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Evaluation of Seawater Intrusion and Impact on Infrastructure in the Coastal Area of North Surabaya

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A B S T R A C T

Several wells of coastal residents at North Surabaya experienced changes in odor, taste, and color indicating seawater intrusion. This phenomenon can cause an increase in groundwater salinity, which impacts clean water quality, public health, and infrastructure resilience. Therefore, it is important to evaluate seawater intrusion in the area. This study aims to evaluate the level of seawater intrusion, determine the distribution pattern of intrusion, and identify high-risk zones for seawater intrusion and the level of infrastructure vulnerability to corrosion. The methods used include analysis of physical and chemical parameters of groundwater, intrusion assessment using the Revelle Index and Electrical Conductivity (EC), and mapping based on Geographic Information System (GIS) to determine the distribution pattern of intrusion. The laboratory's well water sample testing showed an average EC score approaching 1500 µS/cm, and the R-value was far above 1. It meant that well water in North Surabaya has been facing seawater intrusion from medium to high levels. It also predicted the distance of seawater intrusion is about 2,5 km from the coastline and has the most significant risk of infrastructure degradation due to corrosion. Seawater intrusion in Surabaya is caused by geographical proximity to the sea, aquifers' hydrodynamic factors, and high groundwater exploitation. The results of this study contribute to providing a seawater intrusion risk map that can be a reference for the government and policymakers in developing mitigation strategies and groundwater management policies to reduce the impact of seawater intrusion.

1. Introduction

Seawater intrusion is a phenomenon where seawater enters the groundwater system due to excessive groundwater exploitation, climate change, sea level rise, and changes in the hydrodynamics of aquifers [1]. This phenomenon causes an increase in groundwater salinity, which impacts clean water quality, public health, and infrastructure resilience. As Indonesia's second-largest metropolitan city, Surabaya faces tremendous pressure on groundwater

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resources due to population growth, industrial expansion, and rapid urbanization [2]. Excessive exploitation of groundwater is an instant solution to meet the need for clean water, especially in areas with limited supply from the piping system [3]. Based on BPS data, the population of Surabaya is approximately 3 million people. For their clean water needs, around 70% comes from PDAM water, while the rest comes from groundwater through residential wells[4]. Several residents' wells experienced an increase in salinity, indicated by the taste of the water starting from brackish to salty, a change in the color of the water to yellowish, and an abnormal odor. In addition, further impacts were seen in the acceleration of corrosion in the piping system and building infrastructure, indicating the potential for an increase in the content of aggressive ions in groundwater, such as chloride and sulfate. Therefore, an evaluation of the level of seawater intrusion and its impact on groundwater quality and infrastructure is needed. This approach allows the determination of zones with a high risk of seawater intrusion and provides an overview of the level of infrastructure vulnerability due to increased salinity.

Several studies have been conducted to evaluate seawater intrusion in various coastal areas with various approaches. A study in Labuhan Kertasari, West Sumbawa, showed that the increase in Total Dissolved Solids (TDS), Electrical Conductivity (EC), and salinity were the main intrusion indicators, with higher concentrations in wells adjacent to the coastline [5]. In Parangtritis, Yogyakarta, geochemical analysis using the chloride to bicarbonate ratio, the Revelle Index, and the Base Exchange Index (BEX) confirmed the mixing of seawater and groundwater, which significantly increased chloride levels [6]. Research in Kendari City, Southeast Sulawesi, using Geographic Information System (GIS) shows that high intrusion zones depend not only on proximity to the coast, but also on groundwater exploitation and local geological characteristics [7]. A study in Pangandaran, West Java, using the resistivity geoelectric method identified soil layers with low resistivity as an indication of seawater penetration, especially in areas with high permeability [8]. This intrusion seriously impacts infrastructure, with increased chloride levels accelerating corrosion of infrastructure [9]. In addition, sea level rise exacerbates intrusion by increasing the risk of groundwater flooding and drainage systems disrupting the sustainability of coastal urban infrastructure [10].

