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Seawater Intrusion Assessment based on Geological, Hydrogeological, Cl/Br vs Cl Graphical Analysis, Recharge Area, and Groundwater Usage in Makassar Coastal Area, South Sulawesi, Indonesia

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ABSTRACT. Seawater intrusion is a major concern in coastal urban areas like Makassar, where groundwater is a crucial water source. This study assesses seawater intrusion using multiple approaches, including geological and hydrogeological analysis, Cl/Br vs. Cl graphical analysis, recharge area land use, groundwater usage, and previous seawater intrusion vulnerability mapping. The 20 groundwater samples, five were categorized as brackish and then analyzed using these six perspectives. Geologically, two shallow wells in Mariso and Manggala contain brackish water due to trapped marine sediments, supported hydrogeologically by local groundwater flow patterns indicating past shallow seawater traps, while wells in Tallo show no such indications. Cl/Br vs. Cl graphical analysis classifies the shallow well in Tallo as Seawater, one in Manggala as Brine Basin, and three others as landfill leachate, suggesting anthropogenic contamination. Most groundwater recharge areas are residential and built-up, limiting infiltration and contributing to seawater intrusion. Groundwater usage is highest in Tallo, moderately high in Mariso and Manggala, and moderate in Ujung Pandang. Vulnerability mapping places the Tallo well in a high-risk zone, the Mariso well in a low-risk zone, and the Manggala well in a non-vulnerable area. Across these perspectives, only one sample in the Tallo District is confirmed to experience seawater intrusion.

Keywords: Seawater intrusion · Groundwater usage · Land use · Recharge are · Makassar.

1 INTRODUCTION

Makassar, the capital city of South Sulawesi Province in Indonesia, has experienced rapid development alongside significant population growth. Located along the Makassar Strait, this coastal city has a population exceeding 1.4 million (Central Statistics Agency, 2023). The growing population has increased the demand for freshwater in daily life. Essential to fulfilling basic human needs, freshwater can be sourced from surface water, groundwater, and rainwater (Smith, 2020). Many major coastal cities depend primarily on groundwater as their main water supply source (Hamed *et al.*, 2018). Lack of control over groundwater use can result in various groundwater problems, including aquifer depletion, land subsidence, and de-

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terioration of water quality (Custodio, 2002; Famiglietti, 2014; Foster & Chilton, 2003; Galloway & Burbey, 2011; Howard, 2015).

In Makassar, overexploitation of groundwater has led to significant issues such as seawater intrusion, which increases salinity and makes the water unsuitable for consumption (Amsah, 2020; Damayanti & Notodarmodjo, 2021; Hasrianto *et al.*, 2023; Nugroho *et al.*, 2024). Seawater intrusion in Makassar has been studied using various methods, including numerical modeling (Syam, 2015), GALDIT and modified GALDIT (Safitri, 2016; Damayanti & Notodarmodjo, 2021), geoelectrical methods (Amsah, 2020; Hasrianto *et al.*, 2023), and geochemical and isotopic analysis (Nugroho *et al.*, 2024). This study aims to assess seawater intrusion through a multidisciplinary approach, incorporating geological and hydrogeological analysis, Cl/Br vs. Cl graphical analysis, recharge area land use, groundwater recharge perspectives, and a review of previous groundwater vulnerability maps.

Geologically, the brackish groundwater found may be remnants of trapped marine sediments from the formation of alluvial deposits (Davis & De Wiest, 1966). Hydrogeologically, anomalies in groundwater flow patterns and directions may indicate the presence of shallow seawater traps in the past. Additionally, calculating the aquifer discharge rate can help determine aquifer characteristics in coastal areas (Domenico & Schwartz, 1998). Groundwater usage is also closely linked to seawater intrusion, as areas with high groundwater extraction have a greater potential for experiencing intrusion (Custodio, 1987). Furthermore, land use changes in groundwater recharge areas significantly impact groundwater replenishment and are a major cause of seawater intrusion through lateral encroachment, where the seawater interface shifts inland (Ferguson & Gleeson, 2012). This analysis can be further supported if brackish wells are located in high-vulnerability zones on groundwater vulnerability maps for seawater intrusion (Aller *et al.*, 1987).

This study is crucial for developing sustainable water management strategies to ensure the long-term availability of clean water while mitigating the environmental impacts of overexploitation (Tirtosudarmo, 2017). Previous research has not integrated these six perspectives into a comprehensive framework, leaving a gap in understanding the complex mechanisms of seawater intrusion. To address this, the study synthesizes multidisciplinary approaches to provide a more holistic assessment and offer new insights for mitigation strategies. The findings will enhance our understanding of groundwater quality dynamics and support the development of sustainable management practices to protect vulnerable coastal areas.

2 Geological Setting/Site Characterization

The study area is located in the Makassar coastal area, South Sulawesi, Indonesia, as shown in Figure 1, covering 68 km² and encompassing 14 districts in Makassar and Gowa. The study area is bounded by a hydrogeological boundary consisting of the Makassar Strait to the west, the Tallo River to the north, and the Jeneberang River to the south. The eastern and southeastern parts are bordered by hills formed by volcanic rocks, which are part of the Camba and the Baturape Cindako volcanic formations. The study area consists of one geological formation: Alluvium and coastal deposits (Qac).

3 Methodology

This study's research methodology involved analyzing data obtained from secondary sources. Geochemical data from Nugroho *et al.* (2024) were evaluated to identify wells containing either brackish or saline water based on classification criteria using TDS, EC, and Cl values. If TDS, EC, and Cl values indicated brackish water, the groundwater in that well was classified as brackish or even saline. The distribution of the 20 groundwater wells analyzed is shown in Figure 1.

