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Characterization of shallow groundwater in coastal aquifer of urbanized area using stable isotope and hydrochemical approaches

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ABSTRACT

BACKGROUND AND OBJECTIVES: Cirebon City, located in West Java, Indonesia, is one of the coastal cities formed from alluvial deposits with aquifer rocks in form of gravels and sands in the plains, as well as sands in the hills. Due to its urbanized nature, the city experiences a substantial need for access to clean water. A significant number of residents remain reliant on drinking water providers for safe water, given the contamination of seawater in specific regions, while some continue to draw from shallow groundwater. As groundwater abstraction can intensify seawater intrusion, especially in urbanized area, it is important to investigate this matter. This study sought to qualitatively and quantitatively analyze the degree of seawater pollution affecting the shallow groundwater in Cirebon City, Indonesia.
METHODS: Water samples were collected from 44 shallow groundwater wells around Cirebon City. Following collection, the samples were examined for their significant water chemistry content using ion chromatography and for their isotopic composition through a liquid water isotope analyzer. Interpretation was done using graphical tools such as Piper and scatter diagrams, as well as mathematical equation to approximate mixing proportion between fresh groundwater and seawater and its proportion.
FINDINGS: Stable isotope analysis revealed that eight shallow groundwater samples were salinized due to the incorporation of seawater, with the proportion of seawater ranging from approximately 17.3 to 54.9 percent. These samples have very enriched oxygen-18 isotope composition values up to-3.9 permil. Another 14 samples were mixed with surface water, and the remaining 22 samples were fresh groundwater. Analysis of the hydrochemical properties indicates that fresh shallow groundwater primarily exhibits a bicarbonate composition. In contrast, the salinized shallow groundwater is identified as sodium chloride type, with chloride concentrations reaching a maximum of 6980 milligrams per liter and sodium concentrations peaking at 4963 miligrams per liter. Salinized shallow groundwater samples were up to 1.5 kilometer inland from coastline, which can be considered as an environmental concern.
CONCLUSION: The seawater contamination into shallow aquifer have reached up to 1.5 kilometer inland and with seawater proportion is up to 55 percent. Throughout the contamination process, the chemical composition of groundwater is modified not solely due to mixing, but also as a result of ion-exchange mechanisms. The significant rate of seawater contamination necessitates urgent action from all stakeholders, with local government leadership being essential. To effectively address this problem, it is vital to limit the extraction of shallow groundwater by enhancing the capabilities of the government's water piping services and to either slow down or completely halt the advancement of seawater intrusion through the adoption of artificial groundwater recharge strategies.

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38	7	3

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INTRODUCTION

Cirebon City, located in West Java, Indonesia. The city evolved from old settlements built on alluvial deposits. Cirebon is one of the most important cities on the north coast of the island of Java. The rapid expansion of industrial, commercial, and tourism activities in the city have significantly escalated the demand for clean water. Fasa *et al*. (2022) indicate that around 31.6 percent of this water is supplied through water piping services, with the remainder sourced. Excessive abstraction of groundwater has given an extra pressure to groundwater quality especially near the coastal line. Some groundwater especially near the coast categorized as brackish to saline water. In this region, the water table is found at a 2 – 6 meters (m) depth below the surface Moving away from the shoreline, the depth of groundwater ranges from 5 to 10 m, exhibiting a comparatively higher quality. In the southern hilly regions, the most favorable groundwater quality is identified at depths of 20 to 30 m. There has been an increase in the salinization of shallow groundwater in several locations around the coastal area, namely Kejaksan, Pekalipan, and Lemahwungkuk regions. An increase in salinization has been detected in various shallow groundwater wells in the vicinity of the city's coastline. The groundwater salinization in coastal area is caused by factors such as mineral weathering, water-rock interaction (Gassama *et al*., 2011), seawater intrusion (Lu and Werner, 2013) and can be intensified by over-exploitation of groundwater (Mas-Pla *et al.,* 2012). Previous studies showed that Cirebon coastal line is not only facing land subsidence threat (Bramanto *et al*., 2023), but it is also under the threat of shifting into the land due to increasing sea level and abrasion (Pratama *et al*., 2023). These factors may further exacerbate the issue of seawater intrusion (Rositasari *et al*., 2011).

Geology of cirebon, West Java

Fig. 1 shows a geological map of the Cirebon area. Geologically, Cirebon is located on sedimentary alluvial deposits (Qa) facies consisting of gravel, sands, and clay deposits with a thickness of up to 5 m. Meanwhile, the coastal line comprises of coastal sediments (Qac), which consists of marsh sediment,

