 35,000 mg/L are classified as very saline, and more than 35,000 mg/L as brine water (Davis and De Wiest, 1996). If the Cl^{-} concentration less is than 280 mg/L, the water is classified as freshwater, between 280 mg/L and 600 mg/L is slightly brackish, between 600 mg/L and 2,800 mg/L is medium brackish, between 2,800 mg/L and 9,000 mg/L is brackish, between 9,000 mg/L -18,000 mg/L is strong brackish and more than 18,000 mg/L is seawater (Saline Agricultural Worldwide, 2020).

The Simpson ratio method is based on the concentrations of Cl^{-}, HCO_3^{-}, and CO_3^{2-} (Todd and Mays, 2005) with the following equation:

$$\text{Simpson Ratio} = \frac{\text{Cl}}{\text{HCO}_3 + \text{CO}_3} \quad (1)$$

If the value is less than 0.5, it is in good condition, 0.5 - 1.3 slightly contaminated, 1.3 - 2.8 moderately contaminated, 2.8 -6.6 injuriously contaminated, and more than 6.6 highly contaminated. The sodium chloride ratio can be used to indicate seawater intrusion (Bear et al., 1999), with the following equation:

$$\text{Ca Enrichment} = \frac{\text{Ca}}{\text{Mg}} \qquad (2)$$

Seawater intrusion is indicated by a sodium chloride ratio value of less than 0.83, where the effect of pollutants from anthropogenic sources will have a value of more than 1.

To determine indications of seawater intrusion in aquifers, the calculation of base exchange indices (BEX) were carried out with the following equation (Stuyfzand, 2008):

$$\text{BEX} = \text{Na} + \text{K} + \text{Mg} - 1.0716\ \text{Cl} \qquad (3)$$

The positive BEX value indicates the freshening process, and negative BEX value expresses the salinization process, and the BEX value 0 shows no base exchange. The position of the sea-freshwater interface can be predicted based on the groundwater level data. The method using the Ghyben-Herzberg equation as follow (Todd and Mays, 2005):

$$z = \left(\frac{\rho_f}{\rho_s - \rho_f}\right) x\ h_f \qquad (4)$$

Where z is the depth of the sea-freshwater interface from the sea level at that point, h_f the groundwater level from the sea level, ρ_f is the specific gravity of freshwater, and ρ_s the specific gravity of the seawater. If the value of ρ_f is 1 g/cm^3 and ρ_s is 1.025 g/cm^3, then equation 4 can be simplified as follow:

$$z = 40h_f \qquad (5)$$

This equation applies only to an unconfined aquifer and does not include variables such as groundwater inflow and hydraulic gradient change.

Results and Discussion

The groundwater level in the study area generally flows from north to south, as shown in Figure 3. Field measurements show that the groundwater temperature ranges from 29.1 ºC to 39.2 ºC. The Parawedang spring water has a temperature that is the most different from the other groundwater. Meanwhile, groundwater pH in the study area ranged from 6.9 to 8.2. EC values ranged from 410 µS/cm to 18,550 µS/cm, where the water from the Parawedang spring has a much greater value than other groundwater. TDS values range from 190 mg/L to 9,460 mg/L, with the highest value from the Parangwedang spring water. Table 1 shows the results of measurement data in the field and major ions concentrations from laboratory tests. It shows that some of the water has the total dissolved solids (TDS) and Cl^- concentration is more than the freshwater standard, which has a value of more than 1,000 mg/L and 280 mg/L, respectively.

The plotting of groundwater chemistry data on the piper trilinear diagram shows that the research area can be divided into four groundwater classes: Calcium Magnesium Bicarbonate, Alkali Bicarbonate, Calcium Magnesium Chloride, and Alkali Chloride (Figure 4). Most of the water types in the study area were dominated by Calcium Magnesium Bicarbonate located in alluvium. The alkaline bicarbonate type was found along Opak River with lithology from the young Merapi volcanic deposit, while the alkaline chloride type was found in areas close to the coastline. Meanwhile, the Parawedang spring is classified as calcium magnesium chloride. The Parawedang spring indicates geothermal manifestations in Parangtritis beach (Idral et al., 2003).