Samples identified as brackish water in the study area were analyzed from multiple perspectives. From a geological perspective, the analysis utilized the Makassar alluvial evolution map (Safitri, 2016) and the Jeneberang River delta evolution map (1922–2022) (Langkoke, 2023). These were correlated with borehole log data (Safitri, 2016) to examine the formation processes of the Makassar alluvial plain and its correlation with evidence of trapped marine sediment in the study area.

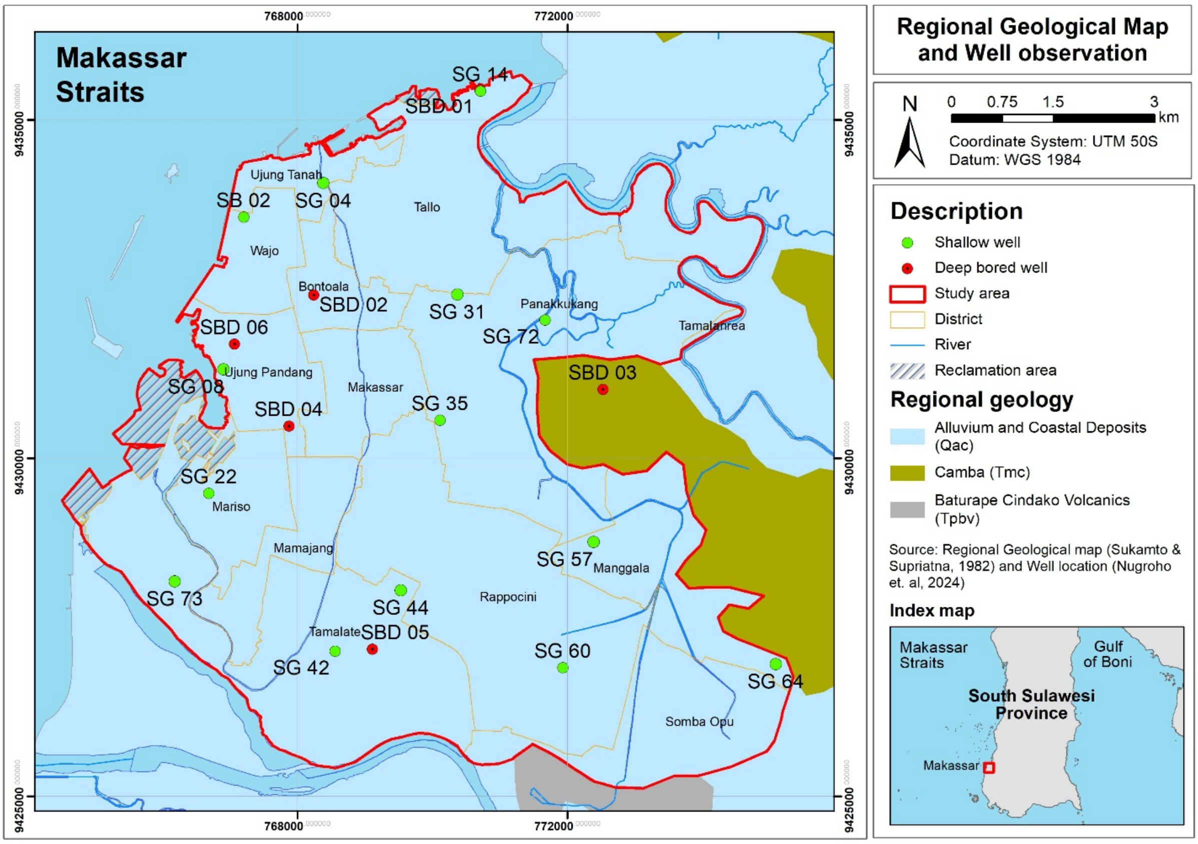

FIGURE 1. Study area with regional geological map (Sukamto & Supriatna, 1982) and well observation.

From a hydrogeological perspective, the analysis was conducted on the pattern and direction of local groundwater flow around brackish water wells, based on water table data from Nugroho et al. (2024), and the freshwater-seawater interface was estimated using the Ghyben-Herzberg principle, applying Equation 1. Additionally, aquifer discharge characteristics were evaluated using Equation 2.

$$z = 40 \cdot bf \quad (1)$$

$$Q' = \frac{Q}{Y} = K\frac{bf - 0}{L}m \quad (2)$$

In the equation, z is the depth below sea level to the freshwater-seawater interface; bf denotes the water table relative to sea level; Q′ represents shoreline discharge per unit length; (bf-0)/L is the hydraulic gradient with bf measured from distance L along the shoreline. Additionally, m is aquifer thickness, and K is the hydraulic conductivity from secondary data.

The pattern and direction of local groundwater flow can be correlated with the geological perspective to confirm the presence of seawater traps, particularly based on flow direction anomalies. Estimating the freshwater-seawater interface helps assess the relationship between interface depth and recommended well extraction depth. Additionally, aquifer discharge are analyzed to compare groundwater usage levels and identify signs of overexploitation.

The Cl/Br vs. Cl comparison graph is another parameter used in analyzing the origin of brackish water. This graphical approach was developed by Panno *et al.* (2006), by plotting the Cl/Br vs. Cl ratio, where both ions are conservative ions in seawater that best reflect the evolution of water and mixing trends. Several groundwater groups on this graph include pristine groundwater, road salt, septic effluent, brine basin, animal waste, seawater, and landfill leachate.