Although various studies have been conducted on seawater intrusion in coastal areas, to date, there has been no study that comprehensively evaluated the level of seawater intrusion in the coastal areas of Surabaya and its impact on groundwater quality and local infrastructure. In addition, there is no mapping of seawater intrusion risk zones that can provide an overview of the level of vulnerability of the area to increased groundwater salinity. Therefore, this study aims to evaluate the level of seawater intrusion, determine the pattern of intrusion distribution,

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and identify high-risk zones for seawater intrusion and the level of infrastructure vulnerability to corrosion. This study will enrich the literature on seawater intrusion in urban coastal areas by integrating hydrogeochemical analysis and Geographic Information System (GIS)-based mapping. The results of this study will provide information for local governments and stakeholders in formulating seawater intrusion mitigation strategies, as well as facilitating evidence-based policymaking in groundwater management and infrastructure protection in affected coastal areas.

2. Research Method

This research was conducted in the Surabaya area, which is directly adjacent to the coast and is at risk of seawater intrusion. Sampling locations are spread across 10 community well points. The research was conducted by sampling, laboratory testing, and GIS mapping to identify intrusion distribution patterns. The main approaches used include groundwater sampling, laboratory testing to measure physical and chemical groundwater parameters, GIS mapping to determine intrusion distribution patterns, and hydrogeochemical analysis using Piper diagrams to determine the characteristics of the primary ions in groundwater. The results of the seawater intrusion analysis will be linked to the impact on infrastructure.

2.1 Sample

The number of samples used was 10 community wells selected based on the distance from the coastline and the potential for seawater intrusion. The coordinate points of each sampling location are presented in **Table 1**. The sampling procedure used sterile sample bottles to prevent contamination and maintain the accuracy of laboratory analysis results at the peak of intrusion (dry season in July) because the sea level is high and there is no rain.

Table 1. Sample Point Coordinates

Sample Location	**Coordinates**		
	X	**Y**	**Z**
S1	7°12'54.17096"S	112°45'54.14976"E	3.79
S2	7°12'52.85758"S	112°45'7.02353"E	3.79
S3	7°13'18.81113"S	112°45'48.21289"E	4.07
S4	7°13'52.52203"S	112°45'55.23988"E	3.79
S5	7°13'40.683"S	112°45'3.09089"E	3.92
S6	7°14'27.39833"S	112°45'18.53809"E	3.79
S7	7°14'43.36811"S	112°44'47.24513"E	3.79
S8	7°15'9.17816"S	112°44'22.99398"E	3.79
S9	7°15'15.84832"S	112°45'2.42514"E	3.79
S10	7°13'28.5824"S	112°44'32.76229"E	3.79

Source: Author Research Results (2025)

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2.2 Testing

Testing was conducted on the groundwater's physical and chemical parameters to determine early indications of pollution and analyze its relationship to seawater intrusion. Physical parameter testing includes odor, taste, color, temperature, pH, Total Dissolved Solids (TDS), and Electrical Conductivity (EC). Odor and taste were tested through sensory observations. Water color was visually observed by comparing it to water clarity standards. Groundwater temperature was measured directly in the field using a digital thermometer. Water pH was measured using a pH meter, because changes in pH can indicate geochemical processes occurring in the aquifer. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) are measured using a TDS-EC meter, which determines the total amount of dissolved substances in water and its level of electrical conductivity. High EC values are often associated with the entry of ions from seawater, so this parameter is the main indicator in detecting seawater intrusion.