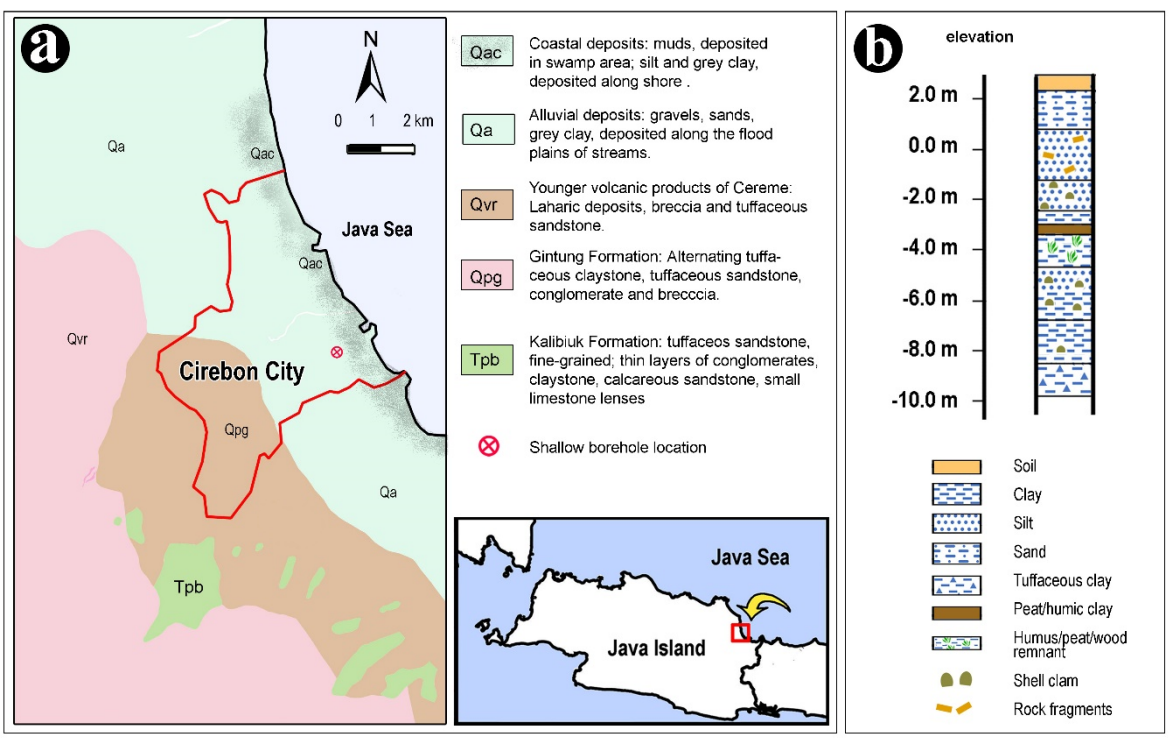


Fig. 1: (a) Geological map of Cirebon region (b) Lithological profile of shallow borehole (Hidayat *et al*., 2009; Silitonga *et al.,* 1996)

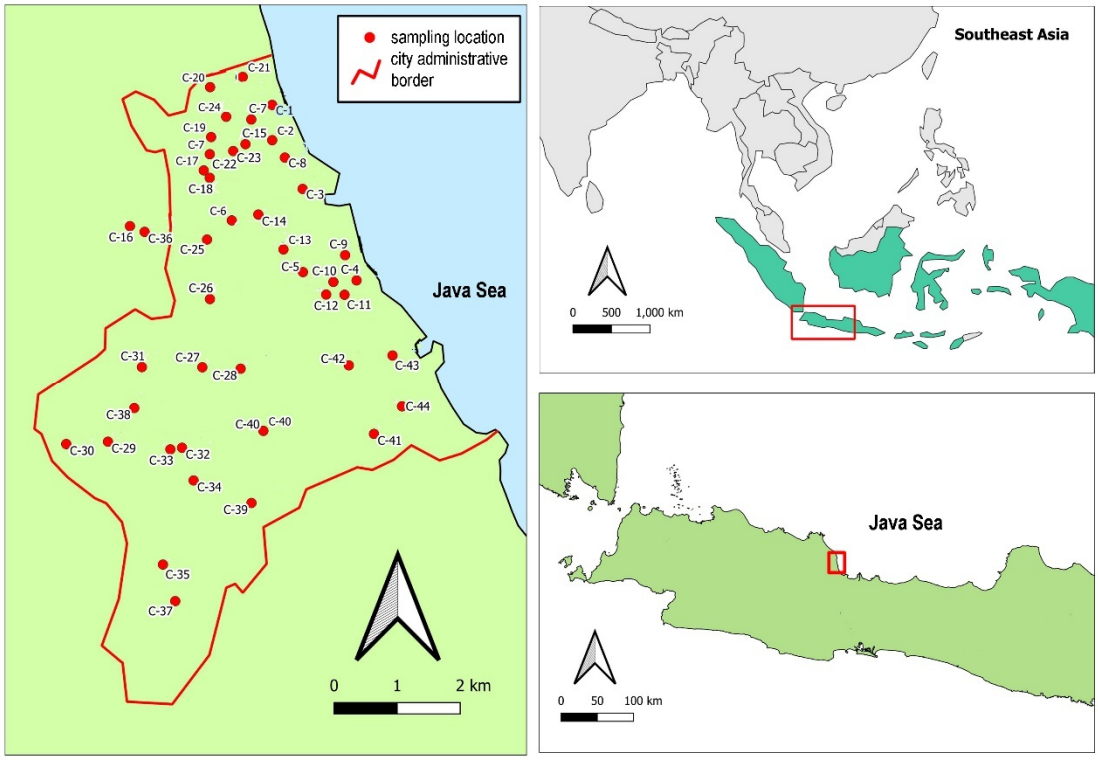


Fig. 2: Geographic location of the study area and sampling location in Cirebon City, West Java, Indonesia (Sampling indicated with red circle marks)

silt, and clay exhibiting a thickness of several meters. In the higher area of Cirebon, Gintung Formation (Qpg) dominates the terrain, consisting of alternating tuffaceous claystone, tuffaceous sandstone, conglomerate, and breccia (Silitonga *et al*., 1996).

According to stratigraphic findings, the alluvial plain is classified into three sedimentation stages, which are determined by fluctuations in sea level: a high sea level phase, a phase of decreasing sea level, and a low sea level. These processes were triggered by changes in environmental conditions and the tectonic activities within the region (Ezquerro *et al*., 2019). While in the study area, sediment succession is divided into three sedimentation intervals which each intervals represents environmental changes due to changes of sea level (Hidayat *et al*, 2009). The groundwater challenges faced by Cirebon City necessitate the implementation of investigations employing isotope and hydrochemical techniques. These methods are essential for collecting data and delineating the properties of shallow groundwater, in addition to assessing the extent of seawater intrusion within the coastal aquifer of Cirebon. This study aimed to qualitatively and quantitatively assess the extent of seawater contamination to shallow groundwater in Cirebon City. The sampling campaign was done in 2022, collecting 44 shallow groundwater samples (Fig. 2) in Cirebon City from the coastline up to about 6 kilometers (km) inland (108.532° – 108.582° East and 6.694° – 6.769° South). Due to the private ownership of the shallow wells by local residents, there exists a lack of lithological documentation and information concerning the depth of the water table.

MATERIALS AND METHODS

There were 44 samples collected during this study. The samples were collected from existing wells located in the vicinity of Cirebon city. The collected samples were then sent to the Center of Research and Technology Radiation Process Laboratory, National Research and Innovation Agency (BRIN) in Jakarta which is about 150 km from the study area.

