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Research article

Spatial Distribution of Seawater Intrusion Based on Various Lithologies in Pesanggaran Subdistrict, Banyuwangi, Indonesia

Dwi Lestari, Sri Astutik*, Fahmi Arif Kurnianto

Geography Education, Jember University, Kalimantan Street 37, Jember 68121, Indonesia

*) Correspondence: tika.fkip@unej.ac.id

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Abstract

Seawater intrusion often occurs in shoreline areas closest to alluvium rock lithology and is caused by excessive groundwater exploration. In Pesanggaran Banyuwangi, saline groundwater was found at approximately 8000 m from the shoreline. Therefore, this study aimed to analyse the spatial distribution of seawater intrusion based on rock lithology, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) in Pesanggaran, Banyuwangi. A descriptive-quantitative survey method was used to assess groundwater quality based on EC, TDS, and spatial distribution parameters. Interpolation with Inverse Distance Weighting (IDW) method was used to map seawater intrusion and its relationship to each parameter. The results showed that moderate-saline groundwater was found in several areas far from the coast with volcanic rock lithology, namely Kalibaru formations (Qpvk) and limestone lithology at Batuampar formation. Groundwater in shoreline areas (Alluvium) was dominated by freshwater due to the deposition process found in alluvium lithology, which could form an aquifer with high quantity. Saline groundwater in Batuampar and Kalibaru formations showed salt minerals flushing related to shallow marine deposition since the tertiary period. In conclusion, Pesanggaran Subdistrict had uneven spatial distribution, and no significant relationship with distance from the shoreline, but it was related to the deformation process for each lithology.

Keywords: Spatial Distribution; Intrusion; Lithology; Electrical Conductivity; Total Dissolve Solids.

1. Introduction

Excessive groundwater extraction in an environmental context is a crucial cause of scarcity, particularly in coastal areas. Seawater intrusion is related to groundwater exploitation resulting from land use changes and lowered water table (Ardaneswari *et al.*, 2016). However, in a geological context, seawater intrusion can be attributed to deformation process at active margin and forearc basin. Banyuwangi Regency has coastal areas associated with forearc basin, formed by deformation processes such as sub-duction and uplift at the southern margin of Sundaland continental crust. Several issues in this area are particularly related to saline groundwater found far from the coast (± 8000 m). This groundwater found in residential areas is unsuitable for community needs.

According to Muchamad *et al.* (2017), seawater intrusion in Pesanggaran, Banyuwangi was caused by salt flushing in limestone lithology. In other regions, saline groundwater was found 2420 m from the coastal area of Kendari City (Kete *et al.*, 2020), and 1500 m from the shoreline in Barombong coastal area, South Sulawesi (Yanti *et al.*, 2016). However, these studies did not use spatial distribution based on lithology as the main approach. Coastal areas on Java Island are influenced by a regional tectonic system, as shown by the aquifer model in various lithologies. Therefore, mapping seawater intrusion is crucial to addressing human-environment issues, particularly in coastal areas.

Groundwater studies in coastal areas mainly focused on passive continental margins dominated by siliciclastic sedimentary rocks (Micallef *et al.*, 2021). The process of aquifer formation on the passive continental margin is related to meteoric water (Micallef *et al.*, 2021, 2016), diagenesis processes (Achilles *et al.*, 2020), and buried paleochannels (Xi *et al.*, 2019 & Jia *et al.*, 2023). In the context of geological structures, groundwater is significantly influenced by lithological contacts (Michael *et al.*, 2016) and faults (Figueroa *et al.*, 2021).

The quantity and concentration of groundwater are influenced by the age of sediment and the extent of flushing (Postma *et al.*, 2016; Sø *et al.*, 2018). Groundwater quality is influenced by sediment or material above the aquifer, such as organic carbon (Das *et al.*, 2021), clay deposition layers (Donselaar *et al.*, 2017; Hoque *et al.*, 2017; Kazmierczak *et al.*, 2022), and groundwater extraction (Donselaar *et al.*, 2017). Several methods have been adopted to determine an aquifer model at the local scale, including the use of satellite image data (Sahu & Saha, 2015) and geophysical data (Cao *et al.*, 2018 & Chandra *et al.*, 2020).

Generally, intrusion occurs when seawater is trapped in rock formations acting as aquifers and saltwater entry into groundwater. Seawater trapped in aquifers storing groundwater, particularly in alluvium deposits or plains can make the water salty. Saline/brackish well water originating from seawater trapped in aquifer causes uneven distribution of ribbons (Lisan & Adji, 2017; Prihartanto *et al.*, 2017). Studies on seawater intrusion have been conducted in Rembang (Central Java), Surabaya (East Java), and Tegal (Central Java), where intrusion occurs due to high population density and massive land use changes. Moreover, the coastal areas of Rembang, Surabaya, and Tegal are dominated by alluvium lithology and directly adjacent to the Java Sea in the back-arc basin (Nurrohim, 2012; Ariyanto & Mardyanto, 2016; Ismawan, 2016).