Parawedang spring has a water chemical composition that is very similar to seawater where the concentration of Na^+ is very high and Cl^- higher than a total of HCO_3^- and SO_4^{2-}, but the concentration of Ca^{2+} is more dominant and the concentration of Mg^{2+} is low (Wang et al., 2018). These data indicate that mixing with seawater may be one of the main processes and factors influencing the hydrochemistry of the Parawedang spring water. The variation in geothermal water composition is also strongly influenced by the fluid-rock interaction and seawater contribution. Almost all of the existing water samples have low Cl^-, except in the STA 7 and 9. The relationship between Cl^-, Ca^{2+}, and Mg^{2+} in the Parawedang spring water may be due to the dissolving and deposition of minerals resulting from hydrothermal alteration. The enrichment of Ca^{2+} in Parangwedang spring is related to the cation exchange process between hydrothermal solutions and silicate minerals such as calcium-rich plagioclase feldspar (El-Fiky, 2009). Mg^{2+} will be precipitated into secondary alteration minerals in high-temperature systems by ion-exchange reactions resulting in low Mg^{2+} concentrations in water (Nicholson, 1993).

Seawater roughly has a concentration of total dissolved solids of 35,000 mg/L, of which 19,000 mg/L is chloride (Lyles, 2000). As a result, the high concentration of chloride in groundwater in coastal aquifers tends to be related to seawater intrusion (Werner et al., 2013). Indications of seawater intrusion are based on the TDS, Cl^- concentration, Simpson ratio, sodium chloride ratio, and BEX, as shown in Table 2. According to TDS value, only two locations were very saline (STA 7) and slightly saline (STA 9) and other freshwater sites.

From the Cl^- concentration value, it can be seen that only two groundwater samples have concentrations of more than 280 mg/L is in STA 7 and 9. These locations are categorized as strong brackish and slightly brackish, respectively. The Simpson ratio values that exceed the standard freshwater value (> 1) are STA 7 and 9. Besides, the sodium chloride ratio, which indicates seawater intrusion with a value of <0.83, was found at STA 4, 5, 7, 8, and 9. However, the BEX value, which indicates seawater intrusion, only occurs at STA 7 and 9.

Table 1. Field measurement and laboratory result of water analysis.

No STA	Coordinate X	Coordinate Y	GWL (M-SWL)	Temperature (°C)	pH	EC (µS/cm)	TDS (mg/L)	Major Ion (mg/L) Na^{+}	Ca^{2+}	K^{+}	Mg^{2+}	HCO_3^-	$SO4^{2-}$	Cl^-	CO_3^-	RE
1	423154	9116165	2.8	29.7	7.1	966	460	33.1	89.0	9.2	25.0	358.0	25.9	34.6	N.D	0.05
2	423364	9115629	3.9	29.6	7.1	550	270	108.0	60.0	18.0	18.0	360.9	47.0	65.0	N.D	0.05
3	424414	9114469	3.5	29.1	7.3	410	190	106.0	73.5	15.0	18.5	355.8	46.0	85.4	N.D	0.05
4	425331	9113919	5.6	29.4	6.9	929	440	80.9	63.9	6.9	25.3	315.0	3.1	105.0	N.D	0.04
5	422941	9113975	2.9	30	7.1	800	390	130.0	28.7	8.0	32.7	261.3	43.0	147.0	N.D	0.03
6	425262	9114497	6.3	29.3	7.2	620	300	50.0	83.6	3.0	16.1	354.6	12.0	43.0	N.D	0.03
7	426014	9113313	2.5	39.2	6.9	18,550	9,460	2,319.0	2,360.2	24.0	29.0	65.3	143.0	6,997.8	N.D	0.04
8	426047	9113313	3.3	29.3	7.7	850	440	99.0	88.7	5.0	30.3	429.3	1.9	124.1	N.D	0.04
9	425990	9113109	2.4	31	8.2	5,500	2,610	186.0	104.9	10.0	11.3	211.5	34.0	312.4	N.D	0.05
10	423815	9116151	4.2	30.3	6.9	1,120	540	125.0	74.0	23.0	26.4	419.5	94.0	67.5	N.D	0.05
11	422898	9115120	2.65	30.2	7	700	340	129.0	62.7	14.0	17.1	448.0	48.0	44.0	N.D	0.05
12	423488	9114820	2.9	30.1	7	950	450	55.7	93.0	8.4	21.2	365.0	24.3	58.1	N.D	0.05
13	427049	9112811	2.7	29.9	7.3	589	280	30.0	75.8	1.5	12.8	360.0	2.3	32.9	N.D	-0.05
14	423394	9114820	1.3	29.8	7.1	950	450	75.6	91.0	8.1	30.3	415.0	46.1	62.0	N.D	0.05
15	425553	9113436	3.2	29.9	7	920	430	45.3	82.6	2.9	29.8	420.0	12.5	65.9	N.D	-0.02
16	424645	9115715	7.1	30.2	7	900	440	62.1	103.0	1.2	20.8	435.0	12.3	45.0	N.D	0.05

