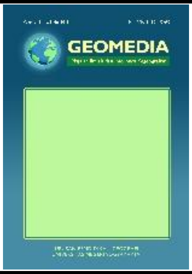

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Geostatistical Mapping of Groundwater Salinity and Seawater Intrusion in Coastal Aquifers of Jember Regency Using Physicochemical Parameters and Seawater Fraction

Muhammad Asyroful Mujib [a, 1*], Sri Astutik [a, 2], Bejo Apriyanto [a, 3], Ikhlas Nur Muhammad [b, 4], Audina Anugra Fitra [a, 5], Tri Rafika Diyah Indartin [c, 6]

[a] Department of Geography Education, University of Jember, East Java, Indonesia
[b] Disaster Management Study Program, Faculty of National Security, The Republic of Indonesian Defense University, Indonesia
[c] Department of Language, Communication, and Tourism, Politeknik Negeri Jember, East Java, Indonesia
[1] mujib@unej.ac.id*; [2] tika.fkip@unej.ac.id; [3] apriyanto.bejo@unej.ac.id; [4] ikhlasnurmuhammad@gmail.com; [5]anugraaudina@gmail.com; [6] trirafika_dyah@polije.ac.id
*korespondensi penulis

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A B S T R A K

Intrusi air laut adalah faktor utama yang memengaruhi kualitas air tanah di wilayah pesisir, menimbulkan tantangan signifikan bagi pengelolaan sumber daya air yang berkelanjutan. Studi ini memetakan salinitas air tanah di wilayah pesisir selatan Kabupaten Jember dengan meneliti pengaruh kenaikan muka air laut terhadap kimia air tanah. Parameter fisikokimia utama, termasuk Konduktivitas Listrik (EC), Total Padatan Terlarut (TDS), dan fraksi air laut (f_{sea}), yang ditentukan menggunakan konsentrasi klorida (Cl-), diukur. Penelitian lapangan mencakup 211 lokasi sumur di sepuluh desa, dengan analisis antarmuka air laut-air tawar menggunakan prinsip *Ghyben-Herzberg*. Pemetaan geostatistik menggunakan *Ordinary Kriging* menunjukkan bahwa 83% sampel air tanah diklasifikasikan sebagai air tawar, 16% sebagai air agak asin, dan 1% sebagai air agak asin. Fraksi air laut yang lebih tinggi terdeteksi di sekitar Pantai Payangan dan Watu Ulo, dengan nilai f_{sea} hingga 23%, menunjukkan pencampuran air laut yang signifikan yang dipengaruhi oleh fluktuasi pasang surut periodik. Analisis komparatif dengan akuifer pesisir global lainnya menyoroti respons hidrodinamik unik di wilayah ini akibat efek pasang surut musiman. Studi ini menekankan perlunya pengelolaan air tanah yang terarah, termasuk pengisian buatan, pengaturan pemompaan, dan penggunaan lahan berkelanjutan untuk mengurangi intrusi air laut dan menjaga kualitas air.

Keywords:
Seawater intrusion
Groundwater salinity
Physicochemical
Seawater fraction
Geostatistical analysis

A B S T R A C T

Seawater intrusion is a major factor affecting groundwater quality in coastal areas, posing significant challenges for sustainable water resource management. This study maps groundwater salinity in the southern coastal region of Jember Regency, examining the influence of sea level rise on groundwater chemistry. Key physicochemical parameters, including electrical conductivity (EC), total dissolved solids (TDS), and the seawater fraction (f_{sea}), which was determined using chloride (Cl-) concentrations, were measured. Fieldwork included 211 well sites across ten villages, with the sea-freshwater interface analyzed through the Ghyben-Herzberg principle. Geostatistical mapping using Ordinary Kriging revealed that 83% of groundwater samples were classified as fresh, 16% as slightly saline, and 1% as moderately saline. Higher seawater fractions were detected near Payangan and Watu Ulo beaches, with f_{sea} values reaching up to 23%, indicating substantial seawater mixing influenced by periodic tidal fluctuations. A comparative analysis of this region with other global coastal aquifers highlights its unique hydrodynamic responses driven by seasonal tidal effects. The study emphasizes the need for targeted groundwater management, including artificial recharge, pumping regulation, and sustainable land use, to mitigate seawater intrusion and preserve water quality.

Introduction

Coastal seawater intrusion is a global groundwater issue that occurs in coastal aquifers worldwide (Arslan, 2014; Ouhamdouch et al., 2020; Parizi et al., 2019). Seawater intrusion involves the lateral movement of seawater, both temporarily and permanently, into freshwater aquifers. This process is triggered by declining groundwater levels or rising sea levels, which increase hydrostatic pressure and reduce the density of freshwater (Hussain et al., 2019; Ouhamdouch et al., 2020). Factors contributing to seawater intrusion can be natural, such as the trapping of ancient water, coastal retreat, surface-subsurface interactions, tidal effects, or climate change (Werner et al., 2013), and anthropogenic factors, including excessive groundwater pumping, intensive agricultural activities, and urbanization in coastal areas (Abu Al Naeem et al., 2019; Hussain et al., 2019; Zamroni et al., 2021).

Monitoring groundwater levels and quality in coastal areas is crucial, as it helps assess the extent, rate, and likelihood of seawater intrusion (Jasechko et al., 2020). Several studies have measured groundwater levels to identify seawater intrusion in India (Sathish & Elango, 2016; Seenipandi et al., 2019; Vetrimurugan & Elango, 2015), the coastal United States (Jasechko et al., 2020), and the southern coast of Yogyakarta, Indonesia (Wilopo et al., 2021). Seenipandi et al. (2019) and Wilopo et al. (2021) identified the position of the freshwater-seawater interface using the Ghyben-Hezberg principle, which allows for the determination of landward hydraulic gradients, as referred to by Jasechko et al. (2020). These landward hydraulic gradients indicate aquifers vulnerable to seawater intrusion, especially where hydraulic connectivity exists between the aquifer and the sea. The hydraulic gradient influences groundwater flow and the depth at which freshwater transitions to brackish water (Jasechko et al., 2020; Koussis et al., 2015). Simply put, Manivannan & Elango (2019) state that if the groundwater level is below the average sea level and there is connectivity with the sea, the coastal aquifer will be fully impacted by seawater intrusion. However, Jasechko et al. (2020) clarify that even if the coastal groundwater level is above sea level, intrusion can still occur because the higher density of seawater can cause it to move inland.

