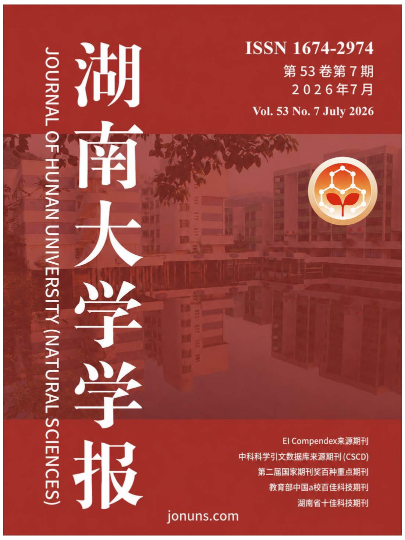

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Seawater Intrusion into Shallow Aquifers in the Coastal Area of Belawan, North Sumatra, Indonesia

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Abstract: Seawater intrusion represents a major threat to groundwater sustainability in rapidly urbanizing coastal areas, particularly where groundwater abstraction and land-use changes are intensifying. This study aimed to evaluate the spatial distribution, intensity, and controlling factors of seawater intrusion into shallow aquifers in the coastal area of Belawan, North Sumatra, Indonesia. Thirty shallow groundwater samples were collected from wells located at approximately 2-km intervals and analyzed for chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and electrical conductivity (EC). Seawater intrusion was evaluated using the chloride-to-bicarbonate ratio (CBR), while groundwater was classified according to chloride concentration and electrical conductivity. Chloride concentrations ranged from 2 to 31,160 mg/L, whereas EC values ranged from 186 to 26,400 μS/cm. Among the 30 sampled wells, 20 were classified as freshwater, three as brackish water, and seven as saline water. Based on the CBR classification, three wells exhibited low seawater intrusion and five showed high seawater intrusion. Spatial analysis revealed that seawater intrusion was predominantly concentrated in densely populated coastal zones characterized by permeable sandy-gravel aquifers and intensive land development. The results provide updated hydrochemical evidence on the extent of seawater intrusion in the Belawan coastal area and may support groundwater monitoring, coastal land-use planning, and sustainable groundwater management.

Keywords: seawater intrusion; coastal aquifer; groundwater salinization; chloride-to-bicarbonate ratio; electrical conductivity; hydrochemistry.

印度尼西亚北苏门答腊勿拉湾沿海地区浅层含水层的海水入侵

摘要： 海水入侵是快速城市化沿海地区地下水可持续利用面临的主要威胁之一，尤其是在地下水开采强度不断增加和土地利用变化加剧的地区。本研究旨在评估印度尼西亚北苏门答腊勿拉湾沿海地区浅层含水层海水入侵的空间分布、入侵强度及其控制因素。研究以约2 km的间距布设采样井，共采集30份浅层地下水样品，并测定氯离子（Cl^-）、碳酸氢根离子（HCO_3^-）、碳酸根离子（CO_3^{2-}）和电导率（EC）。采用氯离子-碳酸氢根比值（CBR）评价海水入侵程度，并依据氯离子浓度和电导率对地下水类型进行分类。氯离子浓度范围为2 - 31,160 mg/L，电导率范围为186 - 26,400 μS/cm。在30口采样井中，20口被划分为淡水，3口为微咸水，7口为咸水。根据CBR分类结果，3口井表现为低程度海水入侵，5口井表现为高程度海水入侵。空间分析表明，海水入侵主要集中于人口密集的沿海区域，这些区域具有渗透性较高的砂砾质含水层，并伴随较高强度的土地开发。研究结果提供了有关勿拉湾沿海地区海水入侵范围的最新水化学证据，可为地下水监测、沿海土地利用规划以及地下水资源的可持续管理提供科学依据。

关键词： 海水入侵；沿海含水层；地下水盐化；氯离子-碳酸氢根比值；电导率；水化学。

1. Introduction

Groundwater is one of the most important freshwater resources supporting domestic, agricultural, industrial, and urban activities worldwide. In many coastal regions, groundwater has become the primary source of freshwater due to increasing population growth, rapid urbanization, and economic development [1]. However, excessive groundwater abstraction has disrupted the natural hydraulic equilibrium between freshwater and seawater, resulting in seawater intrusion into coastal aquifers [2]. This phenomenon has become a major environmental challenge because it deteriorates groundwater quality, reduces freshwater availability, threatens public health, and limits sustainable socio-economic development in coastal areas. Moreover, climate change and sea-level rise further increase the vulnerability of coastal aquifers to salinization, particularly in densely populated coastal cities [3].