In a geological context, Pesanggaran Subdistrict cannot be equated with other areas because it is influenced by tertiary tectonic deformation at the southern mountain of Java and located at the fore-arc basin. Pesanggaran Subdistrict in Banyuwangi has various rock formations and differs from the North East Java Coast as a part of the back-arc basin. Therefore, seawater intrusion in North East Java Coast is primarily caused by human interventions such as land use changes, industrial activities, and groundwater exploration. For example, Surabaya experienced seawater intrusion up to ± 9000 m, located in alluvial as the main lithology in this area. However, previous studies have focused more on seawater intrusion and its relationship with land cover dynamics and distance to the coast. Only a few investigated the relationship between the distribution of intrusions and lithological factors, particularly in the eastern part of the Southern Mountains of Java, with various lithological characteristics resulting in deformation of the fore-arc basin in the tertiary period. Therefore, this study aimed to investigate the distribution of seawater intrusion based on rock lithology in Pesanggaran Subdistrict, Banyuwangi Regency.

2. Research Methods

2.1. Study Area

Pesanggaran sub-district is one of the sub-districts located in Southern Coastal Areas of Banyuwangi Regency, East Java. This area consists of five villages, namely Pesanggaran, Sumbermulyo, Sumberagung, Kandangan, and Sarongan. Pesanggaran sub-district is 802.50 km^2 with a population of 53.62 thousand in 2019. This area has several springs used by local communities. Moreover, the recapitulation of water availability in the sub-district shows a surface water volume of 299.10 million m^3/year. Based on Figure 1, Pesanggaran has various rock lithologies, including the Batu Ampar Formation, Breakthrough Rocks, Kalibaru Formation, Meru Betiri Formation, Sukamade Formation, and Alluvium.

2.2. Method

This is a descriptive-quantitative study with a survey method to determine the condition of seawater intrusion in Pesanggaran Subdistrict, and to make direct measurements of Electrical Conductivity (EC) and Total Dissolve Solid (TDS).

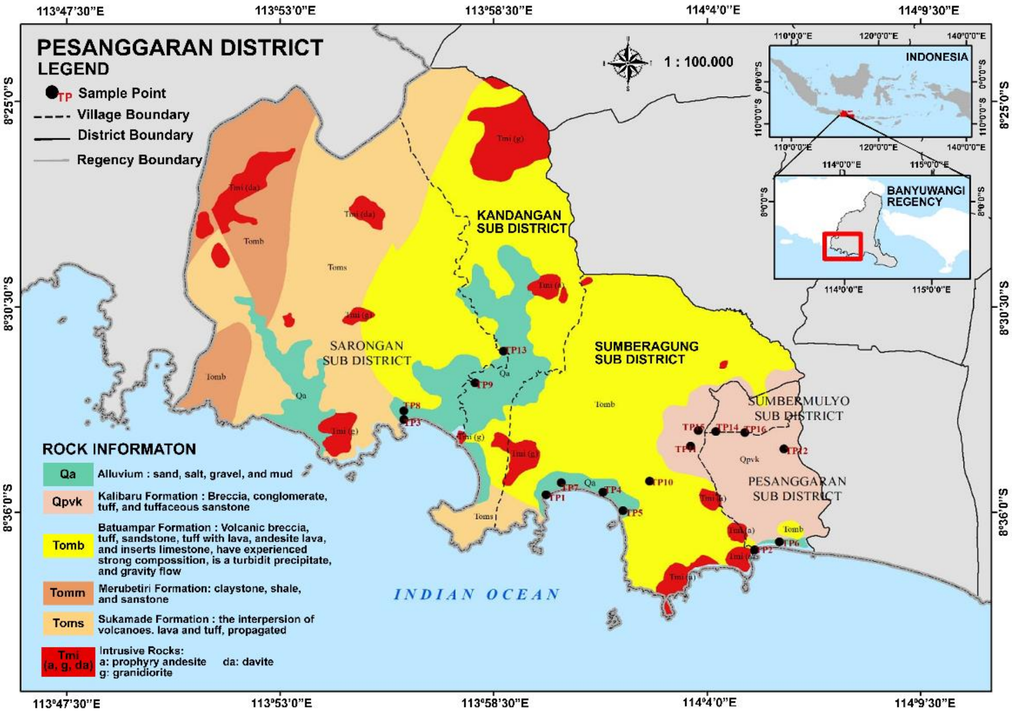

Figure 1. Study area and Sampling Point Based on Rock Formations at Pesanggaran District, Banyuwangi Regency.

The spatial distribution of seawater intrusion in the study area was identified through the interpolation of sample points and Electrical Conductivity values. Interpolation could produce a spatial distribution for the entire region by taking several samples. The analysis was conducted using ArcGIS 10.4 application and Inverse Distance Weighting (IDW) method. IDW is more accurate than Kriging method since it is close to the minimum and maximum data values. Hadi (2013) explained that IDW method considers the distance to determine the weight, representing sample points to the predicted area.