Note:N.D.= Note detected, RE= Ionic error balance.

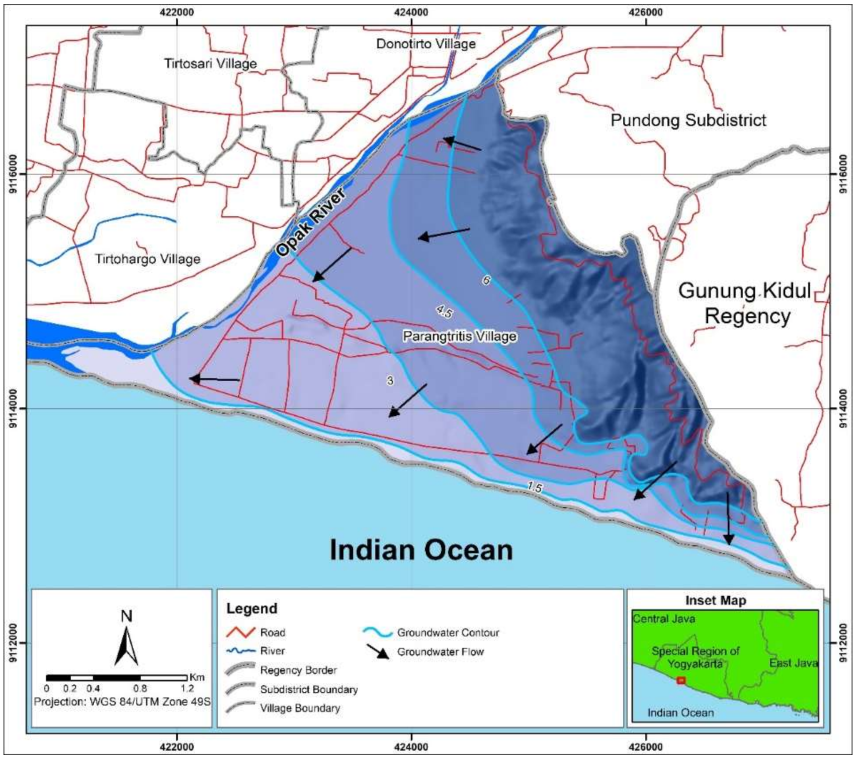

Figure 3. Groundwater flow in the research area.

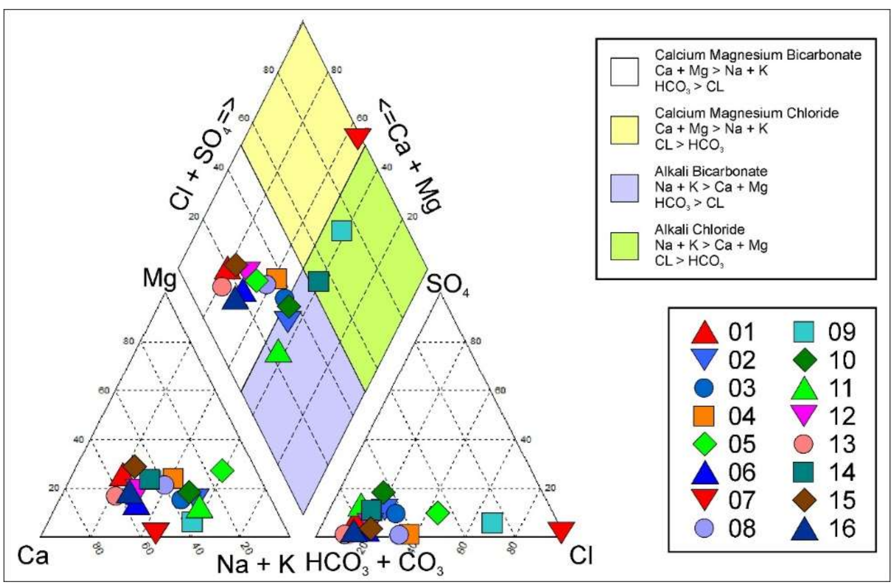

Figure 4. Trilinear piper diagram of water sample.