Seawater intrusion is a complex hydrogeological process controlled by the interaction between natural conditions and anthropogenic activities [4]. Geological formations, aquifer lithology, hydraulic conductivity, groundwater recharge, and hydraulic gradients determine the natural susceptibility of coastal aquifers to saline water migration [5]. At the same time, intensive groundwater extraction, rapid urban expansion, industrial development, land-use change, and increasing population density accelerate groundwater depletion, allowing seawater to migrate inland [6]. Consequently, understanding the spatial variability of seawater intrusion and identifying its controlling factors are essential for sustainable groundwater resource management.

Various hydrochemical indicators have been widely applied to assess seawater intrusion in coastal aquifers [7]. Chloride concentration (Cl^-) is one of the most reliable indicators because chloride behaves conservatively in groundwater and is abundant in seawater [8]. Electrical conductivity (EC) is also commonly used as a rapid indicator of groundwater salinity because dissolved salts increase water conductivity [9]. In addition, the Chloride–Bicarbonate Ratio (CBR) has been extensively employed to distinguish freshwater from groundwater affected by seawater intrusion by evaluating the relationship between conservative chloride ions and bicarbonate ions produced during freshwater circulation. The integration of these hydrochemical parameters provides a more comprehensive assessment of groundwater salinity and intrusion intensity than the use of a single indicator[10].

Numerous studies have investigated seawater intrusion in coastal aquifers across the world using hydrochemical analyses, geophysical surveys, numerical modeling, and geographic information systems. Previous studies in Indonesia have reported seawater intrusion in several coastal cities, including Jakarta, Semarang, Surabaya, and North Sumatra, where excessive groundwater abstraction and rapid urban development have significantly degraded groundwater quality[11]. Similar findings have also been reported in coastal aquifers of Turkey, India, China, Oman, and other rapidly developing coastal regions [12]. Recent studies further emphasize that integrating hydrochemical indicators with spatial analysis can improve the identification of intrusion patterns and support groundwater management under increasing environmental pressures[13].

Belawan, located in the northern coastal area of Medan City, North Sumatra, is one of Indonesia's most important coastal economic zones. The area borders the Malacca Strait and accommodates major port facilities, industrial estates, fisheries, aquaculture ponds, commercial activities, and densely populated residential settlements. Rapid urbanization and economic development have substantially increased groundwater demand for domestic and industrial purposes. Simultaneously, extensive land-use conversion has reduced natural recharge areas, while coastal geological formations composed predominantly of sand, gravel, and clay facilitate groundwater movement. These conditions increase the susceptibility of shallow aquifers to seawater intrusion and groundwater salinization, posing potential risks to freshwater availability for local communities.

Although seawater intrusion has previously been reported in several coastal areas of North Sumatra, updated information regarding the current spatial distribution and intensity of seawater intrusion in the shallow aquifers of Belawan remains limited. Most previous studies primarily focused on groundwater salinity or individual hydrochemical parameters without integrating chloride concentration, electrical conductivity, and the Chloride–Bicarbonate Ratio with geological conditions, land use, and population density to explain spatial intrusion patterns. Consequently, there remains a need for an updated hydrochemical assessment that provides a more comprehensive understanding of seawater intrusion in this rapidly developing coastal environment.

The novelty of this study lies in the integrated hydrochemical assessment of seawater intrusion in the shallow coastal aquifers of Belawan by combining chloride concentration, electrical conductivity, and the Chloride–Bicarbonate Ratio with geological characteristics, land-use conditions, and population density to provide an updated spatial interpretation of seawater intrusion. This integrated approach improves the understanding of the spatial variability of seawater intrusion and provides scientific evidence to support sustainable groundwater management in coastal urban environments.