Water sampling

Groundwater and seawater samples were collected into 20 milliliter (mL) plastic bottles each. It is essential that the bottles are entirely filled with water, devoid of any air bubbles, and securely closed to inhibit evaporation (Wijatna *et al.*, 2019). For the analysis of anions and cations, water samples were collected in individual bottles, each with a capacity of 500 mL. To prevent the precipitation of cation samples and to ensure the stability of bacterial activity during shipping and storage, it is necessary to add several drops of concentrated (68%) pro analysis (pa) nitric acid (HNO3) (Sanchez, *et al.*, 2017; Satrio *et al.*, 2021). To prevent contamination and to minimize evaporation, biological or chemical changes, samples were stored in clean and chemically inert containers (i.e., polyethylene bottles), and cooled below ambient temperatures, respectively (F. Liu *et al.*, 2019).

Water sample analysis

The stable isotope contents of oxygen-18 (^{18}O) and hydrogen-2 (^{2}H) were measured using Liquid Water Isotope Analyzer - Los Gatos Research (LWIA-LGR). The instrument measures the isotopic ratio of oxygen-18 to oxygen-16 ($^{18}O/^{16}O$) and hydrogen-2 to hydrogen-1 ($^{2}H/^{1}H$), with respect to Vienna Standard Mean Oceanic Water (VSMOW) standard to obtain its d value. The isotopic composition of water samples is represented by a delta value (δ) in parts per thousand, known as permil (‰), following the formulation provided in Eq. 1 (Gourcy *et al.*, 2005):

$$\delta = \frac{(R_{sample} - R_{SMOW})}{R_{SMOW}} \times 1000‰ \quad (1)$$

Where, R_{sample} and R_{SMOW} are ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ and ratio of $^{2}H/^{1}H$ or $^{18}O/^{16}O$ in sample and standard reference SMOW. Chemistry analysis was performed using the Metrohm ion chromatography system. For anions analysis, a Metrosep A Supp 5 column was used with carbonate-bicarbonate eluent (Merck, pa). The cation analysis was performed using a Metrosepp C4 column, with dipicolinic acid (Merck, pa) as the eluent. Sample analyses were performed at the Center of Research and Technology Radiation Process Laboratory, National Research and Innovation Agency (BRIN).

Data interpretation

Natural stable isotope such as ^{18}O and ^{2}H were employed to study groundwater characteristics and its origin (Aksever and Davraz, 2018; Sidibé *et al.*, 2019). These isotopes functioned as unique identifiers to differentiate between various water sources, including groundwater, rainwater, seawater, surface water, or any combinations thereof. The analysis of isotopic data and the chemical properties of groundwater was applied to investigate the challenge posed by seawater encroachment. Isotope ^{18}O value exhibits correlations with chloride (Cl), electrical conductivity (EC), and sulfate (SO_4) (Ersoy *et al.*, 2021). In the context of hydrological studies, the isotopes present in water molecules are utilized as effective tracers to ascertain the source and progression of water throughout the soil layers (Tweed *et al.*, 2020). Data on ^{18}O and ^{2}H isotopes, along with water chemistry data, were utilized to obtain information on the salinization process in Cirebon coastal aquifer. Meanwhile, major hydrochemical ions were applied to classify natural water into types and mixtures, such as distinguishing between fresh water and seawater (Vasu *et al.*, 2017). The mass balance equation (Eq. 2) was employed to compute the percentage of seawater that intermingles with groundwater in each sample (Vera *et al.*, 2021):

$$\chi = \frac{\delta^{18}O_{gw} - \delta^{18}O_{sw}}{\delta^{18}O_{rw} - \delta^{18}O_{sw}} \quad (2)$$

Where, $d^{18}O_{gw}$, $d^{18}O_{sw}$, $d^{18}O_{rw}$ are $d^{18}O$ value in groundwater, seawater and rain water samples (‰) respectively, and χ is the fraction or percentage of seawater component. The hydrochemistry of saline water and groundwater in coastal aquifers is closely interconnected, largely due to the processes of ion exchange that occur within these systems (Amiri *et al*, 2016). Other indicators used to study the characteristics of groundwater included graphical correlation such as chloride to bicarbonate ratio (Cl/HCO_3) vs Cl (Hajji *et al.*, 2022), Cl vs EC (Panno *et al.*, 2006), and $d^{18}O$ vs Cl (Geyh and Sofner, 1989).

RESULTS AND DISCUSSION

Stable isotope characteristics

The results of isotope analysis were reported in Table 1, while the correlation between $d^{18}O$ and $d^{2}H$ data was shown in Fig. 3. The graphic served to delineate the different processes that can significantly