In addition to physical testing, chemical parameter testing was also carried out to understand the ion composition in groundwater and its relationship to seawater intrusion. Cation testing includes Sodium (Na^{+}), Calcium (Ca^{2+}), and Magnesium (Mg^{2+}), which are analyzed using atomic absorption spectrophotometry (AAS) or ion chromatography, which allows accurate measurement of ion concentrations. High Na^{+} levels are often associated with the influence of seawater, while Ca^{2+} and Mg^{2+} can provide information about the mineral dissolution process of aquifer rocks. Anion testing includes Chloride (Cl^{-}), Bicarbonate (HCO_3^{-}), Carbonate (CO_3^{2-}), and Sulfate (SO_4^{2-}), which are analyzed using the argentometric titration method for Cl^{-} and UV-Vis spectrophotometry for SO_4^{2-}, while HCO_3^{-} and CO_3^{2-} are determined using the acidimetric titration method. High Cl^{-} content is one of the main indicators of seawater intrusion, because this ion is the dominant component in seawater. Meanwhile, the ratio between HCO_3^{-} and Cl^{-} is often used in the Revelle Index (R) to determine the level of seawater intrusion in an area.

2.3 Data Analysis

Data analysis was conducted to determine the level of seawater intrusion, hydrogeochemical characteristics of groundwater, intrusion distribution patterns, and their impact on corrosion. Seawater intrusion indicators are determined based on the Revelle Index (R) and Electrical Conductivity (EC) values, where if $R > 1$ and $EC > 1500$ µS/cm, then the increase in salinity is caused by seawater intrusion, while if $R < 1$ and $EC > 1500$ µS/cm, then the increase in salinity is caused by the dissolution of salt minerals in the aquifer [14]. Classification of seawater intrusion levels is carried out based on EC measurements, with

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categories of fresh water (EC < 1500 μS/cm), slightly brackish water (1500 – 5000 μS/cm), brackish water (5000 – 15000 μS/cm), salt water (15000 – 50000 μS/cm), and very salty (EC > 50000 μS/cm). In addition, the level of intrusion is also classified based on the chloride-bicarbonate ratio (R), with categories ranging from fresh water (R < 0.5), low intrusion (R 0.5 – 1.3), moderate intrusion (R 1.3 – 2.8), relatively high intrusion (R 2.8 – 6.6), high intrusion (R 6.6 – 15.5), to sea water (R 15.5 – 20). Piper Diagram analysis is used to further understand groundwater's hydrogeochemical characteristics, which functions to determine the type of groundwater based on ion dominance and identify whether groundwater is closer to the characteristics of seawater or freshwater.

The results of this analysis are then visualized through GIS mapping, by displaying EC and Revelle Index value maps to identify the zones most vulnerable to seawater intrusion and their distribution patterns based on distance from the coastline. The map was created using Surfer 16, which involves entering the study area boundary, the coordinate data, and EC and R values from each sample. The software will automatically generate a contour map of the study area, allowing us to identify areas with the same level of intrusion. This study also analyzes the impact of seawater intrusion on corrosion. The groundwater quality standard for Electrical Conductivity (EC) values ranges from 20-1500 μS/cm³, where EC exceeding this limit can cause varying levels of corrosion, ranging from low (20-500 μS/cm), medium (500-1000 μS/cm), high (1000-1500 μS/cm), to very high (>1500 μS/cm). Likewise, the Revelle value is also an indicator of corrosion potential, where an R value < 0.5 is considered harmless, while an R value between 0.5 – 1.5 can cause mild corrosion, an R value of 1.5 – 3.0 can cause severe corrosion, and an R value > 3.0 can cause very severe corrosion [14].

3. Results and Discussions

3.1 Physical Parameters of Groundwater

Table 2 shows that most of the well water samples in the study area have characteristics that do not fully comply with clean water standards. Two locations, namely S2 and S10, have a detectable odor. In addition, S1 and S3 have a brackish taste, while S10 has a salty taste, indicating an increase in salt levels in groundwater due to seawater intrusion or other sources of pollution. Regarding clarity, three locations, S2, S3, and S10 are yellowish, while the other locations remain clear. This yellowish color can be associated with certain mineral content such as iron (Fe), often found in shallow groundwater or due to environmental pollution such as domestic waste. From temperature measurements, almost all locations have temperatures within the normal range (26-31°C), except for S10, which has the highest

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temperature, namely 34°C. Temperatures higher than these standards can be caused by increased biological activity in the soil or the influence of external pollution, such as domestic or industrial waste around the well.