A purposive sampling with several considerations was conducted, including rock formations and the distance of the well from the shoreline. A total of 16 points were selected to represent each rock formation in Pesanggaran Subdistrict (Figure 1). However, Sukamade and Merubetiri formations were not included since there were no settlements or groundwater problems. Each sample was taken within a range of 0-300 m from the coastline due to the average groundwater intrusion of seawater being 300 m from the shoreline (Maghfirah, 2018).

2.3 Data Collection Techniques

Data were collected using observation and field measurements. The measurements were taken using Hanna HCI038, while plotting area was used to map sample points through Garmin Etrex 30x GPS. GPS was used to determine the coordinates of each sample. Parameters measured in the field included Electrical Conductivity and TDS values obtained from the EC meter at each sample point.

2.4 Data Analysis Techniques

An interpolation map derived from the results of measurements of EC and TDS showed the spatial distribution of seawater intrusion. IDW considered several aspects, such as the closer distance between sample points and the predicted area, assigning greater value or weight accordingly. Interpolation was conducted using IDW with the assistance of Arc GIS 10.4. IDW offered the advantage of adjusting interpolation characteristics by limiting the input points used in the process (Gong *et al.*, 2014).

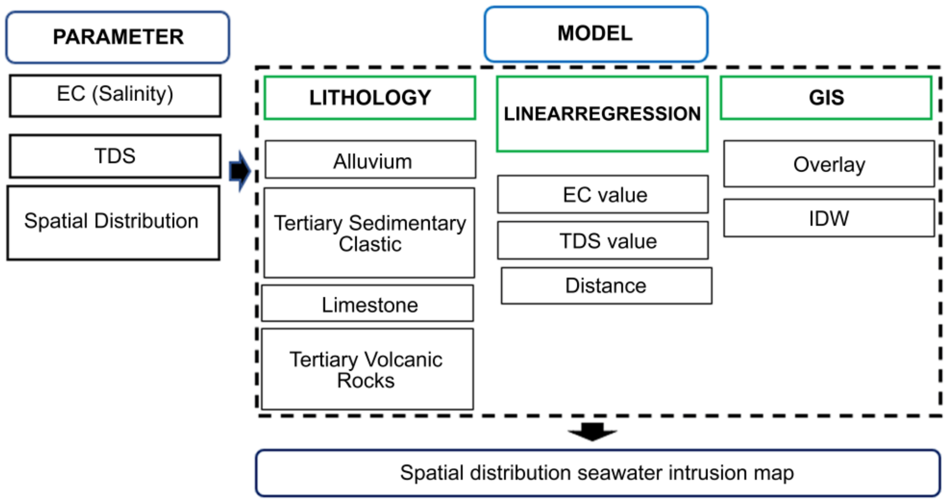

Figure 2. General Framework of Study.

Simple linear regression analysis was carried out to ensure the correlation between EC values and the distance of sample points to the shoreline. The distance of the sample points to the beach served as the independent variable (Predictor), while the EC/TDS value was the dependent variable. Both datasets were processed using MS Excel 2010. The TDS were verified by Badan Geologi and Pusat Sumber Air Tanah dan Geologi Lingkungan in 2014 (Table 2).

Table 1. Groundwater Salinity Based on Electrical Conductivity (EC).

Class	EC (µS/cm)
Fresh Water	< 700
Slight salinity	700 – 2000
Moderate salinity	>2,000 – 10,000
High salinity	>10,000 – 20,000
Very High salinity	>20,000 – 45,000
Sea Water	>45,000

Table 2. Groundwater damage classification based on Total Dissolve Solid (TDS).

TDS (Miligram/liter)	Water damage rate	Classification
<1000	Secure	Fresh
>1000 – 10,000	Prone	Brackish
>10,000	Serious	Salty

Source: Badan Geologi, Pusat Sumber Air Tanah dan Geologi Lingkungan, 2014

A lithological aspect was adopted as a new perspective to ensure seawater distribution since various lithology areas differed from homogeneous lithology. This proposed model was suitable for fore-arc basin regions, such as southeast Java coastal influenced by several tectonic deformations from tertiary to quarternary periods. The general framework of this study is presented in Figure 2.

3. Results and Discussion

3.1. Results

Using a spatial perspective, groundwater salinity was ensured by commencing measurements in coastline areas with alluvium lithology. Based on field measurements, Table 3 shows that alluvium rock had EC and TDS values representing low salinity, mostly ranging from 302-1300 μS/cm. There was no interface between seawater and groundwater in this area. Therefore, the data showed no lowered water table related to seawater intrusion in the current system.

Table 3. Measurement Result of EC and TDS.