Table 1: Stable isotope composition of water samples

No.	Sample code	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
1	C-1	-5.47 ± 0.49	-37 ± 1.47
2	C-2	-6.66 ± 0.40	-45.2 ± 1.2
3	C-3	-6.43 ± 0.28	-41.1 ± 1.4
4	C-4	-6.47 ± 0.41	-41.4 ± 1.3
5	C-5	-3.91 ± 0.68	-28.8 ± 1.8
6	C-6	-6.13 ± 0.24	-40.7 ± 1.0
7	C-7	-6.06 ± 0.44	-40.1 ± 1.3
8	C-8	-5.68 ± 0.75	-38.8 ± 1.7
9	C-9	-6.26 ± 0.37	-41.5 ± 0.8
10	C-10	-7.07 ± 0.45	-50.4 ± 1.3
11	C-11	-6.63 ± 0.39	-40.6 ± 0.8
12	C-12	-7.36 ± 0.44	-44.1 ± 1.1
13	C-13	-7.76 ± 0.37	-45.8 ± 1.3
14	C-14	-8.28 ± 0.32	-52.9 ± 1.8
15	C-15	-7.33 ± 0.40	-46.2 ± 1.1
16	C-16	-8.11 ± 0.33	-51.3 ± 1.3
17	C-17	-7.38 ± 0.30	-50.0 ± 1.5
18	C-18	-7.21 ± 0.37	-51.1 ± 1.1
19	C-19	-7.41 ± 0.43	-46.8 ± 1.2
20	C-20	-7.09 ± 0.38	-51.0 ± 1.1
21	C-21	-7.10 ± 0.61	-48.9 ± 1.3
22	C-22	-6.92 ± 0.38	-47.8 ± 1.1
23	C-23	-7.15 ± 0.51	-51.8 ± 0.9
24	C-24	-7.64 ± 0.14	-45.1 ± 1.7
25	C-25	-6.88 ± 0.56	-50.4 ± 1.1
26	C-26	-6.73 ± 0.38	-51.9 ± 1.5
27	C-27	-7.29 ± 0.28	-46.5 ± 1.1
28	C-28	-8.80 ± 0.11	-55.8 ± 1.0
29	C-29	-8.15 ± 0.15	-49.9 ± 0.9
30	C-30	-8.39 ± 0.56	-50.2 ± 1.1
31	C-31	-7.10 ± 0.59	-43.5 ± 1.6
32	C-32	-7.66 ± 0.35	-48.4 ± 1.1
33	C-33	-7.74 ± 0.52	-43.7 ± 1.5
34	C-34	-5.37 ± 0.50	-43.6 ± 1.2
35	C-35	-7.45 ± 0.21	-47.0 ± 0.2
36	C-36	-6.87 ± 0.56	-42.1 ± 0.9
37	C-37	-7.53 ± 0.49	-47.7 ± 0.7
38	C-38	-7.41 ± 0.08	-52.8 ± 1.4
39	C-39	-6.70 ± 0.40	-40.5 ± 1.3
40	C-40	-6.39 ± 0.28	-50.7 ± 1.2
41	C-41	-5.77 ± 0.46	-45.3 ± 1.2
42	C-42	-7.52 ± 0.20	-42.7 ± 1.7
43	C-43	-8.41 ± 0.08	-52.0 ± 1.4
44	C-44	-7.90 ± 0.61	-48.9 ± 1.3
45	Cirebon seawater 1	-0.73 ± 0.11	-6.8 ± 1.8
46	Cirebon seawater 2	-0.70 ± 0.25	-7.6 ± 2.0
47	Java Seawater	-0.84 ± 0.35	-3.6 ± 1.6

affect the properties of each water sample (Pang *et al*., 2017; Krishan *et al*., 2020).

Upon examination of the sample data points against the meteoric water line, the attributes of groundwater extracted from the Cirebon coastal aquifer can be delineated as follows:

a. Fresh groundwater

Most groundwater samples, consisting of 22 sites or around 50% of total samples in the Cirebon coastal

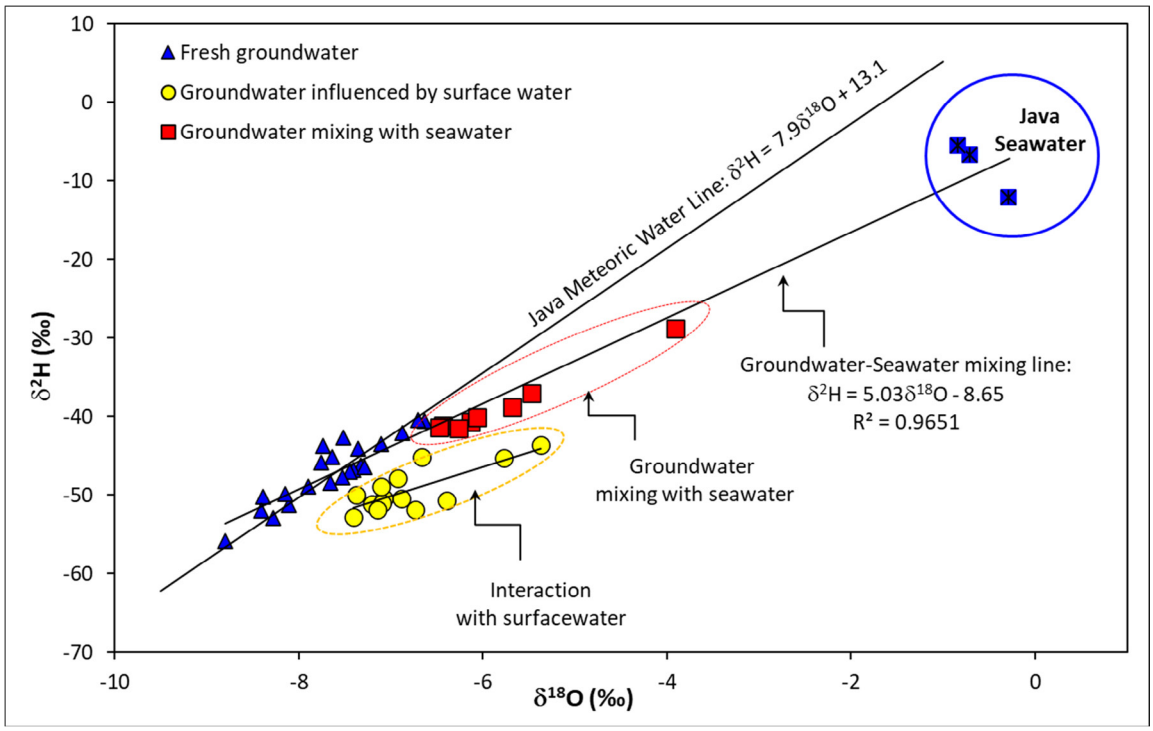


Fig. 3: Plot of δ^2H vs $\delta^{18}O$ of samples in comparison with Java meteoric water line (Sidauruk *et al.*, 2024).

aquifer still retain meteoric water characteristics. The aquifer is underlined more than 1 km from the coastline and is located in the southern part area, which features a hilly landscape.

b. Groundwater – surface water interaction

A total of 14 samples (around 32% of 44 total samples) were plotted similarly to the evaporation line (Horita, 2005). Given that there was no evaporation occurring in the saturated zone, it is plausible that this trend resulted from the interaction between groundwater and surface water, or from the infiltration of water from other sources (Oteng *et al.*, 2014). One of the probable mechanisms of this interaction is recharge by runoff (Prada *et al*, 2016), since the study area is located in relatively flat area in the foot of Mount Ciremai. In addition, some of these wells are located near pond and water channel (e.g. C-20, C-23, C-40 and C-41) that might allowed water infiltrating into aquifer (Deng and Bailey, 2022).

c. Groundwater-seawater mixing

A total of 8 (18%) of the 44 samples passed through the salinization process due to seawater intrusion. These sites were positioned at an approximate distance of 1 km from the coastline. The application of Eq. 1 involved the seawater composition detailed in Table 1 as the seawater end member, with the intersection point between the mixing line and the meteoric line illustrated in Fig. 3 representing the rainwater end member, which is -7.55‰. The result of the mixing fraction calculation was presented in Table 2, which indicated that a mixture of about 17.3% – 54.9% of seawater portion has mixed with shallow groundwater in the Cirebon coastal aquifer.