The interface between freshwater and seawater is typically considered the boundary between these two immiscible fluids, resulting from their different densities, viscosities, and flow domains (Bear & Cheng, 2010). However, in reality, this interface is a transitional zone with mixing, dispersion, and diffusion between the two fluids, so the thickness of this transitional zone depends on the hydrodynamic characteristics of the groundwater aquifer (Custodio, 1997). Therefore, measuring the water table needs to be supported by other approaches, such as hydrogeochemistry and geophysics, to better understand the transitional zone between groundwater and seawater, which can trigger seawater intrusion (Manivannan & Elango, 2019).

The hydrogeochemical approach has been widely applied by researchers and combined with several other methods. Common chemical parameters that can be used as indicators of groundwater salinity conditions are Total Dissolved Solids (TDS) and Electrical Conductivity (EC) (Singhal & Gupta, 2010; Tomaszkiewicz et al., 2014). These two parameters serve as rapid screening tests for the initial mapping of seawater intrusion. On the other hand, chloride is an easily traceable element due to its conservative anion nature (Appelo & Postma, 2005) and is, therefore, widely used to measure the seawater fraction between groundwater and seawater (Behera et al., 2019; Hasan et al., 2023; Kumar et al., 2020; Ouhamdouch et al., 2020; Shin et al., 2020; Tomaszkiewicz et al., 2014). In the process of seawater, the addition of 1% seawater to freshwater aquifers, or the equivalent of 250 mg/l chloride, can reduce the volume of freshwater in the aquifer and contaminate production wells, making them unsuitable for consumption (World Health Orgnization (WHO), 2019). Furthermore, chloride is also a key parameter in several ion ratios for seawater salinity analysis, such as Na^+/Cl^-, Cl^-/HCO_3^-, Ca^{2+}/Cl^-, SO_4^{2-}/Cl^-, and Br^-/Cl^- (Kazakis et al., 2016; Kura et al., 2014; Shin et al., 2020; Wang et al., 2020; Zahroh et al., 2024).

The southern coast of Jember Regency is an area affected by extreme tidal waves annually, with a risk score of 13.54, classified as high risk (BNPB, 2023). During extreme conditions, the wave height of the Indian Ocean along the southern coast of Jember ranges from 1.0 to 3.5 meters, causing coastal flooding (rob) with water levels reaching 0.5 to 1 meter on land (BPBD Jawa Timur, 2024). These tidal surges significantly impact groundwater quality in coastal areas (Guo et al., 2023; Kim et al., 2005).

The interaction between groundwater and tidal forces generates complex hydrological responses that influence both the quantity and quality of groundwater resources. Tidal fluctuations induce periodic changes in groundwater levels, contributing to increased salinity due to saltwater intrusion (Dong et al., 2014; Guo et al., 2023; Zhang et al., 2020). This study focuses on the southern coast of Jember Regency due to its unique conditions where annual tidal events influence seawater intrusion patterns. Moreover, there is a need for comprehensive assessments that integrate various physicochemical parameters and seawater fractions to provide a more detailed understanding of the mechanisms of seawater intrusion in response to specific local hydrodynamic conditions, as observed along this coastal region.

Interpolation methods are applied to observe the spatial distribution of data originating from point sources like groundwater and soil. In this study, physicochemical and seawater fraction mapping are performed using Ordinary Kriging, a method widely recommended for its lowest error value (Arslan, 2014; Kazakis et al., 2016; Kura et al., 2014). Due to limited data at the research site, physicochemical quality and chloride are particularly suitable for mapping seawater intrusion. Therefore, the objective of this study is to map the salinity level of groundwater in coastal areas using physicochemical parameters such as Electrical Conductivity (EC) and Total Dissolved Solids (TDS), as well as the fraction of seawater (f_{sea}) based on chloride.

Materials and Methods

Study area

The research location is in the southern coastal area of Jember Regency, which includes 6 districts and 10 villages, namely: (1) Kencong District (Paseban Village); (2) Gumukmas District (Kepanjen Village and Mayangan Village); (3) Puger District (Mojomulyo Village, Mojosari Village, and Puger Kulon Village); (4) Wuluhan District (Lojejer Village); (5) Ambulu District (Sabrang Village and Sumberejo Village); and (6) Tempurejo District (Curahnongko Village). These ten villages are directly adjacent to the Indian Ocean to the south. The western part of the research area is dominated by flat terrain with coastal deposits and alluvium, while the eastern part consists of hilly topography formed by sedimentary rocks and volcanic formations.

Geologically, the research location is divided into three formations: alluvium and coastal deposits, sedimentary rock, and volcanic rock. The alluvium formation consists of clay, mud, sand, gravel, shell fragments, and boulders, while the coastal deposits are composed of loose sand containing magnetite (Suwarti & Suharsono, 1992). This formation is scattered along the coast from Kencong District to Puger District, and includes Ambulu and Tempurejo Districts. The sedimentary rock formation in the research location, according to Sapei et al. (1992), includes the Puger Formation, which consists of crystalline limestone and calcarenite, and the Sukamade Formation, which consists of claystone interbedded with shale and sandstone. These formations are located in Wuluhan, Ambulu, and

Tempurejo Districts. The Puger Karst in the research area has a less advanced stage of karst development compared to the Gunungsewu karst area (Adji et al., 2019; Mujib et al., 2024). The volcanic rock formation is the Merubetiri Formation, which consists of interbedded volcanic breccia, lava, and pyroclastic rocks, and is located in Tempurejo District, extending slightly along the coral coast of Wuluhan District. The location and geological conditions of the research area can be seen in Figure 1.