Sample Point	Formation	EC (μS/cm)		TDS (mg/L)		Distance to the coastline (m)
		Result	Class	Result	Class	
TP1	Alluvium	740	Slightly saline	712	Fresh Water	196
TP2	Alluvium	6050	Moderately saline	2338	Brackish	55
TP3	Alluvium	4040	Moderately saline	1978	Brackish	168
TP4	Alluvium	880	Slightly saline	624	Fresh Water	165
TP5	Alluvium	1120	Slightly saline	802	Fresh Water	299
TP6	Alluvium	1370	Slightly saline	966	Fresh Water	31
TP7	Alluvium	420	Fresh Water	307	Fresh Water	442
TP8	Alluvium	1320	Slightly saline	967	Fresh Water	80
TP9	Batu Ampar	2030	Moderately saline	1569	Brackish	2975
TP10	Kalibaru	1450	Slightly saline	1066	Brackish	4562
TP11	Kalibaru	2350	Moderately saline	1728	Brackish	4768
TP12	Kalibaru	900	Slightly saline	659	Fresh Water	7163
TP13	Kalibaru	9720	Moderately saline	12745	Brackish	6634
TP14	Kalibaru	1890	Slightly saline	1386	Brackish	6834
TP15	Alluvium	340	Fresh Water	259	Fresh Water	2784
TP16	Alluvium	400	Fresh Water	319	Fresh Water	4976

Table 3 and Figure 5 show groundwater with moderate salinity was found in the Kalibaru rock formation (Qpvk). Moreover, coastal areas with alluvium rock formations (Qa) were still dominated by freshwater conditions due to alluvium being related to the diagenesis process, where sediment had accumulated in coastal areas up to the present. In contrast, Kalibaru formation comprised pyroclastic materials related to modern volcanic products. These materials were not conducive to forming confined aquifers in optimal condition because several products, such as breccia and conglomerate, had low permeability due to poor sorting. The position of Kalibaru formation, including limestone formed during the tertiary period, is shown in Figure 3. The limestone deformation process occurred earlier in the Tertiary period, while the pyroclastic material originated from Quaternary volcanoes in northern Banyuwangi. In this stratigraphy, limestone as a bedrock formed unconfined aquifers where diagenetic processes influenced the aquifers in shallow to deep marine sediments. In the context of environmental deposition, limestone in these areas was related to salt minerals. Meanwhile, in the current position, this formation was created by paleo subduction during the tertiary period to the current subduction model.

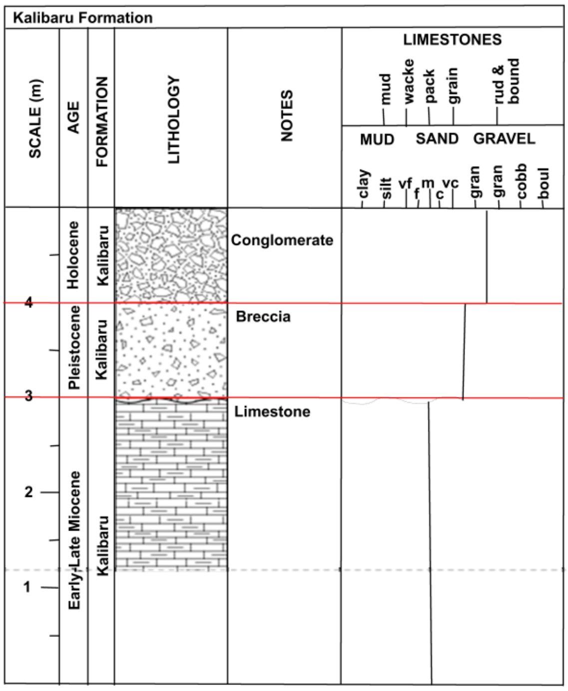

Figure 3. Kalibaru Formation.

Old andesite formation (OAF) was found in Pesanggaran, showing that this area included the tertiary volcanic zone in the southern mountains. Figure 4 shows that granodiorite was part of inactive volcanoes formed by intensive erosion processes since the tertiary period. Moderate salinity in the Batuampar formation was influenced by limestone, an organic sedimentary rock. Moreover, Batuampar Formation comprised sandstone formed by terrigenous sediment, breccia from modern volcanic products, and andesite formed by tertiary volcanic products. These lithologies represented various conditions, particularly concerning aquifer formation. Therefore, groundwater systems in these areas were not dependent on alluvium lithology, as observed in North Coastal of Java.

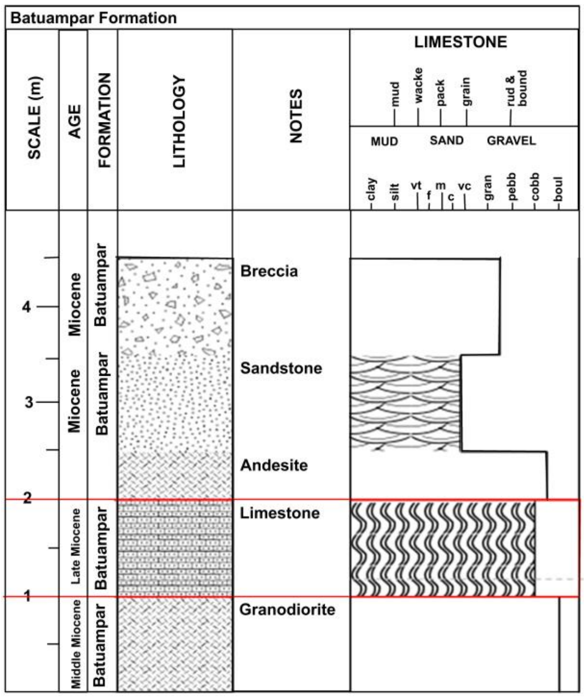

Figure 4. Batuampar formation.