The groundwater usage was analyzed using population and industrial data collected from Central Statistics Agency (2023). The industrial data used in this study is manufacturing industries, which rely on water for production and convert raw materials into finished products. The groundwater usage was analyzed by adjusting the calculated water demand with PDAM's water supply data.

The water demand calculation follows SNI 6728.1-2015 (BSN, 2015). As a metropolitan city, Makassar's water demand is primarily driven by domestic, urban, and industrial needs. Domestic demand is determined based on the city's categories, as shown in Table 1. Urban demand, which covers commercial and social purposes, is assumed to be 30% of domestic water demand. Industrial water demand is calculated based on standard or average water usage for industries, considering the number of employees and the size of the industry. Water demand standards for industrial workers and industry size are referenced from Depkimpraswil (2003) and IWACO (1989), as presented in Table 2 and Table 3, respectively.

This study analyzes land use in groundwater recharge areas using the recharge area map based on Nugroho and Taufiq (2025), South Sulawesi Regional Spatial Planning Map (RTRW) from Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (ATR/BPN), and land-use data from ESRI (2017–2023). By understanding the relationship between land use patterns and groundwater recharge areas, this research provides a more comprehensive perspective on how changes, particularly the expansion of built-up areas, reduce water infiltration and contribute to seawater intrusion in coastal aquifers. Additionally, this study assesses seawater intrusion using previous seawater intrusion vulnerability maps by Safitri (2016) and Damayanti and Notodarmojo (2021).

4 Results and Discussion

Nugroho et al. (2024) analyzed geochemical data to determine groundwater types in the study area. Twenty groundwater samples, consisting of 6 deep bored wells and 14 shallow wells, were analyzed based on TDS, EC, and Cl values. Br values were also used in the Cl/Br vs Cl graphical analysis. These data are presented in Table 4. Five of the 20 samples shows indication of seawater intrusion with brackish water types: 3 shallow wells (SG14, SG22, and SG64) and 2 deep bored wells (SBD04 and SBD06).

The five samples were then analyzed from several perspectives, including geology, hydrogeology, Cl/Br vs Cl graphical analysis, groundwater usage, recharge area, and previous vulnerability maps, to determine whether the brackish water originates from seawater intrusion.

4.1 Geological perspective

The geological perspective on seawater intrusion was analyzed based on the geological history of alluvial plain formation in Makassar, as described in the Makassar alluvial evolution map (Safitri, 2016) and the Jeneberang River delta evolution map from 1922 to 2022 (Langkoke, 2023), which were correlated with borehole log data (Safitri, 2016). The observation well locations were also plotted on both maps to analyze their correlation, particularly for the three shallow wells with brackish water (SG64, SG22, and SG14) from Table 4. Most of the city was shaped by marine processes, where ancient shallow seas and lagoons were later covered by fluvial deposits, which were largely influenced by shifts in the Jeneberang River's flow, ultimately shaping the present Makassar alluvial plain (Safitri, 2016).

The correlation map between the Makassar alluvial evolution map and the observation well location (Figure 2) shows that the area around SG64 was genetically a former lagoon. This lagoon was formed from a shallow sea that became trapped due to changes in the Jeneberang River's flow (Flow 1), which led to the formation of Beach Ridge I. Over time, this lagoon gradually transformed into a backswamp before eventually developing into a residential area. This area has a basin morphology, which serves as a groundwater flow concentration zone and is classified as brackish/saline groundwater. Bore log data from the study area (Figure 3) also indicate the presence of marine sediment deposits (sand to clay) containing shell fossils and fine shells at certain depths. The groundwater salinity is likely caused by the dissolution of salt minerals from these marine sediments. Therefore, the presence of brackish groundwater in this area is more likely due to trapped marine sediments rather than seawater intrusion.

The correlation between the Jeneberang River delta evolution map (Langkoke, 2023) and the observation well locations (Figure 4) shows that

TABLE 1. Domestic water demand based on categories of city (BSN, 2015).

Categories of City	Total Population (persons)	Water demand
Capital of district/village	3,000 - 20,000	60 – 90
Small City	20,000 - 100,000	90 – 110
Medium city	100,000 - 500,000	100 – 125
Big city	500,000 - 1,000,000	120 – 150
Metropolitan	>1,000,000	150 – 200

TABLE 2. Industrial water classification by process and workforce (Depkimpraswil, 2003).

Type of Industry	Type of Industrial Process	Water Demand (Liters/day)	Number of Workers (People)
Household Industry	No specific recommendation, adjusted to household needs	1 - 4	
Small Industry		5 - 19	
Medium Industry	Soft drinks	1,600 - 11,200	20 - 99
	Ice manufacturing	18,000 - 67,000	
	Soy sauce	12,000 - 97,000	
Large Industry	Soft drinks	65,000 - 78 million	> 100
	Fish freezing and other aquatic organisms	225,000 - 1.35 million	
Textile industry	Textile processing	400 - 700 l/capita/day	