Hydrochemistry characteristics

The results of anion and cation concentrations in shallow groundwater are illustrated in Table 3. An ionic balance of under 5% was observed, reflecting a commendable level of precision in the hydrochemical analysis. The pH measurement for all samples was found to be in the range of 6.84 – 8.24, with an average value of 7.64. A significant number of samples recorded pH values greater than 7, which may be a result of the substantial presence of dissolved sodium

Table 2: Fraction of seawater in contaminated shallow groundwater

No.	Sample code	Seawater fraction (%)	Distance to coastline (m)
1	C-1	32.0	285
2	C-3	17.9	520
3	C-4	17.3	330
4	C-5	54.9	1000
5	C-6	22.3	800
6	C-7	23,3	670
7	C-8	28.9	410
8	C-9	20.4	290

(Na) in the groundwater. However, these values were still within the pH natural level for groundwater (WHO, 2011). Electrical conductivity (EC) values, which indicates Total Dissolved Solids (TDS), for the sites at the distance of 0 – 1000 m away from the coastline range from 0.41 to 12.35 milisiemens per centimeter (mS/cm), with an average of 1.77 mS/cm. The values gradually decreased to 0.45 – 1.59 mS/cm for the sites at a further distance of 1000 m from the coastline. In lower elevation zones and coastal areas, there was a notable increase in electrical conductivity (EC) values in groundwater, primarily resulting from the pronounced salinization of seawater within the groundwater system.

The hydrochemical composition of fresh groundwater was dominated by HCO_3, which was about 35% and was a characteristic of fresh groundwater. However, at some locations, the concentration of Na was relatively higher than that of calcium (Ca) or magnesium (Mg). Fig, 4 provides a box plot diagram that represents the distribution of each chemical component within the various groups. The fresh groundwater and groundwater-surface water interaction groups were relatively similar in their chemical composition and distribution, with differences in isotope composition differentiate as presented in Fig. 3. Conversely, the samples that included mixed seawater displayed a greater degree of dispersion than the preceding groups, especially regarding the composition of Na and Cl, which indicates varying mixing ratios..

A piper diagram, depicted in Fig. 5, was utilized to visually represent the hydrochemical characteristics of groundwater. The diagram was employed to delineate distinct hydrochemical facies or groundwater origins by mapping the levels of cations and significant anions. This representation highlights the sources of dissolved salts and the processes that shape the characteristics of these natural water bodies (Reyes-Toscano *et al.*, 2020). The Piper diagram in Fig. 5 showed that at the cation corner, 26 samples (59%) were spread in Na dominant type, one sample had calcium (Ca) type (2%), six samples had Mg type (14%) and eleven samples had Na-K type. At the anion corner, HCO_3 type predominated in 36 samples (82%), Cl type predominated in 7 samples (16%) and only one sample (2%) had no dominant type. Piper diagram also classified the shallow groundwater into three sub-groups of calcium-bicarbonate (Ca-HCO_3) type. This groundwater represents a standard characteristic of shallow freshwater systems, where the ionic composition is largely attributed to the dissolution of minerals such as calcite. Out of the 44 groundwater samples taken in the study area, the 3 water types identified included 31 samples (70%) that have Ca-HCO_3 water type, i.e., fresh groundwater, where 18 samples located at more than 1.5 km from the coastline, 6 samples at a 1000 – 1500 m, 6 samples at a 500 – 1000 m, and 1 sample at a 0 – 500 m from the coastline. Secondly, 5 samples (11%) have calcium-sodium-bicarbonate (Ca-Na-HCO_3) water type, namely C13, C17, C24, C31, and C35 with the composition of Na is more than 50%, more dominant than Cl. While some samples (C13, C17, C24) are found within 1500 m of the coastline, the water types represented by these samples do not derive from the mixing of freshwater with seawater. This assertion is evidenced by their low chloride levels and depleted isotopic signatures. The shifting from freshwater Ca-HCO_3 type into Ca-Na-HCO_3 type may indicate Na and Ca dissolution process from minerals such as feldspar, as shown in Eq. 3 and Eq. 4 (Shi *et al.*, 2018):

$$2NaAlSi_3O_8 + 2CO_2 + 3\ H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+ + 2HCO^- \quad (3)$$

Table 3: Chemical composition of water samples in milligram per liter (mg/L)