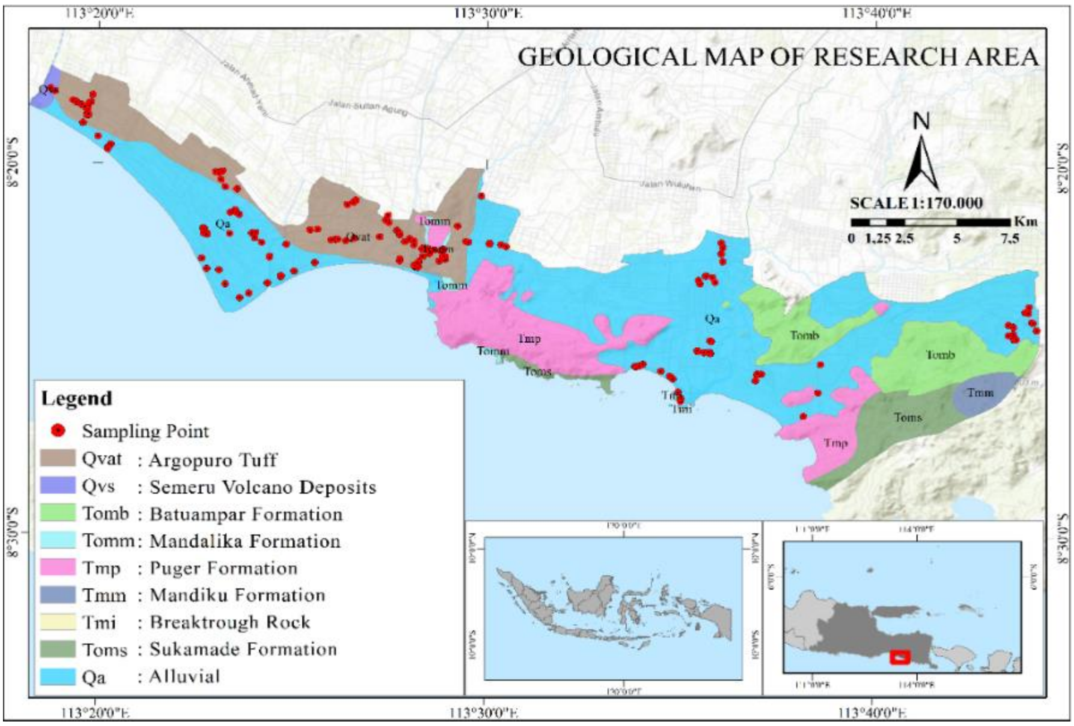

Fig 1. Research location and sample points

Water sampling and analysis

Groundwater samples were obtained from 211 wells used to meet domestic, industrial, livestock, and agricultural needs at the research site (Figure 1). The wells consisted of 202 dug wells used for domestic purposes and 9 bore wells used for irrigating agricultural land. All samples were collected during the dry season (June-August). Groundwater levels were measured from the 211 dug wells at the research site to create the piezometric map. A 50-meter probe was used to measure the depth of the groundwater table. The field elevation measurements using the Global Positioning System (GPS) were also validated using Google Earth and GPS Visualizer, ensuring that the coordinates matched the actual field elevation (https://www.gpsvisualizer.com/). Based on the piezometric map data, the position of the sea-freshwater interface can be predicted using the Ghyben-Herzberg formula, which can only be applied to unconfined aquifers (Formula 1).

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f \quad (1)$$

Where *hf* is the groundwater level above sea level, *hs* is the depth of the sea-freshwater interface below sea level, ρf is the density of freshwater (assuming ρf = 1.00 g cm^{-3}), and ρs is the density of seawater (assuming a value of 1.025 g cm^{-3}). Furthermore, *hs* will be 40 times *hf*. This indicates that, regardless of the distance from the sea, the depth of the sea-freshwater interface below the sea surface is 40 times the height of the water surface above sea level (Singhal & Gupta, 2010).

Temperature, pH, EC, and TDS measurements were conducted in the field using the HI 9813-5 Portable Hanna Instrument. The sample was pumped for 5 minutes before collecting the water in polythene bottles. Each bottle was washed with distilled water before being used for sample collection. Physicochemical data measurements, including temperature, pH, EC, and TDS, were conducted on all research samples (211 wells), while chloride parameter measurements were conducted on 11 selected samples based on EC and TDS values, representing freshwater, slightly saline groundwater, and moderately saline groundwater. Chloride measurements in the field were conducted using the Chloride Test Kit HI 3815. Chloride is a conservative anion that can indicate the mixing process between seawater and freshwater, as shown by high chloride concentrations in the aquifer. High chloride levels in the aquifer can indicate seawater intrusion. Based on the classification of EC, TDS, and chloride in Tomaszkiewicz et al. (2014) and Wang et al. (2020), groundwater is divided into 5 classes, ranging from fresh groundwater (0-500 µS/cm) to slightly saline and seawater. The class divisions are shown in Table 1.

Table 1. Classification of water based on total dissolved solids, electrical conductivity, and chloride

Class	**TDS (ppm)**	**EC (µS/cm)**	**Cl (meq/l)**
Fresh groundwater	0-500	<700	<2.8
Slightly saline groundwater	500-1500	700-2000	2.8-7.1
Moderately saline groundwater	1500-7000	2000-10000	7.1-14.1
Highly saline groundwater	7000-15000	10000-25000	14.1-28.2
Very Highly saline groundwater	15000-35000	25000-45000	28.2-282.2
Seawater	>35000	>45000	>282.2

Adapted from (Tomaszkiewicz et al., 2014; Wang et al., 2020)

Another common and easily applicable parameter for identifying seawater intrusion is the Seawater Fraction (f_{sea}). This equation is used to determine the level of mixing between seawater and freshwater, with values ranging from 0 to 100. As the f_{sea} value decreases, the groundwater becomes less saline. The Seawater Fraction equation by Appelo & Postma (2005) is presented in Formula 2.

$$f_{sea} = \frac{Cl_{sample} - Cl_{freshwater}}{Cl_{seawater} - Cl_{freshwater}} \qquad (2)$$

Where f_{sea} is the fraction of seawater, Cl_{sample} is the chloride concentration in the water sample, $Cl_{freshwater}$ is the average chloride concentration in samples with an electrical conductivity (EC) of less than 1 dS/m, and $Cl_{seawater}$ is the chloride concentration from seawater. The value of $Cl_{seawater}$ is obtained by taking a seawater sample and testing it in the laboratory.

The spatial distribution mapping of each groundwater hydrochemical parameter is analyzed using geostatistics. Geostatistical analysis is a branch of applied statistical techniques that aims to detect, model, and estimate the spatial patterns of various groundwater parameters. To date, geostatistical analysis has been widely applied in hydrogeological research. Ordinary Kriging (OK) is the most commonly used method in geostatistical analysis and is preferred for its low error values. OK is shown in Formula 3.

$$Z = \sum_{i=1}^{n} \lambda_i Z(x_i) \qquad (3)$$

Where Z is the estimated value, Zi is the measured value at location Xi, λi is the weight of the measured value at the location, and n is the number of measured values.