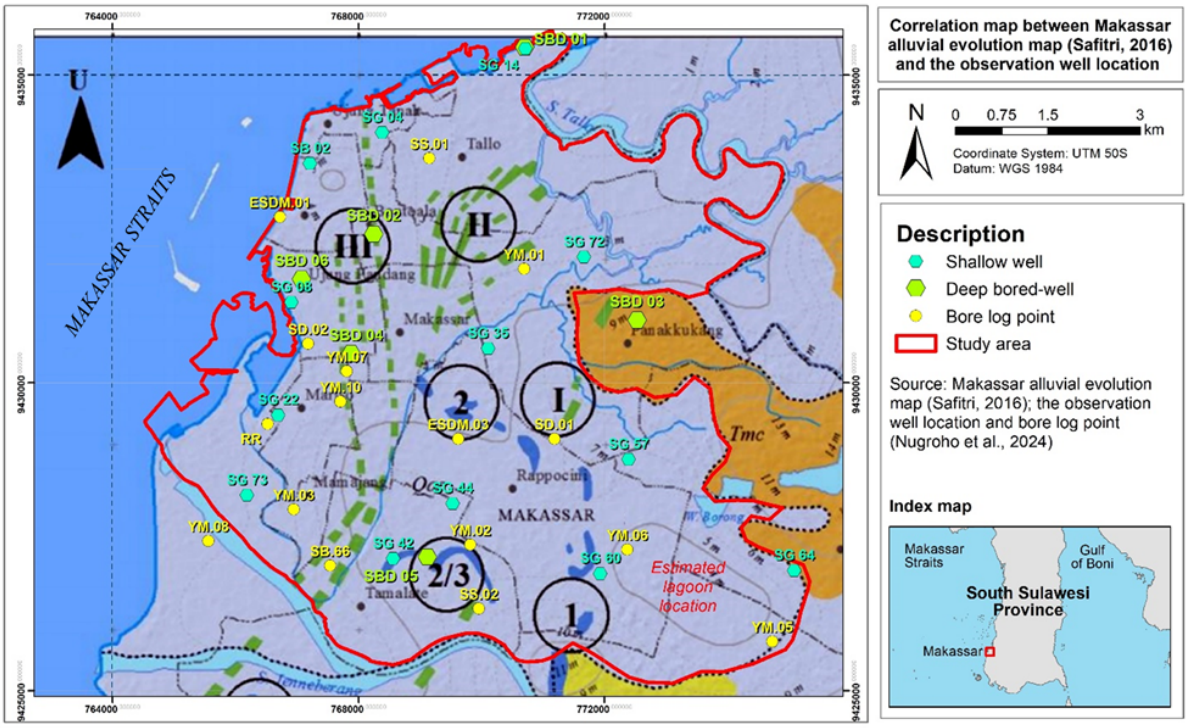

FIGURE 2. Correlation map between Makassar alluvial evolution map (Safitri, 2016) and the observation well location.

the area around SG22 was still seawater in 1922 and only transformed into land over the past 100 years through sedimentation from the Jeneberang River and land reclamation in this area. This indicates that the brackish ground-

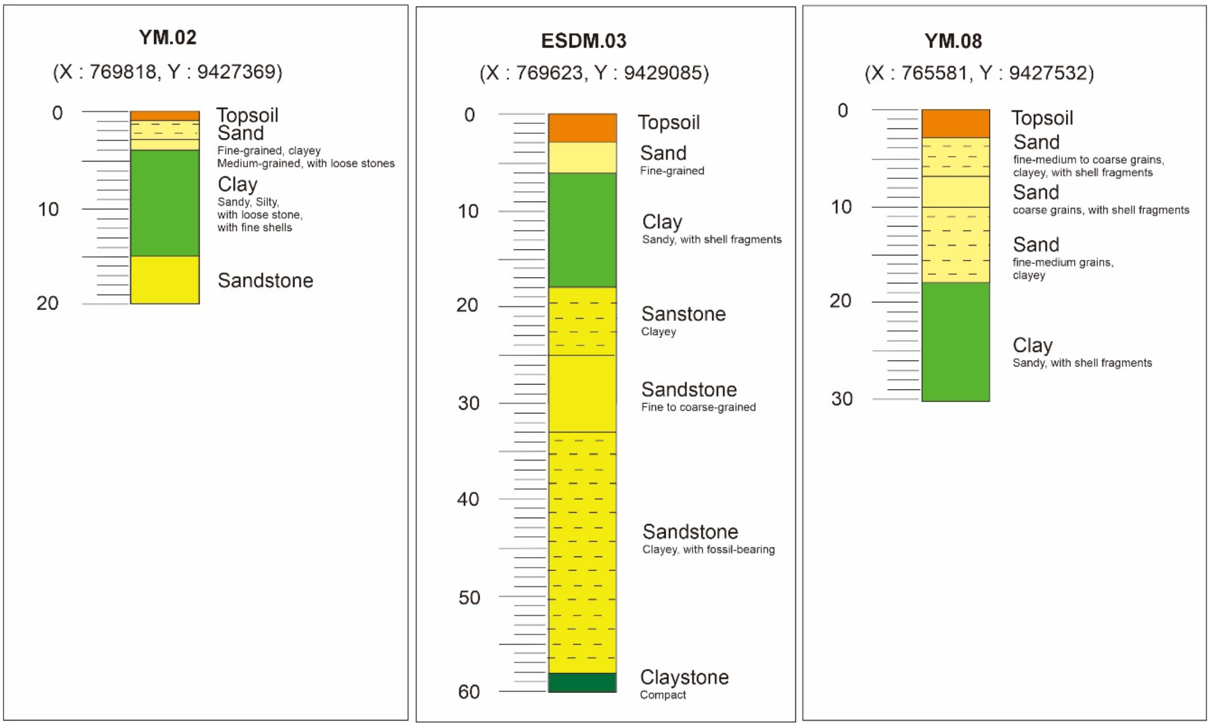

FIGURE 3. The bore log data indicate the presence of shell fragment remains, which suggest marine sediment in the sand to clay layers according to the Wentworth scale (Safitri, 2016).

TABLE 3. Industrial water classification (IWACO, 1989).