Table 2. Groundwater Physical Parameters.

Parameters	**Smell**	**Taste**	**Color**	**Temperature**	**pH**	***TDS***	**EC**
Unit	-	-	-	°C	-	ppm	µS/cm
Standard	No Smell	No taste	No color	26-31	6.5 - 8.5	<500	<1000
S1	No smell	Brackish	No color	29.4	7.19	608	1217
S2	Having smell	No taste	yellowish	29	6.93	557	1116
S3	No smell	brackish	yellowish	28.6	7.13	933	1863
S4	No smell	No taste	No color	29.3	6.98	741	1479
S5	No smell	No taste	No color	29.2	6.84	571	1167
S6	No smell	No taste	No color	29.2	7.01	479	1011
S7	No smell	No taste	No color	28.4	6.61	527	1019
S8	No smell	No taste	No color	29.4	6.73	495	994
S9	No smell	No taste	No color	28.7	6.86	478	959
S10	Having smell	salty	Yellowish	34	6.61	502	1014
Max =				34	7.19	933	1863
Min =				27.8	6.61	478	959

Source: Author Research Results (2025).

Regarding acidity, all water samples still have a pH within the normal range (6.5 – 8.5). Total Dissolved Solids (TDS) measurements show that 7 out of 10 locations have TDS above 500 ppm, indicating increased mineral or salt content in groundwater. S3 has the highest TDS value (933 ppm), potentially from seawater intrusion or mineral dissolution in the aquifer. Electrical Conductivity (EC) measurements show that 8 out of 10 locations have EC values above 1000 µS/cm, indicating an increase in salinity in groundwater. S3 has the highest EC value (1863 µS/cm), strongly showing seawater intrusion. S10 also has a fairly high EC (1014 µS/cm) and is accompanied by a salty odor and taste, which may indicate contamination from sources other than seawater intrusion.

Based on the research results, there are initial indications that most wells in the research area have experienced an increase in groundwater salinity potentially caused by seawater intrusion or other sources of pollution. The combination of several parameters indicates that the groundwater at this location is likely contaminated from more than one source, either from seawater intrusion or environmental pollution such as domestic or industrial waste. This source of pollution can come from surface water flow or wells close to polluted drainage channels. The increase in salinity levels in groundwater indicated by changes in the taste of the

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water to brackish and EC and TDS values that are higher than the clean water quality standard limits may indicate seawater intrusion in amounts that are not too high, but are enough to cause changes in the physical characteristics of the water.

The distribution of EC and TDS values in this study shows a typical pattern, where locations closer to the coast tend to have higher EC values, while locations further away have lower values [16]. These results indicate that intrusion has occurred at several points with a distribution that will likely increase over time [20]. In addition, the results of this study also show that the pH value of groundwater is relatively stable, which means that the increase in salinity has not caused a significant change in the acidity of groundwater. However, if seawater intrusion continues, the pH value will likely decrease further due to mixing with seawater which is generally more acidic than fresh groundwater. Overall, the study results provide an initial indication that the study area has experienced an increase in groundwater salinity, which is most likely caused by seawater intrusion. This phenomenon can directly impact the availability of clean water and accelerate corrosion of building infrastructure around the affected area.

3.2 Groundwater Chemical Parameters

The results of the chemical parameter analysis shown in **Table 3** indicate that the content of major ions in each groundwater sample varies significantly.

Table 3. Groundwater Chemical Parameters

Parameter	Na	Ca	Mg	Cl	HCO3	CO3	SO4
Unit	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Maximum Standard				250	1.5		250
S1	101	83.2	3.89	101.34	0	60.5	18.63
S2	68	66.0	10.69	65.48	0	40.5	21.26
S3	6	57.6	22.60	280.91	0	98.5	20.53
S4	147	72.4	9.72	200.94	0	54.5	19.58
S5	80	73.6	17.01	63.48	0	54.5	20.42
S6	56	90.0	9.23	72.23	0	44.5	15.68
S7	47	96.4	2.92	64.23	0	43.5	15.68
S8	57	95.2	13.85	69.98	0	53.0	6.63
S9	56	101.6	22.60	51.98	0	52.5	19.05
S10	66	75.2	22.36	31.74	0	58.5	13.58
Max	147	101.6	22.60	280.91	0	98.5	20.53
Min	6	57.6	2.92	31.74	0	40.5	6.63

Source: Author Research Results (2025).