Result and Discussion

Groundwater level and sea-freshwater interface

The height of the groundwater level (GWL) determines the hydraulic pressure between the freshwater and seawater boundaries in the transition zone. The interface between freshwater and seawater has a density difference that indicates a clear boundary. It is assumed that if the groundwater level is above the average sea level, the depth of the interface will be 40 meters below sea level (Houben, 2018; Post et al., 2018). Furthermore, a groundwater level above sea level will push the seawater away from the freshwater aquifer, while a groundwater level below sea level will push the hydraulic gradient toward the land (Houben, 2018; Jasechko et al., 2020).

The groundwater level at the research site ranges from -5.20 meters below sea level (mbsl) to 41.87 meters above sea level (masl) (Table 2). Groundwater levels below sea level (-5 to 0 mbsl) account for 13% of the total samples (29 sample points). These 29 samples are distributed in karst aquifer areas with hilly topography and in alluvial sediment areas at the estuaries of the Bedadung River and the Kalimalang River. Most of the locations with groundwater levels below sea level are found in Lojejer Village, which is a karst hilly area. This is similar to studies by Jasechko et al. (2020) and Zahroh et al. (2024), which found that carbonate aquifers tend to have fractures with secondary porosity, making them more susceptible to seawater intrusion. In the alluvial sediment areas, such as the estuaries of the Bedadung and Kalimalang rivers, groundwater levels below sea level are also observed, likely due to groundwater flow toward the rivers.

Table 2. Statistical Analysis of groundwater level and hydrochemical data

Parameter	Temp (°C)	pH	EC (µS/cm)	TDS (ppm)	GWL (mswl)	Cl (mg/l)	Sea-Freshwater Interface (m-swl)
Min	26,5	6,1	120	93,00	-5,20	50	-208
Max	34,6	10,8	6800	3170,00	41,87	6200	1674,8
Mean	28,9	7,4	550	380,46	7,41	998	296,95
SD	1,2	0,6	680	333,30	10,99	1917	439,42

The groundwater level above sea level (0-4 meters above sea level, msl) is predominantly found in sandy aquifers with coastal deposits and alluvium. This is similar to the findings of Recinos et al. (2015) and Wilopo et al. (2021), who stated that sand or sand dune aquifers act as barriers against intrusion because sand has a fast infiltration function. The high groundwater levels are found in the hilly area of Tempurejo District or Meru Betiri National Park. This affects the direction of groundwater flow, which moves from the hills in Meru Betiri National Park toward the west, specifically to Lojejer Village in Wuluhan District. In the eastern part of the research location, the flow direction also leads to the cement factory in Puger Kulon Village and the mouth of the Kalimalang River. Piezometric maps and groundwater flow directions are shown in Figure 2.

The groundwater level is a significant factor in evaluating the vulnerability of aquifers to seawater intrusion (Xie et al., 2011). The sea-freshwater interface prediction is obtained from the initial groundwater analysis using the Ghyben-Herzberg Principle (Formula 1). The results from 211 groundwater levels show that the shallowest interface from the ground surface is at a point 120 meters below sea level. The maximum well depth should be less than the sea-freshwater interface to avoid seawater intrusion. Pumping rates should also be limited to the aquifer's output flow, especially in coastal areas, to minimize seawater intrusion (Lestari et al., 2024; Muhammad et al., 2024)

Physco-chemical parameter

Electrical Conductivity (EC) in the research area ranges from 120 µS/cm to 6800 µS/cm, with an average value of 550 µS/cm. High EC values in groundwater indicate an abundance of salts. This value depends on temperature, concentration, and the types of ions present (Hem, 1985). The maximum suitable EC value for drinking water is 1500 µS/cm, while the maximum EC value suitable for irrigation is 250 µS/cm (Mujib et al., 2020; WHO, 2019). In the research location, EC is divided into three categories: fresh groundwater (<700 µS/cm), accounting for 83%; slightly saline groundwater (700-2000 µS/cm), accounting for 16%; and moderately saline groundwater (2000-10,000 µS/cm), accounting for 1% (Table 3). The spatial distribution of EC classes is shown in Figure 3.

High EC values are found in Payangan Beach and Watu Ulo Beach in Sumberejo Village, which are coastal tourist and residential areas, leading to high groundwater pumping rates. Additionally, a key factor influencing the high EC values in these areas is the annual impact of extreme tidal waves from the Indian Ocean. As noted in the study by Guo et al. (2023), tidal waves can affect groundwater levels and salinity in subsurface aquifers, even up to one kilometer inland.