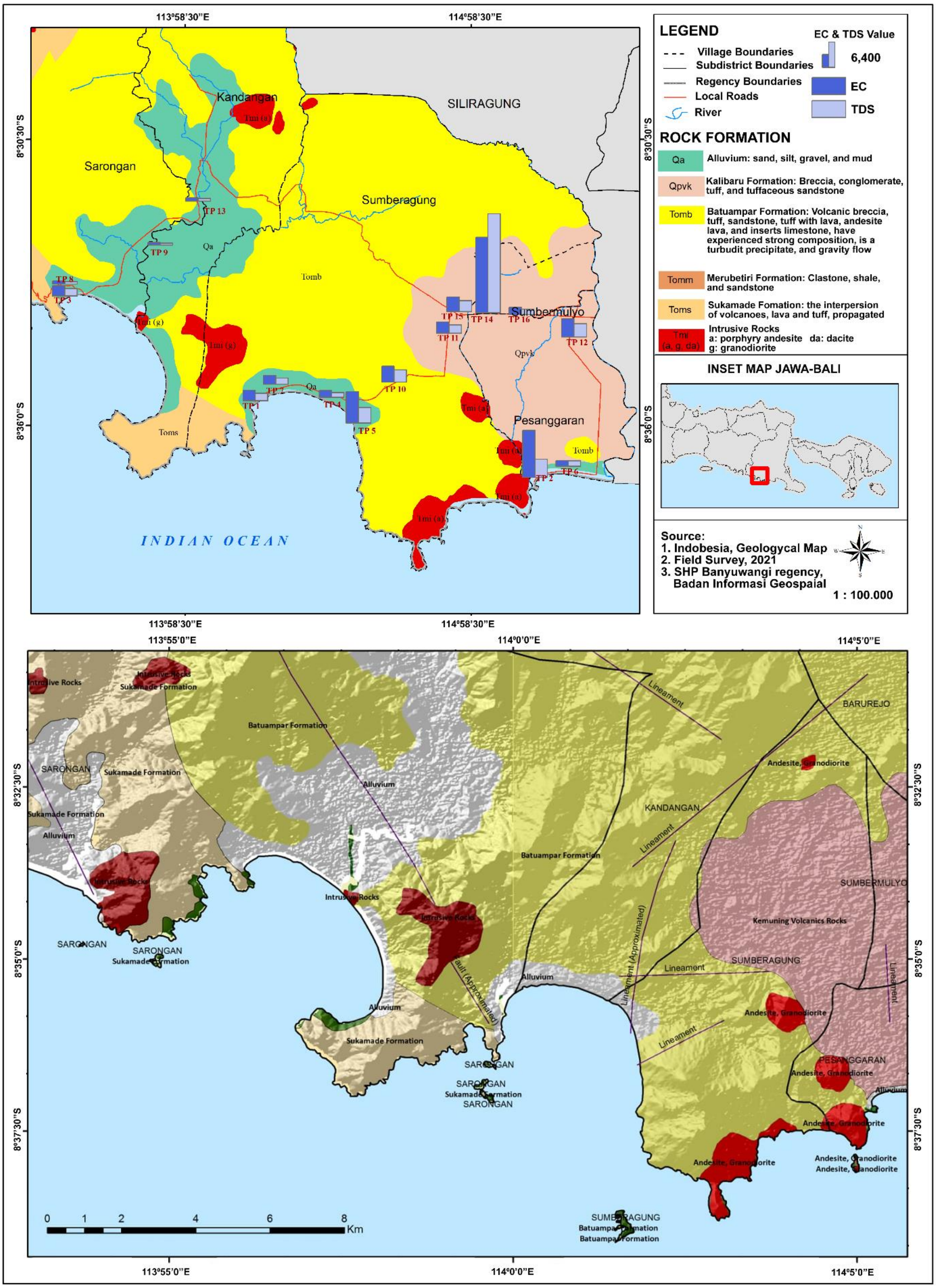

Figure 5. The well water distribution map is based on rock lithology, EC, and TDS, the Pesanggaran sub-district, and the Banyuwangi regency.

Figure 5 shows high EC values concentrated at TP 13, TP 2, and TP 3. Fresh well water, characterised by low EC, dominated the western area of the sample points. Figure 4 shows the distribution of TDS values in well water. In contrast to EC distribution, high TDS values were primarily centred on TP 13. This condition occurred as the threshold values between EC and TDS differed, resulting in varying distributions. Pesanggaran area was part of a tertiary volcano active in the early Miocene. As a formerly active volcano, the area had a tectonic setting where sediment accumulated in the forearc basin until the lithification process formed rocks. The sedimentary rocks in this region were clastic, including sandstone, claystone, and conglomerate, representing sediment accumulation from land. Limestone and turbidite deposits showed that this area also experienced deformation in the form of shallow marine uplift related to paleo-current, including saltwater accumulation.