Table 2. Indication of seawater intrusion based on some approaches and position of sea-freshwater interface.

No STA	Coordinate X	Coordinate Y	TDS (mg/L)	Cl^- (mg/L)	Simpson Ratio	Sodium Chloride Ratio	BEX	Type of Water	Category	Position of Sea-Freshwater interface (m-SWL)
1	423154	9116165	460	34.6	0.1	1.0	30.2	Calcium Magnesium Bicarbonate	FW	112
2	423364	9115629	270	65.0	0.2	1.7	74.3	Alkali Bicarbonate	FW	156
3	424414	9114469	190	85.4	0.2	1.2	48.0	Calcium Magnesium Bicarbonate	FW	140
4	425331	9113919	440	105.0	0.3	0.8	0.6	Calcium Magnesium Bicarbonate	FW	224
5	422941	9113975	390	147.0	0.6	0.9	13.2	Calcium Magnesium Bicarbonate	FW	116
6	425262	9114497	300	43.0	0.1	1.2	23.0	Calcium Magnesium Bicarbonate	FW	252
7	426014	9113313	9,460	6,997.8	107.2	0.3	-5,126.8	Calcium Magnesium Chloride	SWI	100
8	426047	9113313	440	124.1	0.3	0.8	1.3	Calcium Magnesium Bicarbonate	FW	132
9	425990	9113109	2,610	312.4	1.5	0.6	-127.5	Alkali Chloride	SWI	96
10	423815	9116151	540	67.5	0.2	1.9	102.0	Alkali Bicarbonate	FW	168
11	422898	9115120	340	44.0	0.1	2.9	112.9	Alkali Bicarbonate	FW	106
12	423488	9114820	450	58.1	0.2	1.0	23.0	Calcium Magnesium Bicarbonate	FW	116
13	427049	9112811	280	32.9	0.1	0.9	9.0	Calcium Magnesium Bicarbonate	FW	108
14	423394	9114820	450	62.0	0.1	1.2	47.6	Alkali Chloride	FW	52
15	425553	9113436	430	65.9	0.2	**0.7**	7.4	Calcium Magnesium Bicarbonate	FW	128
16	424645	9115715	440	45.0	0.1	1.4	35.9	Calcium Magnesium Bicarbonate	FW	284

Note: FW= Freshwater; SWI= Seawater Intrusion

In general, the results of measurements and analysis of the chemical composition of groundwater at the Parangtritis coastal area show that there are only two locations (STA 7 and STA 9) that indicate seawater intrusion. However, when looking in more detail at STA 7, a Parawedang spring has a relatively hot temperature of around 39 °C that different from other locations. It indicates that this spring is related to the geothermal activity generated from inside of the earth. The spring occurrence probably due to the fault that across this location, as shown in Figure 2. This fault zone becomes a porous zone for hydrothermal water flowing to the surface. It also triggers the intrusion of igneous rocks in the Parangkusumo area in Parangtritis Beach.

The high values of EC, TDS, Na^+, Ca^{2+}, and Cl^- in the water in the Parawedang spring are not caused by seawater intrusion but preferably controlled by natural geological processes in this area. The formation of water dominates water from the spring compare to seawater.

The STA 9 location located in the south of the Parawedang spring also has relatively high EC, TDS, Na^+, Ca^{2+}, and Cl^- values. The distribution of Cl^- in the groundwater, as shown in Figure 5. The flow direction pattern shows a southward direction from the spring to STA 9, as shown in Figure 3. This is more likely was polluted from the Parawedang spring than the seawater intrusion process. The existence of dunes on the Parangtritis beach is one barrier that can minimize the occurrence of seawater intrusion because it functions as an infiltration area. This will also affect the pattern and direction of local groundwater flow, which shows a relative movement to the southwest.