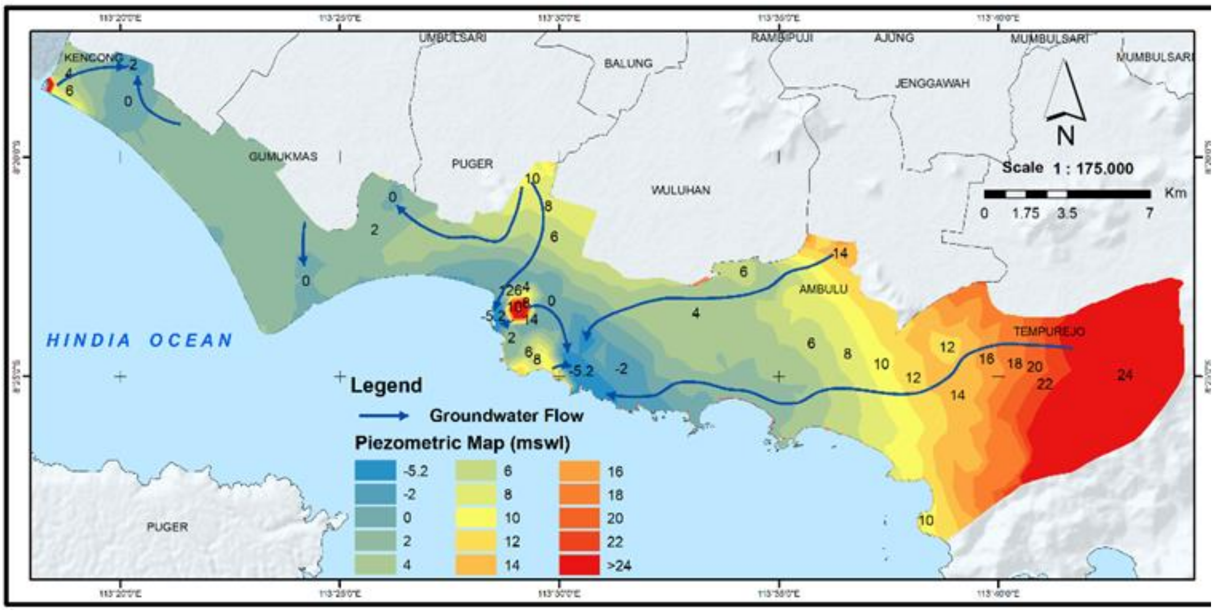

Fig 2. Groundwater flow in research area

Table 3. Classification of groundwater based on TDS, EC, and Cl

Class	TDS (ppm)	Σ Sample	EC (µS/cm)	Σ Sample	Cl (meq/l)	Σ Sample
Fresh groundwater	0-500	175	<700	174	<2.8	3
Slightly saline groundwater	500-1500	33	700-2000	34	2.8-7.1	5
Moderately saline groundwater	1500-7000	3	2000-10000	3	7.1-14.1	0
Highly saline groundwater	7000-15000	0	10000-25000	0	14.1-28.2	1
Very Highly saline groundwater	15000-35000	0	25000-45000	0	28.2-282.2	2
Seawater	>35000	0	>45000	0	>282.2	0

Total Dissolved Solids (TDS) have a strong correlation with EC, with the same class categories: fresh groundwater (0-500 ppm) accounting for 83%, slightly saline groundwater (500-1500 ppm) accounting for 16%, and moderately saline groundwater (1500-7000 ppm) accounting for 1%

(Table 3). The spatial distribution of TDS is shown in Figure 4.

Generally, seawater has a TDS value of 35,000 mg/L, which is equivalent to a Chloride content of 19,000 mg/L (Lyles, 2000). Therefore, high levels of chloride in coastal aquifers can indicate seawater intrusion (Werner et al., 2013). Based on the chloride parameter values at the research site, only 3 samples fall into the category of fresh groundwater with chloride content <2.8 meq/L, namely at Sta 6, Sta 10, and Sta 11. In the second category, there are 5 samples with slightly saline groundwater, and in the fourth category, there is 1 sample with highly saline groundwater. In the fifth category, there are 2 samples with very highly saline groundwater.

Chloride in groundwater originates from various sources, including weathering, soil and sediment washing, intrusion from seawater, wind-blown salt during rainfall, and domestic and industrial waste discharge. At the research site, chloride concentrations range from 50 to 6200 mg/L, with an average value of 998 mg/L. Chloride concentration in natural waters shows a strong correlation with sodium (Na) and EC. Chloride is also useful for indicating seawater intrusion, as well as tracking and measuring the rate and volume of water mass movement.

The primary driver of seawater intrusion in the study area is climate change, notably through rising sea levels, which exacerbate tidal flooding and impact the groundwater systems. The southern coast of Jember Regency, affected annually by tidal flooding, experiences seawater levels that peak at 1 meter above the land surface (BPBD Jawa Timur, 2024), affecting coastal aquifers through saline water mixing. Climate-induced sea-level rise intensifies saltwater intrusion by increasing tidal reach and promoting mixing within coastal aquifers, as corroborated by Polemio & Zuffianò (2020), who identified marine, terrestrial, and anthropogenic sources as primary drivers to groundwater salinity.

Tidal fluctuations also significantly influence salinity dynamics in these aquifers. Changes in sea level associated with tidal cycles facilitate the redistribution of salts within the coastal aquifer, enhancing material exchange between the ocean and groundwater. This interaction leads to complex mixing patterns within coastal aquifers, temporarily shifting the saltwater-freshwater interface landward, before it retreats seaward as equilibrium restores (Pool et al., 2014). This tidal influence can lead to increased chloride ion concentrations, further impacting groundwater salinity and overall aquifer chemistry.

The impact of tidal oscillations on groundwater has been thoroughly documented, indicating rapid seawater exchange within the intertidal zones, as discussed by Guo et al. (2023). This tidal influence intensifies mixing at the saltwater-freshwater interface, a phenomenon further elucidated by Duque et al. (2020), who emphasized the role of subterranean estuaries in altering salinity and groundwater chemistry due to these oscillations. Seasonal sea level variations, such as those observed by Wood & Harrington (2015), further contribute to shifts in groundwater salinity, particularly during high sea level periods, when the freshwater-saltwater mixing zone moves inland. This cyclical process reinforces the importance of considering both periodic and seasonal sea level changes when evaluating coastal aquifer salinity dynamics and the physicochemical responses specific to this region.

The fraction of seawater (f_{sea})

Based on the calculation results of the seawater fraction (Formula 2) using the measured chloride concentration at 11 sample locations, the average chloride concentration in fresh groundwater with TDS <1000 mS/cm was compared to the chloride concentration in seawater. If the chloride concentration in seawater is not available, it is assumed that the chloride concentration in fresh groundwater is equivalent to 0 meq/L, and seawater is equivalent to 566 meq/L (Appelo & Postma, 2005). The range of values in the research locations varies from -0.2% in the middle part of the research area (Puger and Ambulu District) to a value of 23.2% in Ambulu District, specifically in the tourist areas of Pantai Payangan and Watu Ulo, which are close to the coast. The calculation results of the seawater fraction are shown in Table 4.

The value of the seawater fraction, expressed as a percentage, ranges from 0 to 100. A higher value indicates a higher level of mixing between seawater and groundwater, while a lower value suggests more freshwater-dominant groundwater. The categorization of f_{sea} follows the classification of Tomaszkiewicz et al. (2014) and is further elaborated by Zahroh et al. (2024). Based on three parameters (f_{sea}, TDS, and EC), this classification divides fsea into four categories: fresh groundwater (f_{sea} 0.0-0.4%), mixed groundwater (f_{sea} 0.1-10%), saline groundwater (f_{sea} 16-90%), and seawater (f_{sea} = 100%).