Type of Industry	Water Demand (m^3/day)
Medium Industry	2 - 4
Large Industry	5 - 10

water here originates from remnant marine sediments rather than seawater intrusion.

Observation Well SG14, unlike SG22 and SG64, is more influenced by the Tallo River than by the Jeneberang River. The brackish groundwater in this well is likely not caused by geological factors, as seen in SG64 and SG22. Therefore, further analysis using other parameters is needed to confirm seawater intrusion.

4.2 Hydrogeological perspective

Based on the hydrogeological perspective, local flow patterns and directions were analyzed using available hydrogeological observation data from the brackish water wells and their surrounding areas. The analysis was carried out on three shallow wells: SG14, SG22, and SG64. The results of the analysis are presented in Figure 5.

From Figure 5, the local flow patterns directing towards SG22 and SG64 indicate a shallow seawater due to the morphology of the depression/low area, so the brackish water in these two wells is not caused by seawater intrusion but by trapped marine sediments. A different flow pattern is shown by SG14, which instead directs towards SG15. Therefore, the brackish water in SG14 is not associated with the indication of shallow seawater but is likely due to seawater intrusion (supported by the land use around the area).

The estimated interface between seawater and freshwater helps determine the potential depth for groundwater well drilling in the study area, calculated using the Ghyben-Herzberg principle. The interface location is shown in Figure 6, and its cross-section in Figure 7. The interface cross-section is constructed based on stratigraphic cross-section data up to a depth of 50 meters from Nugroho *et al.* (2024). Generally, the interface depth varies, with the maximum depth at -207.60 m elevation found 6 km from the coastline in Rappocini District. It is recommended to drill deep wells up to a maximum depth of 200 m, ideally 6 km from the coast. Closer to the coastline, the interface

TABLE 4. Type of water analysis based on TDS, DHL, and Cl data (Nugroho *et al.*, 2024).

Sample	TDS[a] (mg/L)	Category based on TDS	EC[b] (μS/cm)	Category based on EC	Cl^- (mg/L)	Category based on Cl^-	Br^- (mg/L)	Defined Type of Water
SBD 01	452	Fresh water	892	Fresh water	128.76	Fresh water	0.72	Fresh water
SBD 02	355	Fresh water	715	Fresh water	19.78	Fresh water	0.45	Fresh water
SBD 03	182	Fresh water	363	Fresh water	19.32	Fresh water	<0.01	Fresh water
SBD 04	**8758**	**Brackish**	**17630**	**Saline**	**771212**	**Brackish**	**38.95**	**Brackish**
SBD 05	666	Fresh water	1338	Fresh water	115.75	Fresh water	0.66	Fresh water
SBD 06	**4277**	**Brackish**	**8616**	**Brackish**	**174251**	**Medium brackish**	**9.26**	**Brackish**
SG 14	**1410**	**Brackish**	**2832**	**Slightly brackish**	**593.98**	**Slightly brackish**	**2.01**	**Brackish**
SG 22	**5719**	**Brackish**	**11527**	**Brackish**	**148902**	**Medium Brackish**	**8.59**	**Brackish**
SG 35	807	Fresh water	1628	Slightly brackish	54.75	Fresh water	0.46	Fresh water
SG 42	626	Fresh water	1268	Fresh water	88.89	Fresh water	0.59	Fresh water
SG 60	**1331**	**Brackish**	**2671**	**Slightly brackish**	147.41	Fresh water	0.81	Fresh water
SG 72	**1783**	**Brackish**	**3575**	**Slightly brackish**	274.64	Fresh water	0.99	Fresh water
SB 02	**1833**	**Brackish**	**2566**	**Slightly brackish**	241.53	Fresh water	0.93	Fresh water
SG 04	900	Fresh water	**1811**	**Slightly brackish**	34.97	Fresh water	0.47	Fresh water
SG 08	316	Fresh water	637	Fresh water	34.06	Fresh water	0.45	Fresh water
SG 31	829	Fresh water	**1666**	**Slightly brackish**	62.05	Fresh water	0.53	Fresh water
SG 44	411	Fresh water	824	Fresh water	13.82	Fresh water	<0.01	Fresh water
SG 57	858	Fresh water	**1726**	**Slightly brackish**	136.77	Fresh water	0.68	Fresh water
SG 64	**1067**	**Brackish**	**2154**	**Slightly Brackish**	**352.14**	**Slightly Brackish**	**1.22**	**Brackish**
SG 73	560	Fresh water	1129	Fresh water	83.18	Fresh water	0.59	Fresh water