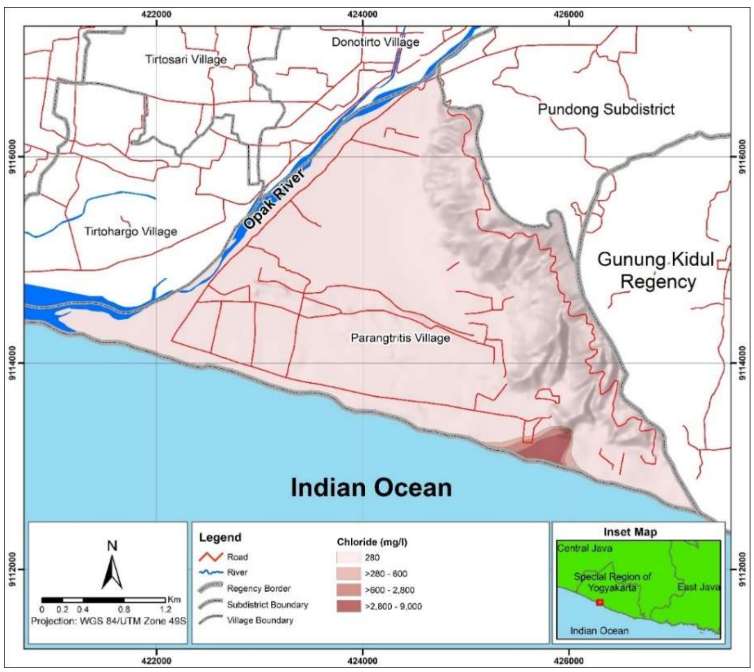

Figure 5. Map of chloride distribution in groundwater.

The ratio of sodium chloride can also indicate groundwater contamination from anthropogenic processes. It is revealed when the value is more than 1. The results showed that almost all research locations had a value of more than 1, including STA 1, 2, 3, 6, 10, 11, 12, 14, and 16. Groundwater pollution from human activities was possible because all water samples were taken from residential or tourism sites. This is in line with the previous research that mentions groundwater pollution in the Parangtritis coastal area due to human activities with a relatively high nitrate concentration (Adji et al., 2013). High nitrate concentration has also been reported in Bojonegero city, East Java, indicating contamination from household wastewater (Wilopo et al., 2020). Nitrate is mostly produced from household waste and agricultural fertilizers (Stevenson, 1982). According to the Ghyben-Herzberg relationship, the sea-freshwater interface can be identified based on the groundwater level using equation 5. Table 2 shows the prediction of the sea-freshwater interface in each well. It shows that the shallowest is 52 meters below sea level, located in the STA 14. This observation point is located nearest to the coastline. Therefore, the maximum depth of the well should be less than the depth of the interface to avoid seawater intrusion. The pumping rate should also be controlled less than the groundwater discharge of the aquifer.

Conclusion

The Parangtritis Beach area consists of Mt. Merapi volcanic deposits and weathered material from The

Tertiary rocks to the east, which forms dune morphology. The pattern and direction of groundwater flow, in general, are south-southwest. The type of groundwater in the study area is Calcium Magnesium Bicarbonate, Alkali Bicarbonate, Calcium Magnesium Chloride, and Alkali Chloride, predominantly calcium magnesium bicarbonate types. The groundwater geochemical analysis results indicate seawater intrusion at the Parangwedang spring and its southern location. However, based on temperature and their occurrence, the Parawedang spring is one of the geothermal manifestations whose water source comes from formation water associated with seawater. This spring is formed due to faults. The water from this spring flows toward the sea, which affects groundwater quality in the southern part. So it can be concluded that the Parangtritis coastal area has not experienced seawater intrusion. However, to prevent seawater intrusion in the future due to excessive groundwater extraction on the coast, it is necessary to regulate groundwater extraction and develop municipal water networks (PDAM) with water sources outside the coastal area. In addition, the development of a new deep well should be less than the depth of the sea-freshwater interface. Besides, the preservation of dune morphology must also be conducted to maintain water catchment areas to increase groundwater volume in the aquifer.

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