No.	Code	EC (mS/cm)	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3
1	C-1	3.69	7.29	716.6	177.5	138.6	129.9	1283.6	181.0	642.8
2	C-2	0.41	8.23	15.6	40.4	15.0	22.6	37.7	27.1	180.7
3	C-3	1.04	7.57	92.1	60.4	26.5	31.1	163.7	28.9	205.2
4	C-4	1.64	7.53	262.5	23.0	30.6	26.7	353.7	4.3	405.8
5	C-5	12.35	6.84	4963.0	162.1	80.7	76.0	6980.9	8.8	698.5
6	C-6	0.87	8.24	135.2	4.8	24.5	20.8	162.9	36.1	275.9
7	C-7	0.95	7.58	156.3	69.4	54.4	78.0	300.4	26.9	428.5
8	C-8	0.90	7.71	80.2	13.6	32.0	37.6	172.1	33.8	225.4
9	C-9	2.29	7.68	368.9	45.0	37.6	43.8	505.0	67.0	571.8
10	C-10	0.71	7.55	44.9	27.5	15.4	41.9	49.4	59.5	269.2
11	C-11	0.62	7.90	75.3	23.1	20.5	47.2	15.3	23.7	429.5
12	C-12	0.86	7.54	80.6	28.4	42.1	18.3	95.3	51.8	290.8
13	C-13	0.48	7.55	89.7	11.5	32.6	16.5	85.4	35.1	222.6
14	C-14	0.53	7.68	38.0	32.2	45.3	12.2	28.9	28.3	252.9
15	C-15	0.62	7.65	71.1	11.6	37.6	19.8	54.7	20.9	342.2
16	C-16	0.65	7.77	53.8	30.4	42.2	12.3	29.4	35.4	301.7
17	C-17	0.81	7.70	101.4	36.4	25.9	27.5	74.0	28.9	375.2
18	C-18	0.88	7.49	40.0	19.7	106.0	33.2	92.5	29.4	371.0
19	C-19	0.48	7.71	29.5	32.3	53.9	18.1	36.7	39.8	242.2
20	C-20	0.49	7.48	27.1	17.8	43.4	37.0	69.7	30.4	228.3
21	C-21	0.48	7.78	33.4	2.5	31.4	27.1	52.8	34.0	213.3
22	C-22	0.45	7.85	57.5	16.0	21.8	31.6	67.6	25.5	225.4
23	C-23	0.67	7.48	18.9	32.1	39.5	48.0	29.2	27.5	407.3
24	C-24	0.89	7.60	110.2	49.3	36.2	22.0	87.4	64.7	402.3
25	C-25	0.86	7.26	82.1	40.5	39.8	32.2	43.7	20.6	507.4
26	C-26	0.98	7.64	95.7	37.9	51.6	66.2	106.6	20.4	520.3
27	C-27	0.52	7.63	56.0	20.2	32.9	15.2	27.1	33.4	288.1
28	C-28	0.57	7.24	73.0	16.4	42.4	41.0	97.1	35.7	289.4
29	C-29	0.67	7.67	38.5	39.9	28.4	34.5	34.7	45.3	334.7
30	C-30	0.63	7.74	40.1	12.7	37.3	32.3	40.0	33.9	278.2
31	C-31	0.95	7.63	170.3	20.6	11.6	67.8	115.5	35.5	542.8
32	C-32	0.94	7.68	90.0	13.0	17.1	64.7	55.2	142.5	404.1
33	C-33	0.87	7.80	95.9	8.1	13.2	78.3	46.5	33.5	551.3
34	C-34	1.03	7.63	117.3	10.1	66.3	64.0	90.3	29.9	584.2
35	C-35	1.01	7.95	123.0	20.5	44.9	31.7	53.5	52.6	504.7
36	C-36	0.56	7.70	50.3	17.4	43.9	46.2	71.2	75.1	261.4
37	C-37	0.91	7.58	53.4	24.5	49.5	36.9	66.1	49.2	357.0
38	C-38	0.58	7.45	39.3	19.1	36.0	25.0	36.5	58.3	192.0
39	C-39	0.61	7.70	30.8	27.4	37.7	45.0	34.5	22.0	354.2
40	C-40	0.89	7.56	83.7	35.7	65.8	60.9	97.6	45.4	489.3
41	C-41	0.69	7.65	53.9	40.7	44.0	50.0	63.0	45.5	371.1
42	C-42	1.59	7.78	171.5	37.8	37.6	76.2	113.9	74.1	797.7
43	C-43	0.55	7.62	61.7	23.1	40.4	31.5	59.6	36.6	300.8
44	C-44	0.80	7.73	71.3	14.5	43.2	43.3	66.2	26.4	466.0

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO^- \quad (4)$$

The two samples (5%) have calcium-magnesium-chloride (Ca-Mg-Cl) mixed water type with less than 1 km from the coastline, namely C7 and C8 with more than 50% Cl compared to Na, indicating a salinization process through the mixing between groundwater

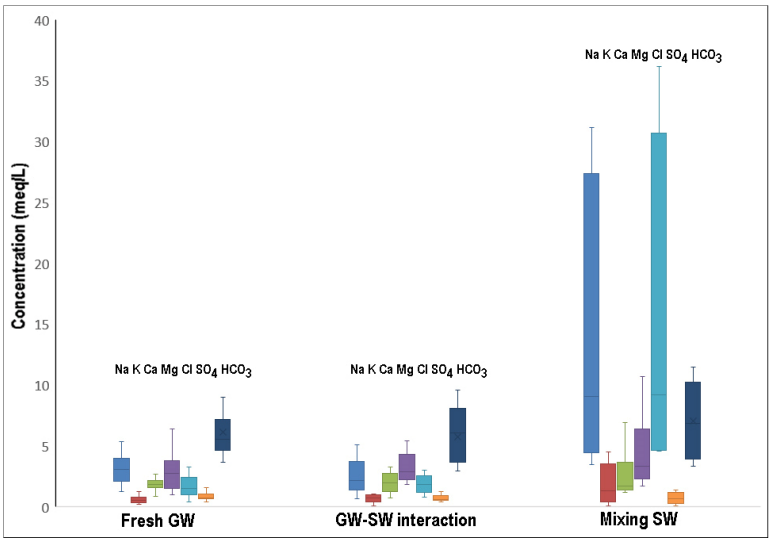


Fig. 4: Boxplot of chemical composition in: fresh groundwater, groundwater – surface water interaction, and groundwater-seawater mixing in Cirebon City

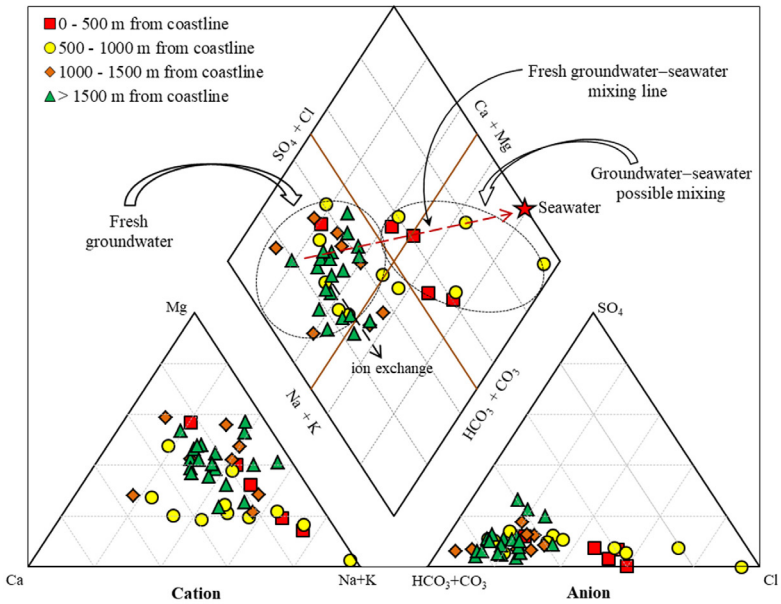


Fig. 5: Piper diagram of shallow groundwater in Cirebon City

and seawater (NaCl), leading to the Ca-Mg-Cl water type. Furthermore, there were 6 samples (14%) of NaCl water type, which indicated a strong seawater influence (Alfarrah and Walraevens, 2018) and were less than 1 km from the coastline.