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Based on the chemical parameter analysis results, several strong indications were found that several locations in the study area had experienced seawater intrusion, especially in S3 which had the highest chloride content (280.91 mg/L). Chloride is the main ion in seawater, so that increasing levels in groundwater are often associated with the entry of seawater into the aquifer system [20]–[23]. In addition, high sodium (Na) levels in S4 (147 mg/L) and S1 (101 mg/L) also indicate the influence of seawater in the groundwater system at the location. Sodium and chloride are often found in high ratios in seawater, so an increase in both in groundwater can be a strong indicator of ongoing seawater intrusion. The fact that bicarbonate (HCO_3) was not detected in all samples indicates that the groundwater in this area has a low buffering capacity. This is also supported by the high levels of carbonate (CO_3) in several locations such as S3 and S4, indicating that the groundwater has changed composition due to mixing with other sources, most likely seawater. This condition is further strengthened by the high magnesium (Mg) levels in S3 and S9 (22.60 mg/L). Magnesium is also an ion commonly found in higher amounts in seawater than in pure groundwater. The increase in magnesium levels in several locations can be a sign that groundwater is starting to experience the influence of seawater entering the aquifer. In contrast, S10 which has the lowest Cl level (31.74 mg/L) and relatively low sodium levels (66 mg/L) indicates that this location is unlikely to experience significant seawater intrusion. However, the water at this location has poor physical parameters (odor, salty taste, and yellowish color), which may indicate pollution from other sources such as domestic or industrial waste.

The distribution pattern of chemical parameters in this study shows that locations closer to the coast have higher chloride, sodium, and magnesium levels, while locations further away have lower levels. This pattern is in accordance with the general characteristics of the seawater intrusion process, where seawater entering the aquifer gradually increases the levels of specific ions in groundwater [24]. The results of this study provide strong evidence that seawater intrusion has occurred at several locations, especially at S3 and S4, with higher chloride, sodium, and magnesium contents compared to other locations.

3.3 Sea Water Intrusion with Revelle's Theory

The analysis results shown in **Table 4** show that seawater intrusion has occurred in most of the study locations, with varying degrees of severity. S3 and S4 have the highest EC and Revelle Index values, indicating that the groundwater at this location has experienced significant mixing with seawater. This finding is in line with the results of physical and chemical analysis. In contrast, locations such as S9 and S10 have low R values (below 1.0), indicating that seawater intrusion at this location is still in the early stages or not too significant.

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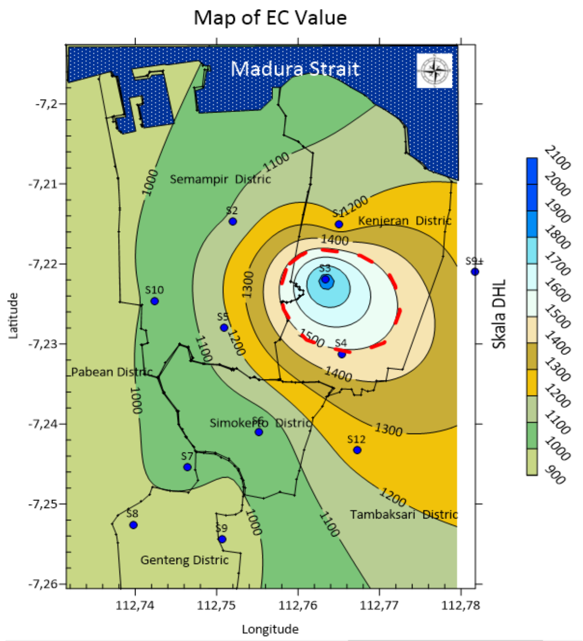
However, S10 has poor physical parameters (odor, salty taste, and yellowish color), which may be caused by seawater intrusion and pollution from other sources.