[a]TDS = Total Dissolved Solid, [b]EC = Electrical Conductivity

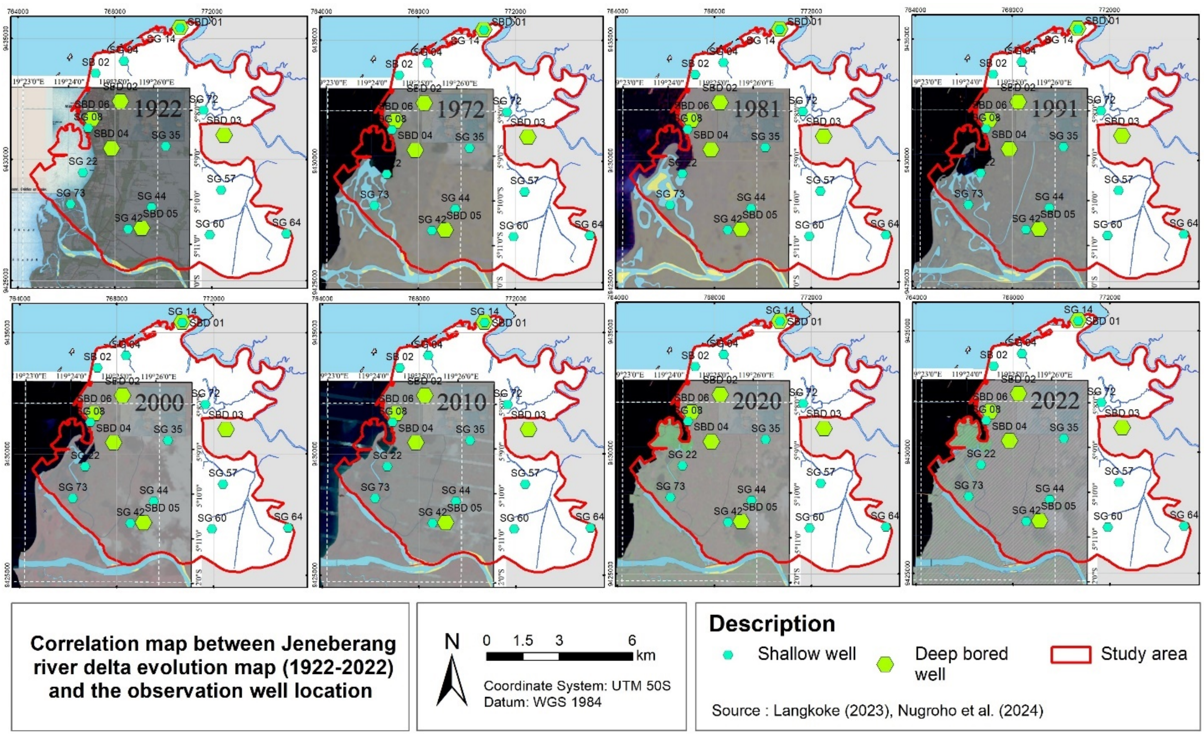

FIGURE 4. Correlation map between the Jeneberang river delta evolution map from 1922-2022 (Langkoke, 2023) and the observation well location.

becomes shallower, requiring further treatment if drilling exceeds this depth.

Alongside the interface boundary analysis, a discharge calculation per unit length of coast-

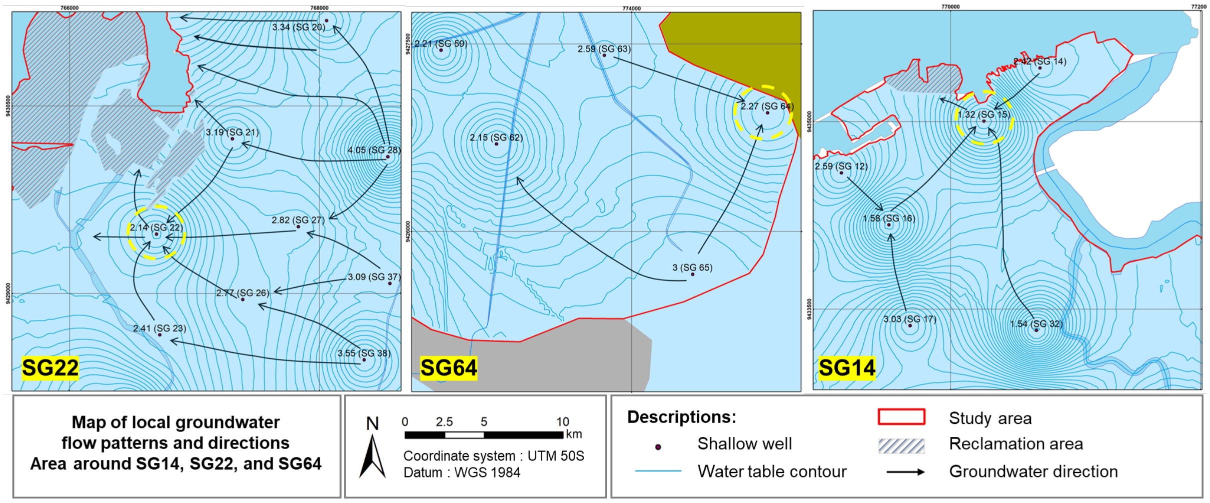

FIGURE 5. Map of local groundwater flow patterns and directions in areas around SG14, SG22, and SG64.