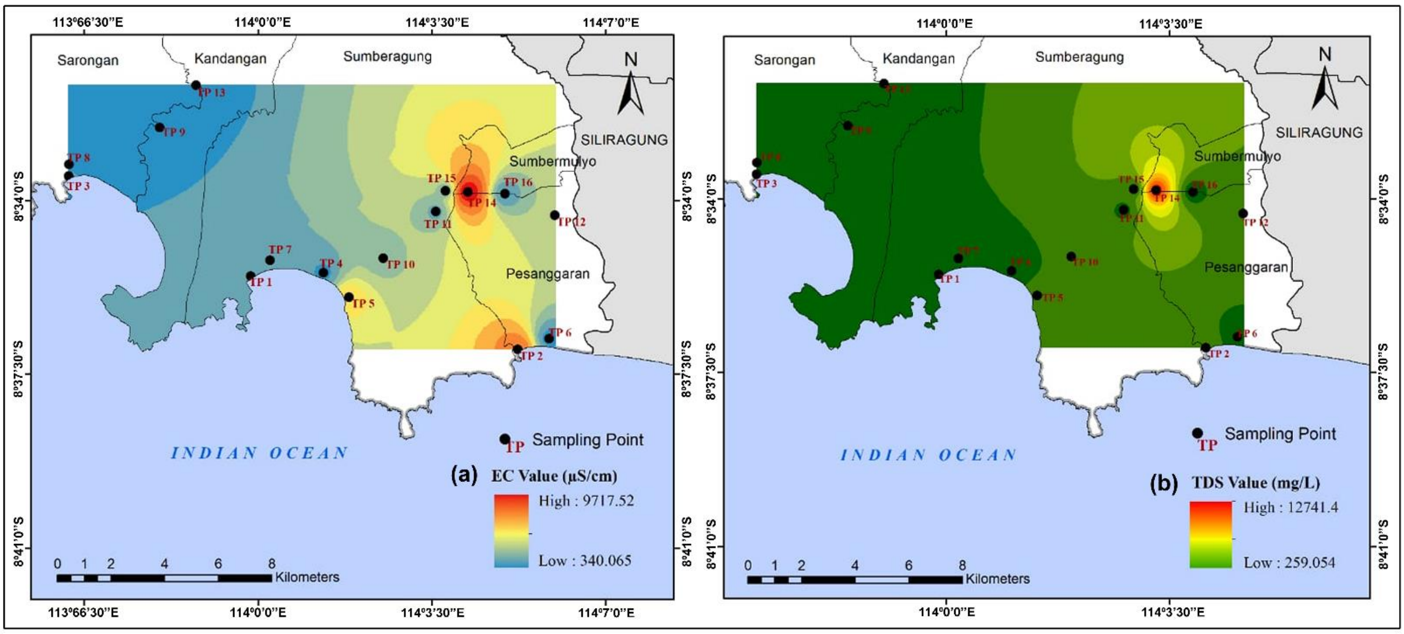

Figure 6. Comparative Spatial Distribution Maps of Seawater Intrusion Based on Electrical Conductivity (EC) and Total Dissolved Solids (TDS). (a) Spatial distribution seawater intrusion map based on EC, (b) Spatial distribution seawater intrusion map based on TDS.

The Linear regression results between EC and distance from the coastline are presented in Figure 7, with a determinant coefficient (R2) value of 0.0394 or a correlation (r) of 0.3%. EC value was influenced by distance to shoreline by only 0.3%, while other factors were influenced by the remainder. Figure 7 shows no correlation between EC value and the distance from samples to shorelines, represented by several points of moderate-slightly saline groundwater (above 2000 µS/cm) located more than 3000 m from the coastline.