Table 4. Seawater Intrusion Assessment.

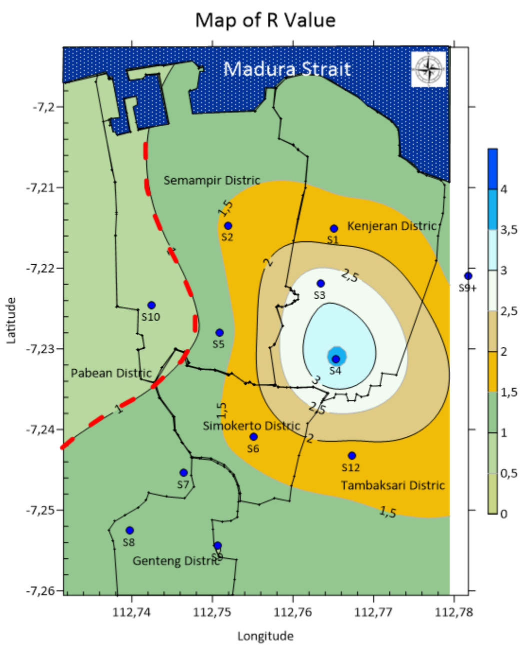
Locations	EC	R	Notes
-	mg/L	-	-
S1	1217	1.68	Medium level of seawater intrusion
S2	1116	1.62	Medium level of seawater intrusion
S3	1863	2.85	Fairly high level of seawater intrusion
S4	1479	3.69	fairly high level of seawater intrusion
S5	1167	1.16	Small level of seawater intrusion
S6	1011	1.62	Medium level of seawater intrusion
S7	1019	1.48	Medium level of seawater intrusion
S8	994	1.32	Medium level of seawater intrusion
S9	959	0.99	Small level of seawater intrusion
S10	1014	0.54	Small level of seawater intrusion

Source: Author Research Results (2025).



Source : Author Research Results (2025).

Figure 1. EC Content Map



Source : Author Research Results (2025).

Figure 2. Ravelle Ratio Map (R)

The distribution pattern of EC and Revelle Index values in **Figures 1** and **2** shows that seawater intrusion is more intense in S3 and S4, with a distribution that is getting weaker towards the land. Areas with high levels of intrusion are generally located closer to the coast, indicating that seawater has entered the aquifer system in the area [25]. This is in accordance with the seawater intrusion process, where seawater seeps into freshwater aquifers due to excessive groundwater exploitation, which causes a decrease in the groundwater level and

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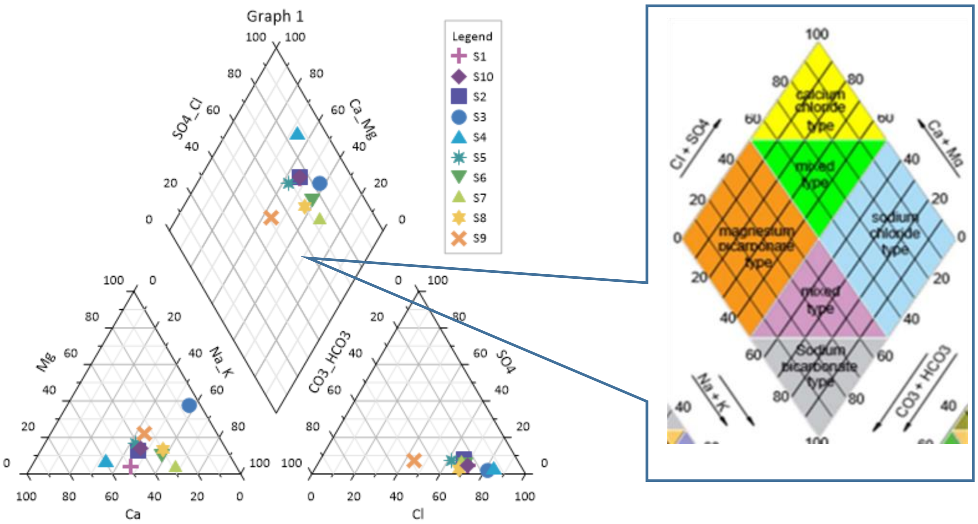
allows seawater to enter deeper into the aquifer system [26], [27]. In addition, the Revelle Index value ranging from 1.16 - 1.68 in most locations indicates that seawater intrusion has spread to a wider area, although at a moderate level. This indicates that seawater intrusion in the study area is not only limited to areas closer to the coastline, but has also begun to reach further areas, along with increasing groundwater exploitation and hydrodynamic changes in the aquifer. Seawater intrusion has reached a fairly worrying stage in several locations, especially S3 and S4, which have the highest salinity indicators based on EC and the Revelle Index. Therefore, mitigation efforts are needed to overcome this problem.