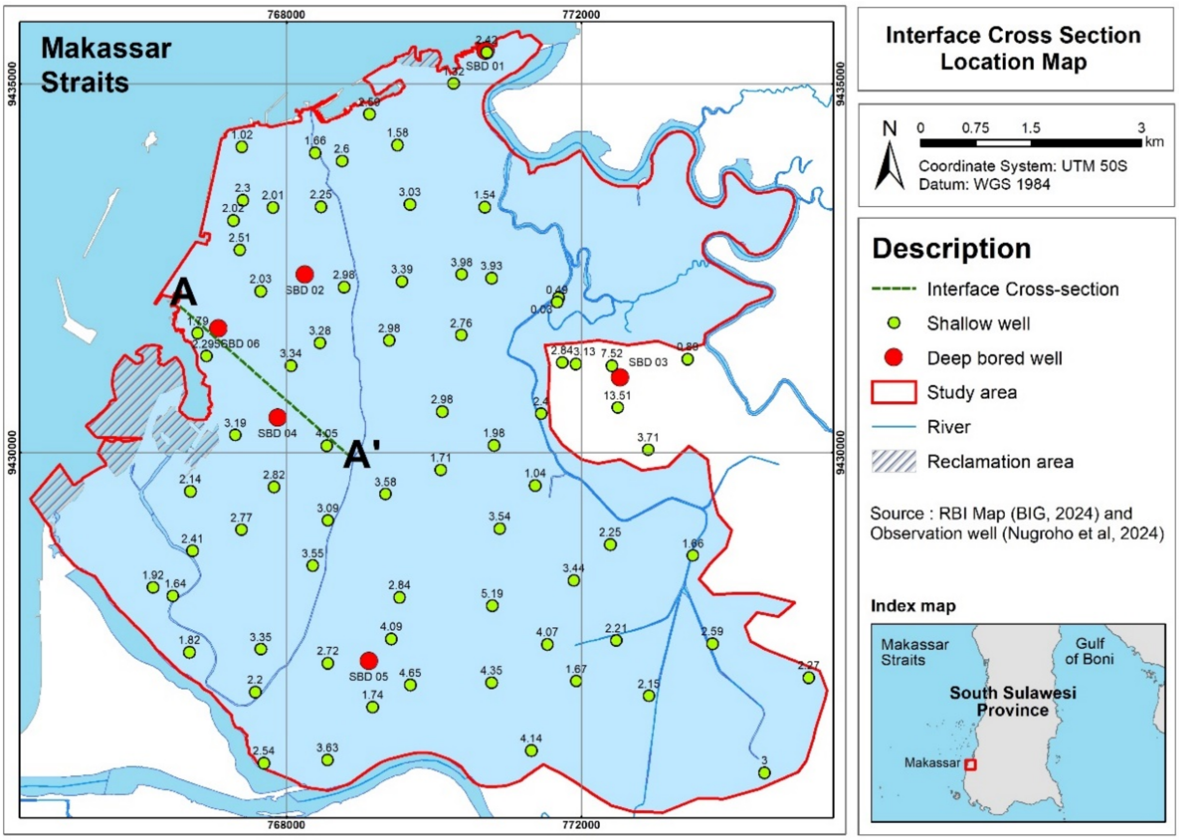

FIGURE 6. The location of the interface cross section map.

line (Q′) was performed to better understand groundwater-seawater interactions in the study area. The discharge rate was calculated using Equation 2, applying aquifer thickness and hydraulic conductivity data up to a depth of 50 meters from Nugroho (2024), with a distance (L) of 10 km. Hydraulic gradient data was derived from shallow wells. The calculated results for the two aquifers are shown in Table 5.

According to Table 5, the combined discharge from Aquifers 1 and 2 is 0.010314 m^3/s (10.31 Liters/second). This discharge rate will be compared with the groundwater usage/extraction rate to analyze groundwater overexploitation.

4.3 Cl/Br vs Cl graphical analysis

To determine the origin and evolution of brackish water, as well as mixing trends, a Cl/Br vs.

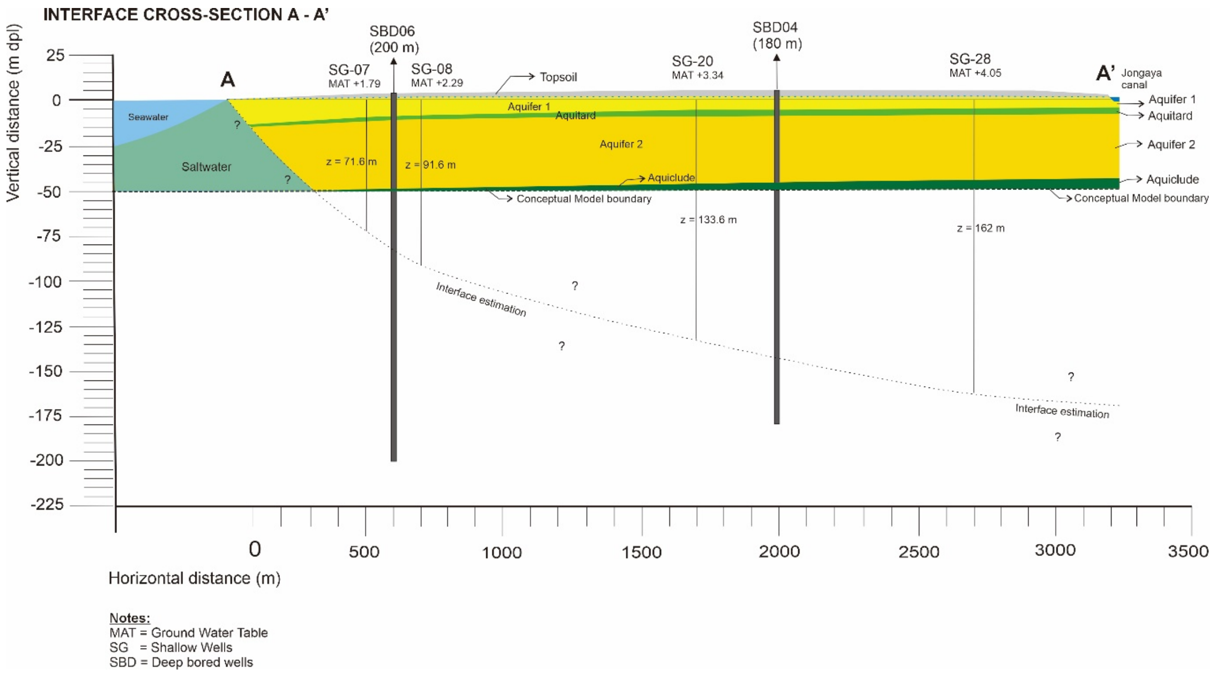

FIGURE 7. Interface cross section A–A'.

TABLE 5. Calculation of discharge per unit length.