Fig. 6a shows a molar ratio plot of Cl/HCO_3 vs Cl, indicating that the shallow groundwater in the Cirebon coastal aquifer was classified into three different characteristics. These included Cl/HCO_3 ratio < 0.5 for unaffected or fresh groundwater. The second group was Cl/HCO_3 ratio 0.5 – 6.6 for slightly and moderately affected groundwater, followed by Cl/HCO_3 ratio > 6.6 for strongly affected by seawater intrusion (Al Farrah *et al.*, 2011; Chidambaram *et*

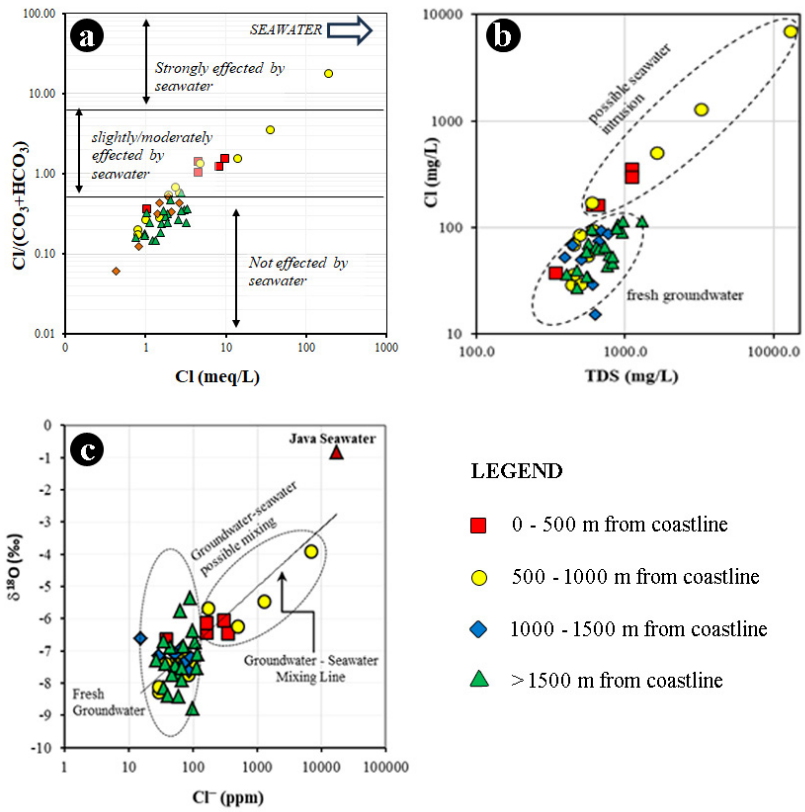


Fig. 6: Plot of (a) Cl/HCO_3 vs Cl, (b) Cl vs TDS, (c) $\delta^{18}O$ vs Cl of shallow groundwater samples in Cirebon City

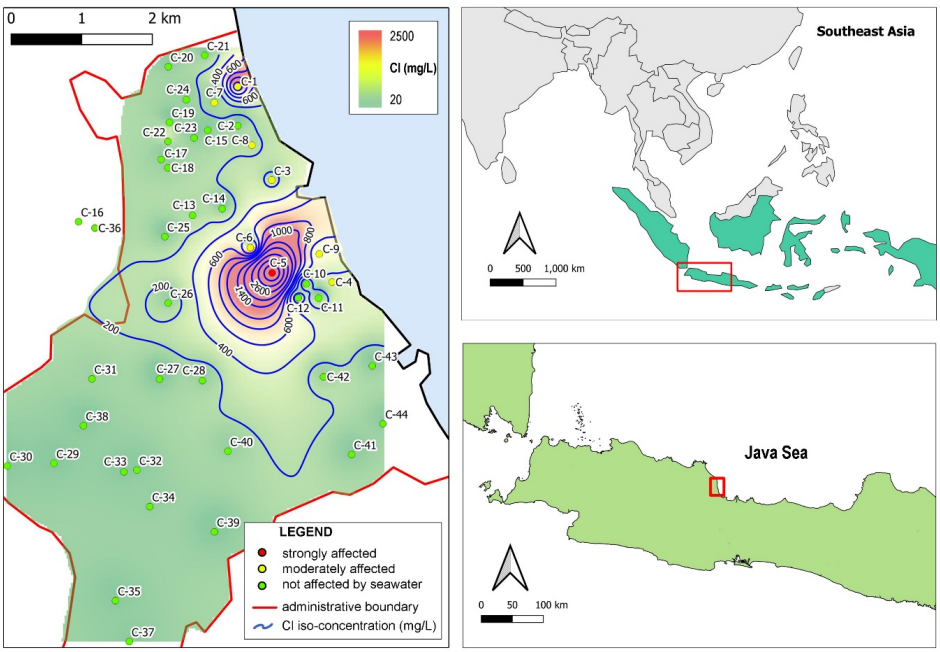


Fig. 7: Chloride distribution in shallow groundwater in Cirebon City

al., 2018). Most shallow groundwater samples were in the first group, while the second group consisted of 7 samples, namely C1, C3, C4, C6, C7, C8, and C9 located approximately 0 – 1000 m distance from the coastline. The third group had one sample, namely, C5 which was located 600 m from the coastline and was the nearest site to the estuary, a highly intruded site by seawater. In terms of hydrogeology, the principal aquifer layer at C5 is formed by alluvial materials, including sand and porous gravel, which have an estimated thickness of around 5 m. Due to its position in the city center, the substantial demand for groundwater has caused a reduction in the water table, potentially leading to greater intrusion of seawater (Jeen *et al.*, 2021). The plotting of Cl vs EC in Fig. 6b and $d^{18}O$ vs Cl in Fig. 6c showed two characteristics of the shallow groundwater, namely fresh groundwater comprising most groundwater samples and groundwater intruded by seawater, consisting of C1, C3, C4, C5, C6, C7, C8 and C9. Consequently, 82% of the shallow groundwater in the study area predominantly exhibited characteristics of fresh groundwater. In contrast, the remaining 8 samples, which constitute 18%, were situated within a distance of 0-1000 meters from the coastline and may have been affected by seawater