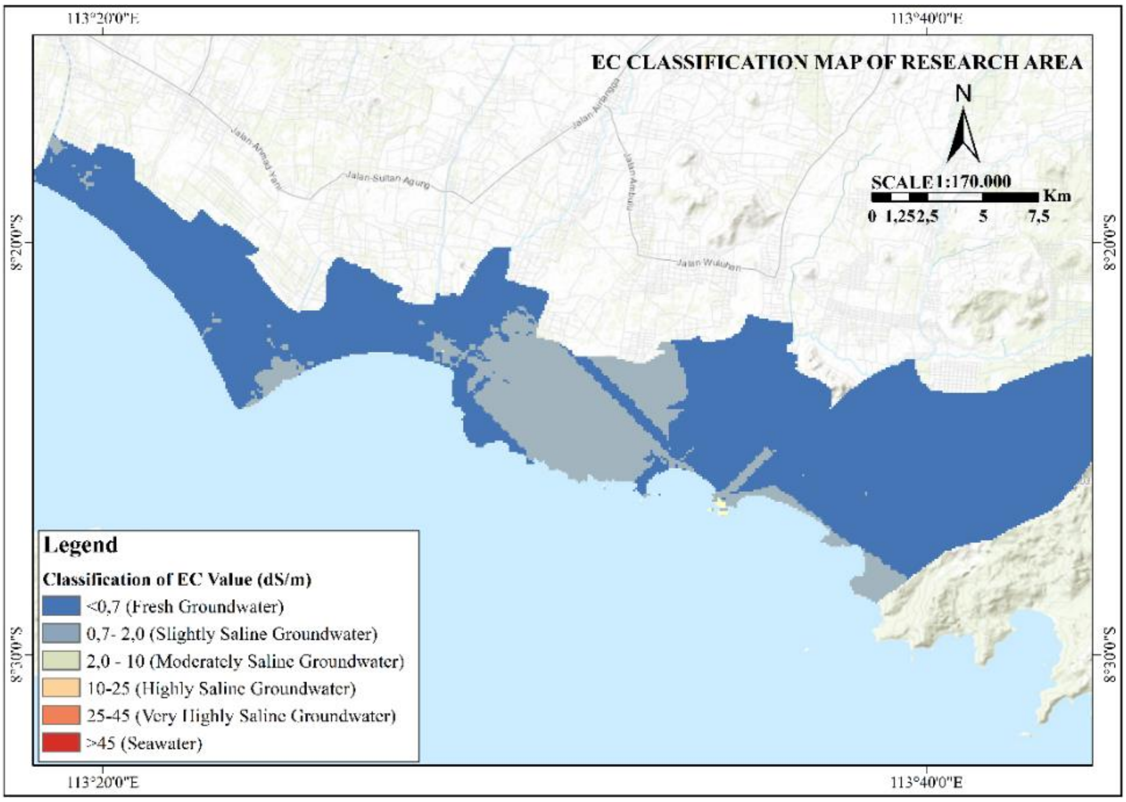

Fig 3. Distribution of EC value at research location

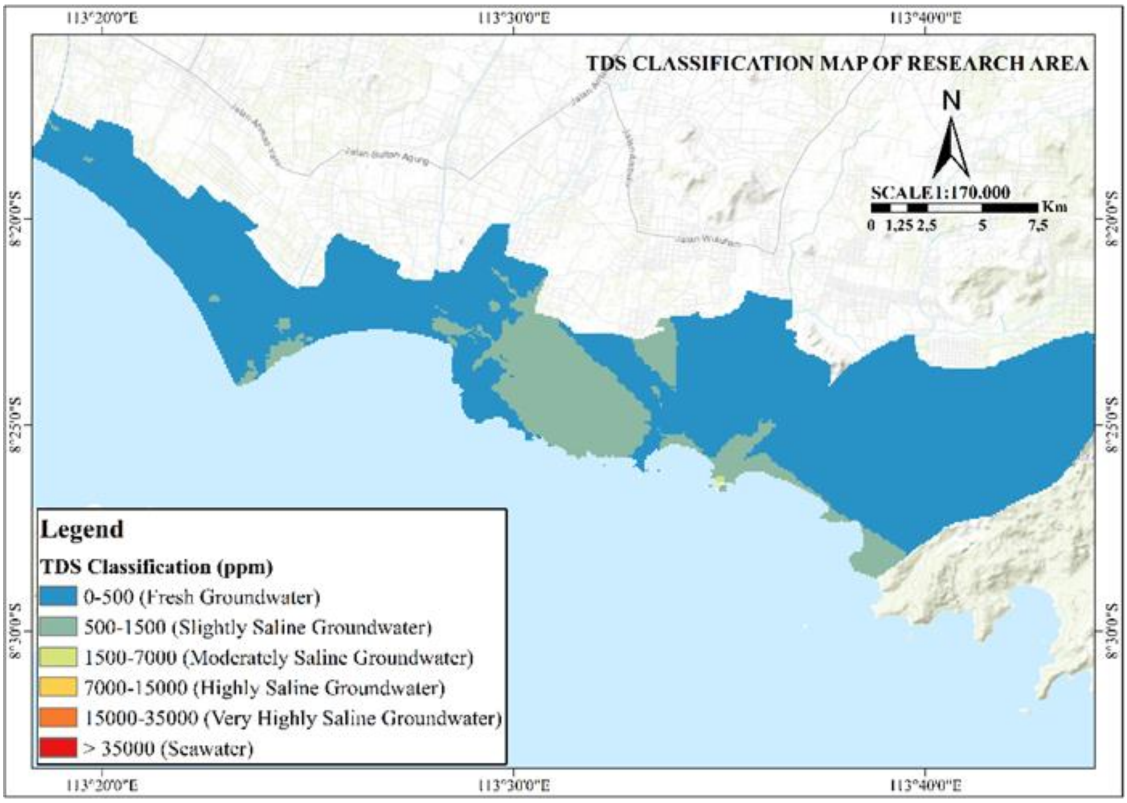

Fig 4. Distribution of TDS value at the research location

Table 4. Classification of of Chloride and Seawater Fraction (f_{sea})