3.4 Hydrochemical Characteristics and Causes of Intrusion



Source: Author Research Results (2025).

Figure 3. Plotting Cation and Anion Results on Piper Trilinear.

The analysis results in **Figure 3** show that the groundwater at locations S3, S4, S6, S7, and S8 are of the Na-Cl type, indicating that seawater intrusion has significantly affected groundwater at these locations. In contrast, samples S1, S2, S5, S9, and S10 are categorized as mixed types, indicating that the groundwater still maintains most of the characteristics of fresh water with moderate to low salinity influences. These differences in ion composition indicate that seawater intrusion does not occur evenly throughout the study area, but is more dominant in areas closer to the coast. S3 and S4 have higher levels of intrusion than other locations, likely due to overpumping or excessive groundwater extraction, which causes a decrease in hydraulic pressure in the aquifer and allows seawater to enter the groundwater system [29]. The results of this analysis are also supported by the high Revelle Index (R) values in S3 and S4, indicating that the main source of salinity in groundwater at this location is seawater intrusion, not just natural mineral dissolution in the aquifer. In addition, the geological and hydrological factors of the research area also play a role in accelerating the seawater intrusion process. This area

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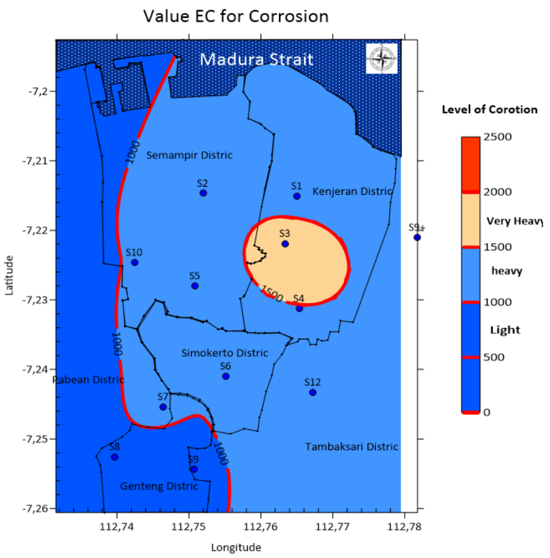
consists of alluvial soil, allowing seawater to seep faster into the groundwater system [30]. The existence of rivers that flow into the sea, such as Kali Tebu and Pogot River, can also be the main route for seawater movement towards land, further accelerating seawater intrusion. Poor drainage systems also accelerate the mixing of seawater with groundwater, especially in areas with low elevations prone to tidal seawater [31].