Therefore, this study aims to (1) evaluate the spatial distribution of seawater intrusion in the shallow aquifers of Belawan; (2) determine the level of seawater intrusion using the Chloride–Bicarbonate Ratio together with chloride concentration and electrical conductivity; and (3) interpret the influence of geological conditions, land use, and population density on the spatial occurrence of seawater intrusion. The findings are expected to provide updated scientific information for groundwater monitoring, coastal land-use planning, and sustainable groundwater resource management in the Belawan coastal area.

2. Methods

2.1. Study Area

The study was conducted in the coastal area of Belawan, located in the northern part of Medan City, North Sumatra Province, Indonesia. The study area lies adjacent to the Malacca Strait and represents one of the most rapidly developing coastal regions in Indonesia. Belawan is characterized by intensive industrial activities, port operations, fisheries, aquaculture ponds, and densely populated residential areas, resulting in increasing groundwater demand. Geologically, the area is dominated by unconsolidated alluvial deposits consisting of sand, gravel, silt, and clay with moderate to high permeability, making shallow aquifers highly susceptible to seawater intrusion. The relatively flat coastal topography and direct hydraulic connection with the sea further increase the vulnerability of groundwater resources to salinization.

2.2. Groundwater Sampling

Groundwater sampling was conducted in the coastal area of Belawan, North Sumatra, Indonesia, using a stratified purposive sampling approach to obtain representative spatial coverage of the study area. The sampling design was established based on the distance of groundwater wells from the coastline, a widely accepted approach for assessing seawater intrusion in coastal aquifers. Accordingly, the study area was divided into four hydrogeological zones: Zone I (0–500 m) representing areas with the highest potential for seawater intrusion, Zone II (500–1,500 m) representing the transitional zone, Zone III (1,500–3,000 m) representing inland areas with lower intrusion potential, and Zone IV (>3,000 m) representing the freshwater control zone. This zonation facilitated the evaluation of spatial variations in groundwater quality along the coastal–inland gradient.The characteristics of each sampling zone are summarized in Table 1.

Table 1. Hydrogeological zoning and groundwater sampling design

Sampling Zone	Distance from Coast (m)	Hydrogeological Characteristics	Groundwater Condition
Zone I	0–500	Coastal zone directly influenced by seawater	High seawater intrusion potential
Zone II	500–1,500	Transitional coastal zone	Moderate intrusion potential

Sampling Zone	Distance from Coast (m)	Hydrogeological Characteristics	Groundwater Condition
Zone III	1,500–3,000	Inland coastal plain	Low intrusion potential
Zone IV	>3,000	Inland control area	Fresh groundwater zone

A total of 30 groundwater samples were collected from representative wells distributed throughout the four sampling zones. The sampling locations were selected at approximately 2-km intervals to ensure adequate spatial representation of the study area while considering the accessibility and availability of operational wells. Previous hydrogeological studies have indicated that a minimum of 30 sampling points is generally sufficient for spatial groundwater quality assessment and interpolation using Geographic Information System (GIS) techniques, thereby providing reliable spatial representation of seawater intrusion patterns.

The investigation focused exclusively on shallow aquifers by selecting only shallow dug wells and shallow bore wells. The selected wells had depths ranging from 5 to 30 m, representing the unconfined aquifer system that is directly influenced by seawater intrusion. Deep groundwater wells (>50 m) were intentionally excluded because they generally exploit confined aquifers with different hydrogeological characteristics and are less susceptible to direct seawater intrusion processes.

Groundwater samples were collected from wells that were actively used for domestic purposes by local communities. Before sampling, each well was purged by allowing groundwater to flow for several minutes to minimize the influence of stagnant water and obtain representative groundwater samples. The geographic coordinates of every sampling location were recorded using a handheld Global Positioning System (GPS) receiver to support spatial analysis and the preparation of groundwater quality distribution maps.

Water samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles that had been rinsed with distilled water and subsequently with groundwater from the respective sampling site. Immediately after collection, the samples were preserved in an insulated ice box at approximately 4°C and transported to the laboratory for hydrochemical analysis. Sample preservation and transportation followed standard groundwater sampling procedures to minimize physicochemical alterations before laboratory analysis.