Sampel	DHL (µS/cm)	Cl (meq/l)	Cl Category	f_{sea} (%)	f_{sea} Category
Sta 1	1050	4,23	Slightly saline groundwater	0.10	Fresh Groundwater
Sta 2	6800	175	Very Highly saline groundwater	23.2	Saline Groundwater
Sta 3	1000	4,51	Slightly saline groundwater	0.1	Fresh Groundwater
Sta 4	790	5,35	Slightly saline groundwater	0.2	Fresh Groundwater
Sta 5	990	3,66	Slightly saline groundwater	0	Fresh Groundwater
Sta 6	720	1,41	Fresh groundwater	-0.2	Fresh Groundwater
Sta 7	3550	25,6	Highly saline groundwater	3	Mixed Groundwater
Sta 8	1250	81,1	Very Highly saline groundwater	10.5	Mixed Groundwater
Sta 9	920	4,23	Slightly saline groundwater	0.10	Fresh Groundwater
Sta 10	560	2,25	Fresh groundwater	-0.1	Fresh Groundwater
Sta 11	780	2,25	Fresh groundwater	-0.2	Fresh Groundwater
	$Cl_{seawater}$	741			
	$Cl_{freshwater}$	3.191			

The lowest values, including negative readings (-0.1 and -0.2), are found at sample points 6, 10, and 11, indicating no mixing of seawater (fresh groundwater). These three locations are within 1.5 km of the coast (Figure 5). In the study by Kumar et al. (2020), negative values were also observed in a village far from the coast.

Furthermore, f_{sea} values ranging from 0% to 3% are found at sample points 1, 3, 4, 5, 7, and 9, with distances ranging from 0.5 km to 3.8 km from the coast. The highest f_{sea} values in the study area appear at points 8 (Watu Ulo Beach) with a value of 10%, and at point 2 (Payangan Beach) with a value of 23%. The proportion of seawater mixed with groundwater at points 8 and 2 is estimated to be 10% and 23%, respectively. These two locations are closest to the coast (<0.5 km), resembling the high f_{sea} values observed in the studies by Ouhamdouch et al. (2020) and Behera et al. (2019) along coastal areas.

In some locations around sample points 8 and 2,, which are within the Sumberejo Village area, the groundwater is also salty, with well depths of only about 4 meters and a distance of 0.5 km from the coastline. Sample points 8 and 2 are located in an alluvial sediment geological formation (Figure 5), and because both locations are in an area affected by rising sea levels, there is a mixing zone between freshwater and saltwater at these points, particularly during periods of high sea levels.

Approach to Mitigating Seawater Intrusion

Strategies for preventing and mitigating seawater intrusion have been explored extensively in previous research (Hussain et al., 2019; Polemio & Zuffianò, 2020; Werner et al., 2013). According to Hussain et al. (2019), these strategies generally fall into three categories: conventional or temporary methods, physical barriers, and hydraulic barriers. Polemio & Zuffianò (2020) further classify seawater intrusion management into three main approaches: engineering solutions, discharge management, and integrated water and land management, which can be applied at both local and regional scales.

Rising sea levels present a significant risk to coastal aquifers by advancing seawater further inland, thereby increasing the potential for aquifer salinization. For example, Sherif & Singh (1999) estimated that a 50 cm sea-level rise could cause seawater intrusion to extend up to 9 km in the semi-confined Nile Delta aquifer, while in the confined Madras aquifer, intrusion might extend only about 0.4 km. Similarly, Dausman & Langevin (2005) observed a 1.5 km inland intrusion due to a 48 cm sea-level rise. In this study's coastal aquifer, seawater intrusion extends up to 0.5 km inland, posing a threat to the quality of well water, especially in areas where groundwater is a primary water source.

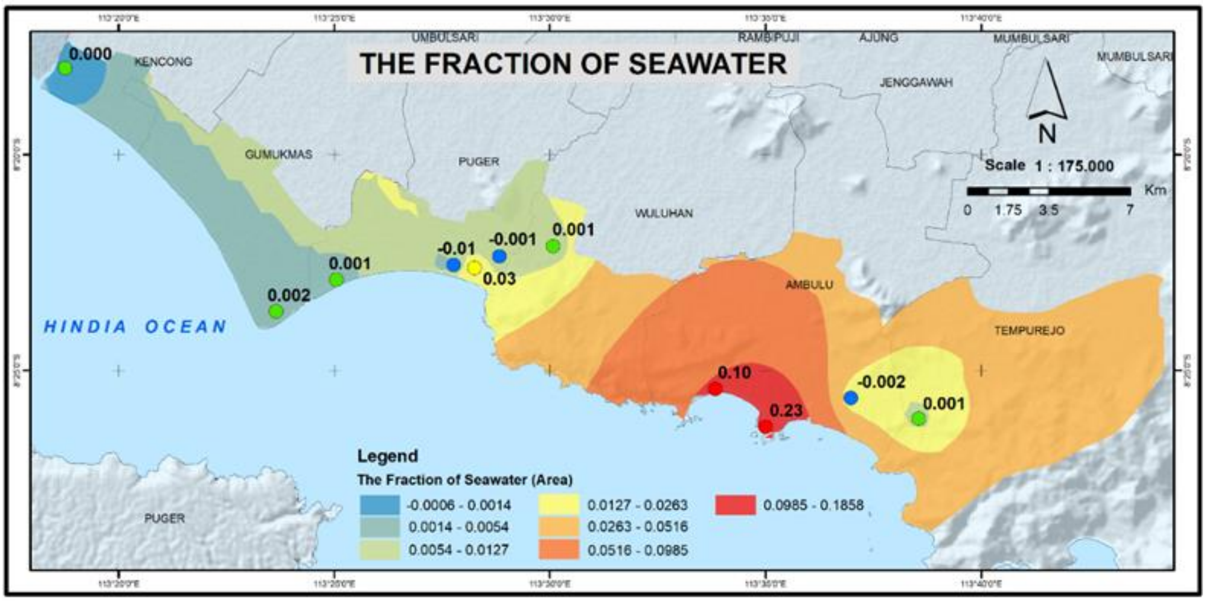

Fig 5. The Fraction of Seawater (f_{sea}) at the research locations

The response of each aquifer to seawater intrusion varies based on its unique geological and hydrological characteristics. Thus, adaptive management strategies that account for localized aquifer conditions, predicted sea-level rise, and climate variability are essential. Effective management should include regular monitoring of aquifer salinity and water levels, enabling timely adjustments to maintain groundwater quality.