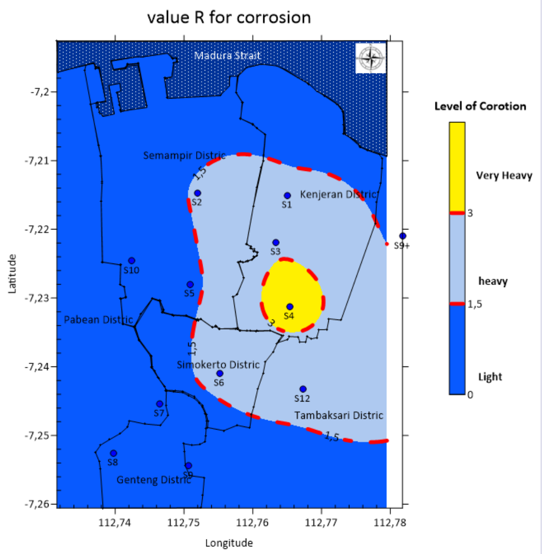
3.5 Impact of Seawater Intrusion on Infrastructure

The mapping results in **Figures 4** and **5** show that the location around S3 has an EC value exceeding 1000 µS/cm and an R value above 1.5, indicating that the groundwater in this area has characteristics that are very corrosive to infrastructure materials. Areas with high EC and R values are generally located within a radius of 2.5 km from the coastline, especially in Semampir, Simokerto, Kenjeran, and Tambaksari, which have the most significant risk of infrastructure degradation due to corrosion. The level of corrosion that occurs has a distribution pattern that is influenced by the intensity of seawater intrusion. Locations closer to the coast have higher EC and R values, indicating that seawater intrusion has caused an increase in salinity in groundwater, which ultimately accelerates the corrosion rate in infrastructure. One of the main factors that accelerates corrosion is the reaction between chloride ions (Cl^-) and iron (Fe) in reinforced concrete, which forms corrosive compounds that can weaken steel reinforcement in the long term [32].



Source : Author Research Results (2025).

Figure 4. EC Value Map for Corrosion



Source : Author Research Results (2025).

Figure 5. R Value Map for Corrosion

The chloride ion (Cl^-) content in groundwater that experiences seawater intrusion can accelerate the oxidation process in steel reinforcement in reinforced concrete, which ultimately causes a decrease in structural capacity and degradation of construction materials. Foundations

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exposed to groundwater with high salt content will experience a reduction in bearing capacity due to corrosion of structural elements, which can trigger cracks in concrete, peeling of protective layers, and reduced mechanical resistance of the foundation. The increase in corrosion rates due to seawater intrusion also impacts the cost of infrastructure maintenance and repair. Buildings and structures that experience degradation due to corrosion require more intensive and repeated maintenance, which has an impact on increasing the maintenance and rehabilitation budget [33].

To reduce the impact of corrosion due to seawater intrusion on infrastructure, corrosion-resistant materials can be selected, structural protection systems can be implemented, and effective environmental and groundwater management can be implemented. In addition, routine maintenance and monitoring are crucial factors in controlling the impact of corrosion. Regular inspections of structural elements susceptible to corrosion, such as building foundations, bridge piers, and road pavements, should be carried out to detect early signs of material degradation. By implementing appropriate mitigation measures, the risk of corrosion on infrastructure due to seawater intrusion can be minimized [34]. Building planning and design that considers the potential for seawater intrusion, combined with appropriate groundwater management strategies and structural protection systems, will increase infrastructure durability, reduce maintenance costs, and ensure the safety and sustainability of structures in the long term.

4. Conclusion

Seawater intrusion has occurred in several coastal areas of Surabaya, especially in areas closer to the coastline. This is indicated by a significant increase in salinity, especially at points with high Electrical Conductivity (EC) and Revelle Index values. The main factors causing intrusion are excessive groundwater exploitation and local geological characteristics allowing seawater to seep into the aquifer. The impact of this intrusion not only reduces the availability of clean water for the community but also increases the risk of corrosion in infrastructure. Predicted the distance of seawater intrusion is about 2,5 km from the seashore, especially in Semampir, Simokerto, Kenjeran, and Tambaksari, which have the most significant risk of infrastructure degradation due to corrosion. This encourages the importance of a more comprehensive mitigation strategy. The results of this study can provide a basis for policy making by the PU Department, Environmental Department, PDAM, and groundwater management agencies in reducing the impact of seawater intrusion.

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