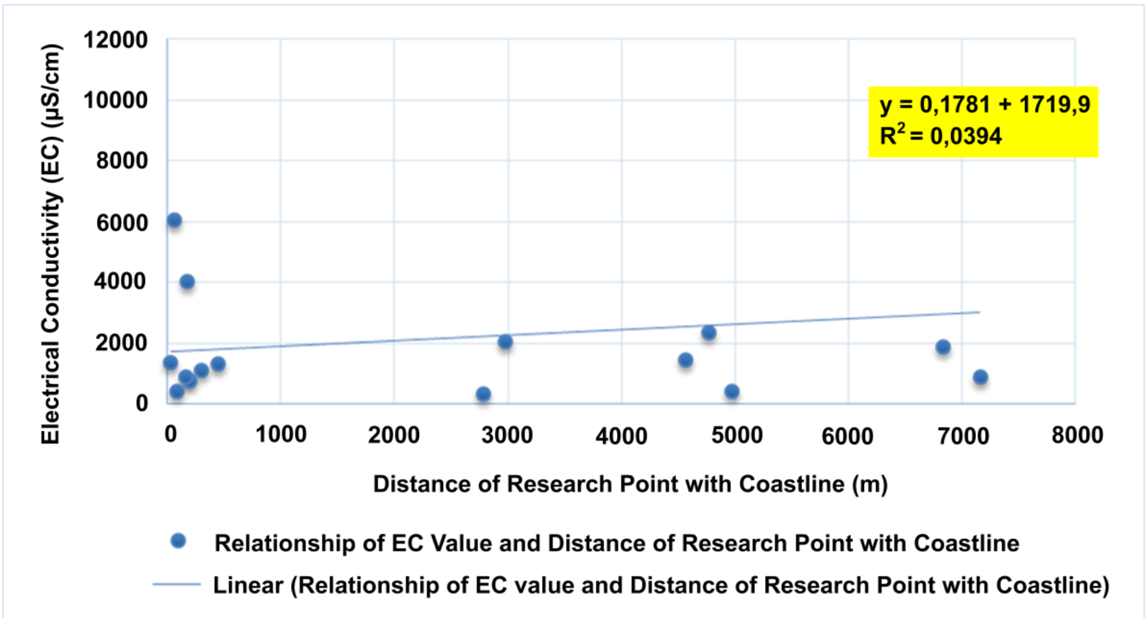

Figure 7. Linear Regression of EC Values and Distance of Study Points from the Coastline.

Linear regression calculation shows that the R2 value for TDS and distance was 0.132 or 1%, respectively. Figure 8 shows there was no correlation between the measured TDS value and the distance of the sample points from the coastline.

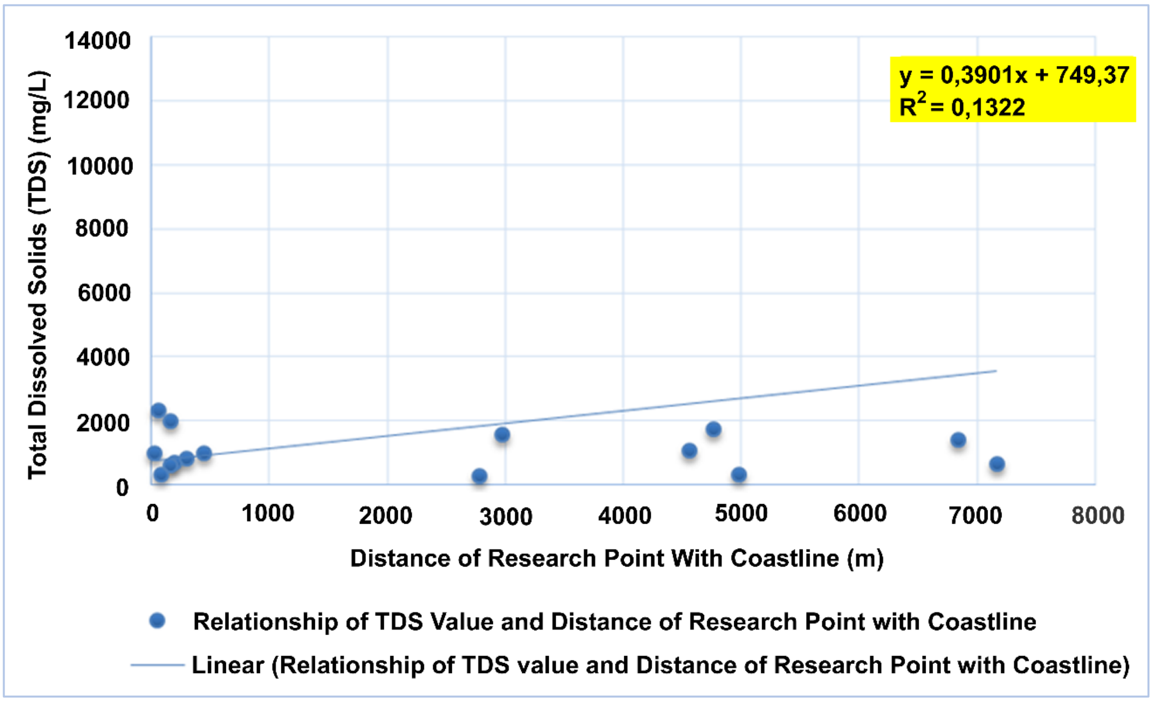

Figure 8. Linear Regression of TDS Value and Distance of Study Points from the Coastline.

3.2. Discussion

The spatial distribution of seawater intrusion based on rock lithology, EC, and TDS in Pesanggaran Subdistrict, Banyuwangi Regency, was unrelated to distance from the coastline. EC and TDS values in coastal areas with alluvium lithology showed fresh water. In contrast, high values were concentrated in areas far from the coastline, with a distance of 7000 m. The age of alluvium formations from the quarternary period showed that sediment deposits continued to accumulate until the present. Alluvium rock formations found in coastal areas consisted of several sediments undergoing deposition processes. In contrast, Hounsinou (2020) showed that groundwater in Benin City, found in an alluvium formation close to the coastline, had high TDS and EC values Other studies, including Ikhsan *et al.* (2019), Sarah *et al.* (2018); & Erban *et al.* (2014), showed that the dominance of human activities in an area could lead to changes in groundwater quality. Asfar *et al.* (2019) also found that high EC was present in alluvium (Qa) and Maluku (TRjm) formations, which were directly adjacent to the sea on the coast of Kendari City. These results differed from groundwater quality at Pesanggaran Subdistrict, where alluvium formation contained fresh water with low TDS and EC values.