2.3. Laboratory Analysis

Groundwater samples were analyzed to determine **chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and electrical conductivity (EC)**. These hydrochemical parameters were selected because they are widely used to evaluate groundwater salinity and seawater intrusion in coastal aquifers.

Chloride concentration was used as the principal indicator of seawater influence because chloride behaves conservatively during groundwater movement. Bicarbonate and carbonate concentrations were analyzed to calculate the Chloride–Bicarbonate Ratio (CBR), whereas electrical conductivity was measured to evaluate the degree of groundwater mineralization resulting from dissolved salts.

All chemical analyses were conducted following standard laboratory procedures. Prior to measurement, analytical instruments were calibrated according to laboratory protocols to ensure measurement accuracy. The concentrations of dissolved ions were expressed in **mg L^{-1}**, whereas electrical conductivity was reported in **µS cm^{-1}**.

2.4. Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) procedures were implemented throughout field sampling and laboratory analysis to ensure data reliability.

Sampling bottles were cleaned before use and rinsed with groundwater from each sampling location prior to sample collection. Samples were immediately transported to the laboratory to minimize physicochemical changes during storage and transportation.

Laboratory instruments were calibrated before each analytical session following standard operating procedures. All analytical results were examined for consistency before being used for subsequent interpretation and mapping.

2.5. Assessment of Seawater Intrusion

The degree of seawater intrusion was evaluated using the Chloride–Bicarbonate Ratio (CBR), which compares chloride concentration with the combined concentration of bicarbonate and carbonate ions in groundwater. This hydrochemical index has been widely applied to distinguish freshwater from groundwater affected by seawater intrusion because chloride is the dominant conservative ion in seawater, whereas bicarbonate generally predominates in freshwater.

The Chloride–Bicarbonate Ratio was calculated using the following equation:

$$\mathbf{CBR = Cl^- / (HCO_3^- + CO_3^{2-})}$$

where:

Cl^- = chloride concentration (mg L^{-1})

HCO_3^- = bicarbonate concentration (mg L^{-1})

CO_3^{2-} = carbonate concentration (mg L^{-1})

The degree of seawater intrusion was interpreted according to the classification proposed by Revelle (1941).

Table 2. Classification of seawater intrusion based on the Chloride–Bicarbonate Ratio (Revelle, 1941).

Chloride–Bicarbonate Ratio	Intrusion Category
< 0.50	No intrusion
0.50–1.30	Low intrusion
1.30–2.80	Moderate intrusion
2.80–6.60	High intrusion
> 6.60	Very high intrusion

2.6 Groundwater Classification

Groundwater quality was classified based on chloride concentration and supported by electrical conductivity measurements. Chloride concentration was used to distinguish freshwater, brackish water, and saltwater because chloride is the most reliable hydrochemical indicator of seawater intrusion. Electrical conductivity was used to support groundwater salinity interpretation because dissolved salts increase the electrical conductivity of groundwater.

Table 3. Groundwater classification based on chloride concentration

Chloride concentration (mg L^{-1})	Groundwater type
<250	Freshwater
250–1000	Brackish water
>1000	Saltwater

2.7 Spatial Analysis

The spatial distribution of groundwater quality and seawater intrusion was analyzed using a Geographic Information System (GIS). Sampling locations were plotted according to their field coordinates, and thematic maps were generated to illustrate the spatial distribution of chloride concentration, groundwater type, electrical conductivity, and seawater intrusion levels across the study area.

The spatial patterns obtained from GIS were interpreted descriptively by considering geological characteristics, land use, settlement density, and proximity to the coastline to identify the main factors controlling seawater intrusion in the Belawan coastal area.

3. Result and Discussion

3.1. Hydrochemical Characteristics of Shallow Groundwater

The hydrochemical analysis revealed considerable spatial variability in groundwater quality across the Belawan coastal area. Chloride concentrations ranged from 2 to 31,160 mg L^{-1}, while electrical conductivity (EC) varied from 186 to 26,400 µS cm^{-1} (Table 1). These wide ranges indicate substantial differences in groundwater salinity among sampling locations, reflecting varying degrees of seawater influence on the shallow aquifer system.