As depicted in Fig. 7, the spatial distribution of chloride in shallow groundwater samples reveals that seawater intrusion is notably more intense at the central region of Cirebon City's coastline, particularly in proximity to the C-5 well. In this area, the seawater intrusion spread inland for about 1.5 km from the coastline. Simultaneously, on the northern coastline, the penetration reached an inland distance of about 400 m. The coastline on the southern side of Cirebon has remained largely impervious to seawater intrusion, attributed to its classification as a residential zone. Conversely, the regions close to the coastline and the urban center are allocated for activities related to maritime industries, commerce, and public service functions. Although the World Health Organization (WHO) does not set the health-based limit of Na and Cl concentration in drinking water (WHO, 2011), it is important for local government to address this issue for environmental concern, not only by enforcing stricter regulation for groundwater abstraction, but also from technological intervention such as groundwater artificial recharge (Hussain *et al.*, 2019; Verma *et al.*, 2019).

CONCLUSION

Based on the analysis results of ^{18}O and ^{2}H stable isotopes, the characteristics of the shallow groundwater from the Cirebon coastal aquifer were classified into three groups. Fresh groundwater constituted the largest share, representing 50% of the total groundwater assessed. Meanwhile, 32% demonstrated interactions with surface water, and the remaining 18% was characterized by seawater intrusion. The shallow groundwater that contaminated by seawater was found within 1.5 km distance from the coastline, in contrast to fresh groundwater, which was predominantly found at greater distances inland. The composition of seawater in shallow groundwater in the study area was estimated around 16.1% – 54.2%. The hydrochemistry of fresh and evaporated groundwater was dominated by HCO_3, with a proportion of 35% and 34%, respectively. Simultaneously, the groundwater influenced by seawater was characterized by a high concentration of sodium ions (41.4%) and chloride ions (39.3%), indicating the phenomenon of salinization. The piper diagram classified the shallow groundwater into 3 types, namely (1) Ca-HCO_3 type, accounting for 31 samples of groundwater (70%), most of which were more than 1.5 km from the coastline. (2) The mixed water type (Ca-Na-HCO_3), consisting of 5 samples of groundwater (11%) which were found beyond 500 m from the shoreline. Meanwhile, in a mixed water type (Ca-Mg-Cl), there are 2 samples of groundwater (5%) with Cl ion composition more dominant than other ions, indicating salinization, located within 1.5 km from the coastline. (3) Lastly, Na-Cl water type, which consisted of 6 samples of groundwater (14%). Located within 1.5 kilometers of the coastline, this shallow groundwater was heavily affected by seawater intrusion, resulting in its inadequate quality for consumption. The disparity in the distance from the coastline associated with seawater contamination prompts an inquiry into whether this occurrence is naturally driven, specifically by lithological factors, or if it is a consequence of anthropogenic activities, particularly the over-extraction of groundwater. In this study, this question is still unanswered due to the lack of lithological data and groundwater extraction data. The chemical techniques implemented in this study facilitate a prompt analysis of the chemical profiles of shallow groundwater and serve as indicators of potential seawater contamination. In the other hand, isotope technique can give unseen

information by chemical data, i.e. surface water infiltration into shallow groundwater. This finding is important because surface water is more vulnerable to anthropogenic contamination, thus also elevating the risk of groundwater anthropogenic contamination. The significant infiltration of seawater into shallow aquifers is a pressing concern that requires urgent attention through evidence-based strategies. It is essential to conduct additional chemical analyses, including examinations for heavy and trace metals, in order to determine the possible health effects on the local community. Further investigation is required to address the insufficient hydrogeological data present in the area. It is important for all stake holders led local government to address this issue, i.e., to limit the abstraction shallow groundwater by increasing the capacity of water piping service owned by the government; to slow or to stop the propagation of seawater intrusion by introducing the artificial groundwater recharge.

AUTHOR CONTRIBUTIONS

S. Satrio contributed in the conceptualization, methodology, original draft preparation and initial writing. R. Prasetio performed data visualization, map generation, writing finalization, editing. E.R. Pujiindiyati supervized chemical analysis and data processing. M.F. Ramadhani supervized field works and in-situ measurement. P. Sidauruk contributed in data interpretation and writing finalization.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent (part per hundred)
δ	Delta value
‰	Permil (part per thousand)
^{16}O	Oxygen-16 isotope
^{18}O	Oxygen-18 isotope
^{1}H	Hydrogen-1 isotope
^{2}H	Hydrogen-2 isotope
Ca	Calcium
Ca-Mg-Cl	Calcium-magnesium-chloride type
Ca-Na-HCO_3	Calcium-sodium-bicarbonate type
Cl	Chloride
Cl/HCO_3	Chloride to bicarbonate ratio
EC	Electrical conductivity
HCO_3	Bicarbonate
HNO_3	Nitric acid
i.e.	That is
K	Potassium
km	Kilometer
LWIA-LGR	Liquid water isotope analyzer - Los gatos research
m	meter
m	Meter

meq/L	Milliequivalent per liter
Mg	Magnesium
mL	Mililiter
mm	Milimeter
mS/cm	MiliSiemens per centimeter
Na	Natrium (sodium)
pa	Pro analysis
Qa	Sedimentary alluvial deposits
Qac	Coastal sediments
Qpg	Gintung Formation
SO_4	Sulfate
TDS	Total dissolved solids
VSMOW	Vienna standard mean oceanic water
WHO	World Health Organization
χ	Fraction of seawater

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