In Southern Mountain of Java, the current study was supported by Muna (2016); Zamroni *et al.* (2022); & Oehler *et al.* (2018), stated that groundwater in Purwoharjo Banyuwangi District (7000 m from the coastline) had high salinity. In Gunungkidul Regency, the salinity was related to limestone lithology. Batuampar Formation (Tomb) in Purworharjo District shared the same stratigraphy as the Pesanggaran Subdistrict. Batuampar (Tomb) was derived from deep marine sediment, as evidenced by sedimentary and organic clastic accumulation. Muchamad, *et al* (2017) also explained that the Batuampar (Tomb) formation, located 3000 from Pulau Merah, produced salt water due to the leaching of salts from limestone. Examined seawater intrusion up to 3000-4000 m from Tegaldlimo coast. Tegaldimo area was dominated by rock formations containing limestone because it was located in karst zone of southern mountains.

This condition allowed several areas far from coastline to have high salinity. Febriarta & Widyastuti (2020); Siebert *et al.* (2023); and Vallejos *et al.* (2018) stated that limestone lithology could influence groundwater salinity due to its relationship with paleo coastal areas. Elubid *et al* (2019) found that groundwater salinity was increased due to shallow marine deposition, such as limestone, while low salinity was found in alluvium lithology. Salt minerals were trapped in aquifer far from coastal areas.

The Kalibaru Formation consisted of young volcanic rocks, including Quaternary pyroclastic rocks. In the context of aquifer formation, young volcanic areas had deep aquifer. However, the current study focused on Batuampar formation, which comprised outcrops of deep igneous rocks such as granodiorite and organic sedimentary rocks such as limestone, showing tertiary volcanic rocks. The presence of granodiorite outcrops was evidence of erosion that occurred at tertiary volcano, where the height of the volcano was eroded since the tertiary era, leading to the exposure of deep igneous rocks.

The coastline in Pesanggaran Subdistrict is part of Java's southern coast, directly adjacent to the Indian Ocean. There had been no groundwater exploitation or excessive land use change in this area. Therefore, groundwater quality was dependent on geological factors. Setyawan & Pamungkas (2017) and Wijatna *et al.* (2019) explained that the northern coastal plains of Java Island had several alluvial plains with delta landforms and high deposition intensity. Kurnianto *et al.* (2021) and Riyanto *et al.* (2020) also showed that East Java had various types of coastal areas related to different lithologies, such as alluvium, tertiary volcano, and carbonate platforms.

Different lithologies had various models, particularly related to groundwater aquifer forming and seawater intrusion. The current study showed that seawater intrusion was not dependent on lowered aquifer along alluvium lithology. Instead, it was related to diagenesis process since the tertiary period, and currently, saline groundwater is far from the coastline. This condition showed no correlation between EC and TDS values with the distance from the coastline. In contrast, Putri *et al.* (2016) explained that conductivity and chloride values decreased with the distance of the well water points from the coast of Ketah Beach, Situbondo. Ximenes *et al.* (2018) found that TDS value varied in alluvium lithology in the coastal areas of Timor Leste. Putra *et al.* (2021) stated that excessive water caused seawater intrusion in Bengkalis islands. In the long term, groundwater quality in Pesanggaran remained consistent with the current conditions due to tectonic deformation processes causing high groundwater salinity. The results differed from groundwater quality in major cities on Java's north coast, which was more influenced by groundwater exploitation.

4. Conclusion

In conclusion, seawater intrusion spatial distribution in Pesanggaran sub-district occurred in limestone lithology far from the coastline due to mineral salt flushing, which had become part of tertiary sediment. Alluvium lithology in areas closest to the coastline had low salinity due to engagement in the current deposition process. The forearc basin zone influenced groundwater salinity in Pesanggaran during the tertiary period, characterised by sedimentary clastic formation and uplift of shallow marine sediment resulting from subduction process. Seawater intrusion models were not only related to current aquifer conditions due to groundwater exploitation. However, in forearc basin like Pesanggaran, the models were influenced by tectonic deformation, lithological aspects, and diagenesis-lithification process of shallow marine sedimentary rock.

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Author Contributions

Conceptualization: Lestari, D., Astutik, S., Kurnianto, F. A; **methodology**: Lestari, D., Kurnianto, F. A; **investigation**: Lestari, D., Kurnianto, F. A; **writing—original draft preparation**: Lestari, D.; **writing—review and editing**: Lestari, D., Astutik, S.; **visualization**: Lestari, D., Astutik, S., Kurnianto, F. A. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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