Table 3. Data classification of groundwater and the level of intrusion

No.	Code	Location	EC (µmhos/cm)	Chlorida (mg/l)	Category	The level of intrusion
1	SG1	Medan Labuhan	1354	22.27	Fresh Water	Normal
2	SG2	Medan Labuhan	1783	25.25	Fresh Water	Normal
3	SG3	Medan Labuhan	1682	28.44	Fresh Water	Normal
4	SG4	Medan Labuhan	1724	23.82	Fresh Water	Normal
5	SG5	Medan Labuhan	1587	29.54	Fresh Water	Normal
6	SG6	Medan Belawan	377	18.85	Fresh Water	Normal
7	SG7	Medan Belawan	368	71.47	Fresh Water	Normal
8	SG8	Labuhan Deli	402	31	Fresh Water	Normal
9	SG9	Labuhan Deli	370	32	Fresh Water	Normal
10	SG10	Medan Marelan	3740	1490	Salt Water	Low Intrusion
11	SG11	Medan Labuhan	26400	10200	Salt Water	High Intrusion
12	SG12	Medan Deli	453	40	Fresh Water	Normal
13	SG13	Medan Deli	674	320	Brackish Water	Low Intrusion
14	SG14	Medan Deli	686	1500	Salt Water	Low Intrusion
15	SG15	Medan Labuhan	1252	340	Brackish Water	Normal
16	SG16	Medan Labuhan	883	102	Fresh Water	Normal
17	SG17	Labuhan Deli	753	107	Fresh Water	Normal
18	SG18	Medan Labuhan	770	42	Fresh Water	Normal
19	SG19	Medan Belawan	2367	105.2	Fresh Water	Normal
20	SG20	Medan Labuhan	379	48	Fresh Water	Normal
21	SG21	Medan Labuhan	513	76	Fresh Water	Normal
22	SG22	Medan Labuhan	884	83	Fresh Water	Normal
23	SG23	Medan Belawan	1640	9167	Salt Water	High Intrusion
24	SG24	Medan Belawan	1092	294	Brackish Water	Normal
25	SG25	Medan Labuhan	1947	13719	Salt Water	High Intrusion
26	SG26	Medan Labuhan	1962	31160	Salt Water	High Intrusion
27	SG27	Medan Labuhan	1715	8656	Salt Water	High Intrusion
28	SG28	Medan Labuhan	262	2	Fresh Water	Normal
29	SG29	Medan Sicanang	186	3	Fresh Water	Normal
30	SG30	Medan Belawan	218	3	Fresh Water	Normal

Table 3 shows that 20 of the 30 groundwater samples (66.7%) were classified as freshwater, 3 samples (10.0%) as brackish water, and 7 samples (23.3%) as saltwater. Freshwater samples generally exhibited low chloride concentrations, indicating minimal seawater influence. In contrast, saltwater samples, particularly those collected from wells SG11, SG23, SG25, SG26, and SG27, showed exceptionally high chloride concentrations ranging from 8,656 to 31,160 mg L^{-1}, suggesting significant mixing between seawater and groundwater.

Electrical conductivity exhibited a trend consistent with chloride concentration. Wells with elevated chloride concentrations also showed high EC values, confirming that groundwater salinity was primarily controlled by dissolved marine salts. The highest EC value (26,400 µS cm^{-1}) was recorded at well SG11, corresponding to a chloride concentration of 10,200 mg L^{-1}, whereas the highest chloride concentration (31,160 mg L^{-1}) was observed at well SG26. This strong agreement between chloride concentration and EC demonstrates that both parameters are reliable indicators of seawater intrusion in the Belawan coastal aquifer.

The spatial variability of groundwater salinity suggests that seawater intrusion is not uniformly distributed throughout the study area. Instead, saline groundwater occurs only at specific locations, indicating that local hydrogeological conditions exert greater control on seawater intrusion than simple proximity to the coastline. Similar hydrochemical characteristics have been reported in other coastal aquifers where groundwater salinity is governed by lithological heterogeneity, groundwater abstraction, and aquifer permeability rather than distance from the shoreline alone.