The primary mitigation measure in the study area is reducing groundwater pumping, a conventional and cost-effective method of managing groundwater balance in coastal aquifers (Hussain et al., 2019). This strategy has shown efficacy, especially in regions where groundwater demand is primarily for domestic use. However, in areas with high groundwater demand, such as arid regions and agricultural zones, additional measures are often necessary. In this study area, where demand is mainly domestic, water use has been minimized in affected wells, prioritizing wells not impacted by seawater intrusion. To further limit seawater intrusion, management strategies should incorporate the following best practices:

a) Artificial Recharge: Enhancing aquifer recharge through the introduction of treated freshwater can help maintain the hydraulic gradient, thus reducing seawater encroachment. This approach has proven effective in regions with available recharge water sources.
b) Physical Barriers: Installing subsurface barriers or extraction wells along coastal boundaries can physically restrict the inland movement of saline water. Purnama & Marfai (2012) recommended a combination of artificial recharge and extraction barriers for coastal aquifers in Semarang, Indonesia, due to their cost-effectiveness and efficiency in developing regions.
c) Sustainable Land Use and Water Management: Integrating land and water resource management, such as regulating agricultural water use and adopting drought-resistant crops, can reduce excessive groundwater extraction, helping to preserve aquifer quality.

By implementing a combination of these strategies, coastal areas can enhance the sustainability of groundwater resources and effectively mitigate risks from seawater intrusion effectively.

Comparison with Coastal Aquifers Worldwide

Table 5 compares seawater intrusion levels in various coastal aquifers, including the Jember aquifer, through physicochemical parameters (TDS, EC, and Cl) and seawater fraction (f_{sea}). Each aquifer exhibits distinct seawater intrusion characteristics, influenced by environmental conditions and salinization processes such as climate-induced sea level rise, evaporation, and anthropogenic activities.

The Gaza coastal aquifer in Palestine shows the highest seawater fraction, ranging from 11.08% to 48.54%, indicating significant seawater mixing due to both anthropogenic activities and historic seawater encroachment (Al Naeem et al., 2019). In contrast, the Jido-Eup Island aquifer in South Korea has an fsea value below 10%, which is attributed to high rainfall and water-rock interactions that reduce saltwater influence (Shin et al., 2020). Similarly, Heuningnes Catchment in South Africa is affected by paleo-saltwater intrusion and recent seawater mixing processes, as observed by Xaza et al. (2023)

Table 5. Comparison of Groundwater Salinity Parameters in Various Coastal Aquifers Worldwide

Country	Coastal Aquifer	Physicochemical parameter TDS (mg/l)	EC (μS/cm)	Cl (meq/l)	Seawater Fraction Fsea (%)	Category*)	Reference
Palestine	Gaza Coastal Aquifer	5434	597	2,19	11.08	FG	Al Naeem et al., 2019
		18,848	30400	291	48,54	SG	
India	Point Calimere Wetland	282	440	1,69	-0.7	FG	Kumar et al., 2020
		11,968	18700	119,89	37.7	SG	
South Korea	Jido-Eup Island	72.7	120	0,38	0	FG	Shin et al., 2020
		2870	4800	43,86	10.4	SG	
Republic of South Africa	Heuningnes Catchment	218	311	0,00	0.01	FG	Xaza et al., 2023
		43030	61471	40,52	43	SG	
Morocco	Ghis-Nekor Plain	1449.47	1612	4.46	0.57	FG	Bourjila et al., 2023
		10,014.78	15300	24.53	25.77	SG	
Indonesia	Kebumen Regency, Java Island	143	204	0.31	-0.29	FG	Zahroh et al., 2024
		977	1395	14	1.57	MG	
Indonesia	Jember Regency, Java Island	407	560	2.26	-0.1	FG	Mujib et al. 2024
		2945	6800	174.89	23.2	SG	

*) FG=Fresh Groundwater; MG=Mixed Groundwater; and SG=Saline Groundwater

In tropical regions like Java Island, which shares climate similarities with Jember, seawater intrusion levels are relatively low (fsea <10%) due to high precipitation that dilutes salt concentrations, although specific areas exhibit higher salinity levels in coastal zones (Zahroh et al., 2024). In contrast, Jember's aquifer, despite also being in a high-rainfall region, experiences pronounced seawater mixing with a maximum fsea of 23%. This is primarily due to seasonal tidal flooding along the coast, which facilitates seawater infiltration and chloride buildup within the aquifer.

Meanwhile, coastal aquifers in arid regions, such as Morocco's Ghis-Nekor Plain, experience elevated groundwater salinity due to prolonged droughts and high evaporation rates, raising salinity levels and the seawater fraction significantly over time (Bourjila et al., 2023). This highlights a contrast with the tropical environment of Jember, where salinity dynamics are more influenced by tidal effects than evaporation.

In summary, Jember's coastal aquifers exhibit distinct salinity characteristics shaped by annual tidal influences and local hydrology, making them distinct from other coastal regions where climate and anthropogenic factors dominate seawater intrusion processes.

Conclusions

The southern coast of Jember Regency features a landscape of alluvial deposits and karst hills, with predominant groundwater flow moving southward from Meru Betiri National Park to the Puger Formation and toward the coastal areas. This study identified Electrical Conductivity (EC), Total Dissolved Solids (TDS), and chloride concentrations as effective indicators for assessing groundwater salinity. Findings reveal that most groundwater samples (83%) are classified as fresh, 16% as slightly saline, and 1% as moderately saline.. Notably, the fraction of seawater intrusion is highest near Payangan and Watu Ulo beaches, where the seawater fraction (f_{sea}) reaches up to 23%, indicating significant seawater mixing influenced by tidal fluctuations and rising sea levels.

This study underscores the critical need for sustainable groundwater management practices in Jember's coastal areas. To mitigate seawater intrusion, effective strategies should include reduced groundwater pumping, artificial recharge, and installation of physical barriers. Moreover, integrating land and water management approaches, such as controlled agricultural water use and adopting drought-resistant crops, can further support aquifer stability. Comparisons with other coastal aquifers worldwide highlight Jember's unique salinity dynamics, primarily influenced by tidal and seasonal sea level variations rather than evaporation-driven processes observed in arid regions. These findings reinforce the importance of region-specific management to address seawater intrusion, helping to ensure the sustainability of groundwater resources in the face of climate change and anthropogenic pressures.

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