3.2 Assessment of Seawater Intrusion

The degree of seawater intrusion was evaluated using the Chloride–Bicarbonate Ratio (CBR), which is widely recognized as a reliable hydrochemical index for identifying seawater mixing in coastal groundwater systems. The CBR results indicate that groundwater quality varies considerably across the Belawan coastal area. Among the 30 sampling locations, three wells (SG10, SG13, and SG14) were classified as experiencing low seawater intrusion, whereas five wells (SG11, SG23, SG25, SG26, and SG27) exhibited high seawater intrusion. The remaining groundwater samples were categorized as normal, indicating that freshwater conditions remain dominant in most parts of the study area.

The distribution of seawater intrusion generally corresponds with the observed groundwater salinity. Wells classified as experiencing high intrusion also exhibited elevated chloride concentrations and electrical conductivity values, confirming that seawater mixing is the principal source of groundwater salinization [14]. These findings demonstrate that the combined use of chloride concentration, electrical conductivity, and the Chloride–Bicarbonate Ratio provides a robust approach for evaluating seawater intrusion in shallow coastal aquifers.

The spatial distribution of seawater intrusion is presented in Figure 1. High intrusion zones are concentrated in several locations within Medan Labuhan and Medan Belawan, whereas freshwater conditions predominantly characterize inland areas. This pattern suggests that seawater intrusion is spatially localized rather than occurring uniformly throughout the coastal plain.

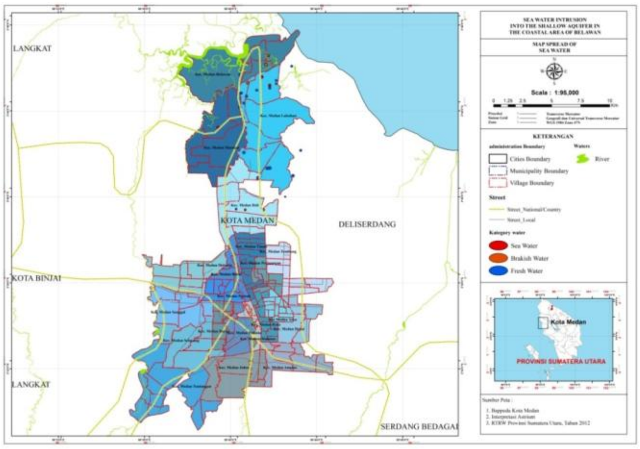

Figure.1 Map the spread of Sea Water

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The spatial distribution of seawater intrusion is presented in Figure 2. High intrusion zones are concentrated in several locations within Medan Labuhan and Medan Belawan, whereas inland areas are predominantly characterized by freshwater conditions. This pattern suggests that seawater intrusion is spatially localized rather than occurring uniformly throughout the coastal plain.

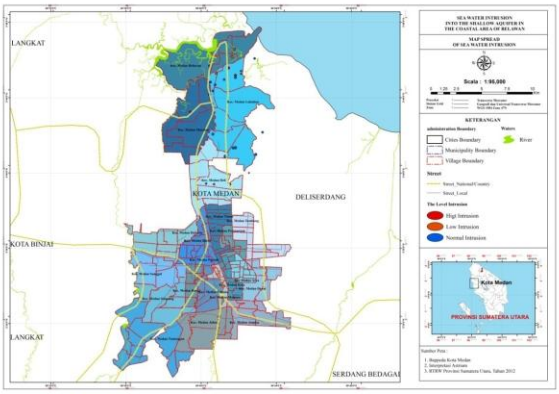

Figure 2. Map of the spread of seawater intrusion

3.4. Spatial Distribution and Controlling Factors of Seawater Intrusion

The spatial distribution map (Figure 2) demonstrates that seawater intrusion is concentrated in specific sectors of the Belawan coastal area rather than following a simple coastal-to-inland gradient. Several groundwater wells located close to the shoreline remained unaffected by seawater intrusion, whereas some wells situated farther inland exhibited relatively high salinity. This finding indicates that distance from the coastline alone is insufficient to explain the occurrence of seawater intrusion in the study area.

The occurrence of seawater intrusion is primarily controlled by local hydrogeological conditions. The shallow aquifer consists predominantly of unconsolidated gravel, sand, and clay deposits with moderate to high permeability, facilitating the lateral movement of saline water into the aquifer system [15]. Highly permeable sandy and gravelly sediments allow rapid groundwater flow and enhance seawater migration, particularly when freshwater hydraulic pressure decreases.

Land-use characteristics further contribute to groundwater salinization. The study area is dominated by residential settlements, industrial facilities, fishponds, and commercial activities, all of which require substantial groundwater abstraction. Continuous pumping reduces groundwater levels, creating a hydraulic gradient that promotes landward migration of seawater. Furthermore, the extensive development of aquaculture ponds along the coastline may enhance seawater infiltration into shallow groundwater, thereby increasing groundwater salinity.

Population density also influences groundwater conditions through increasing domestic water demand. Areas with dense settlements experience greater groundwater extraction, which may accelerate seawater intrusion when groundwater recharge is insufficient to compensate for abstraction [16]. Consequently, seawater intrusion in Belawan results from the combined effects of aquifer characteristics, groundwater exploitation, and coastal land use rather than from shoreline distance alone.

3.5. Implications for Groundwater Management

The present findings demonstrate that although freshwater remains the dominant groundwater type in the Belawan coastal area, localized seawater intrusion has already affected several shallow groundwater wells. This condition represents a potential threat to groundwater sustainability because increasing groundwater abstraction associated with urban expansion and population growth may further accelerate seawater intrusion in the future.

These findings emphasize the importance of implementing integrated groundwater management strategies in the Belawan coastal area. Such strategies should include groundwater abstraction control, protection of groundwater recharge areas, regular hydrochemical monitoring, and sustainable coastal land-use planning. Continuous monitoring using chloride concentration, electrical conductivity, and the Chloride–Bicarbonate Ratio can provide an effective early-warning system for detecting future changes in groundwater quality

4. Conclusion

This study demonstrates that groundwater quality in the shallow coastal aquifer of Belawan exhibits considerable spatial variability as a consequence of seawater intrusion. Hydrochemical analysis showed that chloride concentrations ranged from 2 to 31,160 mg L^{-1}, while electrical conductivity varied between 186 and 26,400 µS cm^{-1}, indicating groundwater conditions ranging from freshwater to saltwater. Of the 30 groundwater samples analyzed, 20 samples (66.7%) were classified as freshwater, three samples (10.0%) as brackish water, and seven samples (23.3%) as saltwater, confirming that seawater intrusion has affected several parts of the study area.

The Chloride–Bicarbonate Ratio (CBR) successfully identified the degree of seawater intrusion, revealing low intrusion at three sampling locations and high intrusion at five locations. The spatial distribution of intrusion indicates that seawater intrusion is localized rather than uniformly distributed throughout the coastal area. The results further demonstrate that distance from the coastline alone is not the primary controlling factor. Instead, seawater intrusion is strongly influenced by the hydrogeological characteristics of the shallow aquifer, particularly the moderate-to-high permeability of alluvial deposits, together with intensive groundwater abstraction, residential development, aquaculture activities, and increasing population density.

The integration of chloride concentration, electrical conductivity, and the Chloride–Bicarbonate Ratio provides a practical and reliable hydrochemical approach for identifying and mapping seawater intrusion in shallow coastal aquifers. These findings provide valuable scientific information for groundwater management in Belawan and other coastal areas with similar hydrogeological settings. Sustainable groundwater management should therefore prioritize the regulation of groundwater abstraction, protection of recharge areas, and periodic groundwater quality monitoring to reduce the future risk of seawater intrusion.

Declarations

Author Contributions

D.P. conceptualized the study, designed the methodology, conducted field investigations and laboratory analyses, curated and analyzed the data, prepared the original draft, and managed the project. J.T. supervised the research, contributed to the study design and methodology, validated the results, provided critical revisions, and reviewed the manuscript. A.R. contributed to field investigations, data curation, formal analysis, validation, and manuscript review. E.S.M.N. contributed to field investigations, data curation, visualization, and critical review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available because they form part of an ongoing research project and contain supporting research materials.

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Conflicts of Interest

The authors declare that there is no conflict of interest 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 redundancies, have been completely observed by the authors.

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