Aquifer	Aquifer Thickness (m)	K (m/s)	Hydraulic Gradient (Δh / L)	Q' (m^2/s)	Q (m^3/s) Coastal line 9 km
Aquifer 1 (Unconfined aquifer)	20	1.40×10^{-4}	0.0003	8.40×10^{-7}	0.00756
Aquifer 2 (Semi-unconfined aquifer)	44	2.32×10^{-5}	0.0003	3.06×10^{-7}	0.002754

Cl comparison graph was used. This graph is considered suitable as it uses Cl and Br ions, which are conservative ions in seawater. The plotting results of twenty groundwater samples are shown in Figure 8. Five brackish water samples were categorized into three distinct groups: the Seawater group (SG14), the Brine Basin group (SG64), and the Landfill Leachate group (SG22, SBD04, and SBD06). The plot for the Seawater group suggests seawater intrusion, observed only in SG14.

SG64, classified in the Brine Basin group, indicates the presence of formation water, likely due to the geological history of the area, which is believed to have once been a paleo-lagoon. Meanwhile, the Landfill Leachate group, represented by three other brackish water wells (SG22, SBD04, and SBD06), suggests contamination likely stemming from anthropogenic factors, as no landfills are located nearby. This contamination is most likely due to unmanaged sanitary waste or industrial and domestic activities.

4.4 Groundwater usage perspective

The analysis of seawater intrusion based on the groundwater usage perspective is conducted by calculating groundwater usage zones and correlating it with the well location. Calculated domestic and urban water demand is based on population data from the Central Statistics Agency (2023), while industrial demand was calculated based on the number of industries and industrial water demand standards from Tables 2 and 3.

The calculation of domestic water demand is set at 150 Liters/person/day based on city population categories, with Makassar classified as

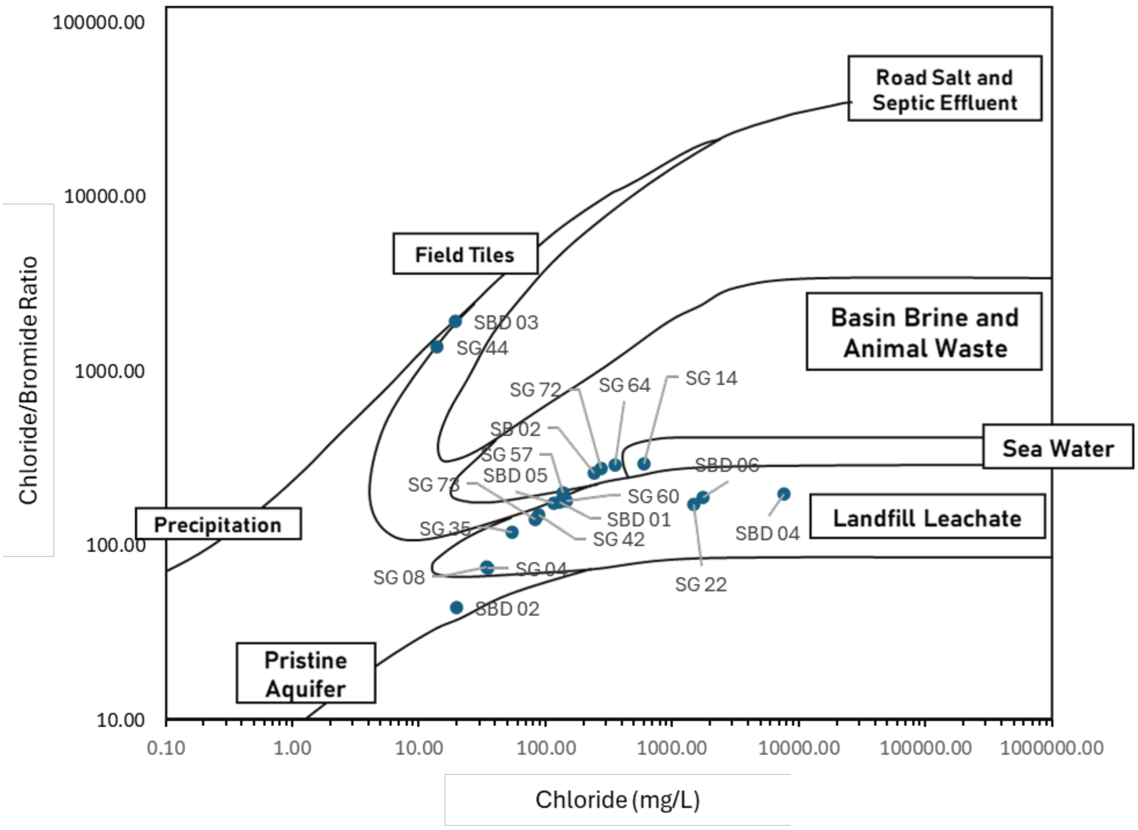

FIGURE 8. Cl/Br vs Cl comparison graph.

a metropolitan city. The urban water demand is set at 30% of domestic water usage. Industrial water demand was calculated using the South Sulawesi Manufacturing Industry Directory (Central Statistics Agency, 2023), identifying 29 medium and large-scale companies in the study area, including sectors such as garment, food, palm oil, fiberglass boat manufacturing and repair, steel, printing, plastics, zinc, concrete, and bottled water production. The population and industrial data with calculated water demand can be seen in Table 6.

The total water demand was then compared with PDAM water supply data. PDAM supplies 63,578,624 m^3/year (Central Statistics Agency, 2023), representing the total clean water distribution for Makassar, with no data available by district. To make it relevant to the study area, an estimate of PDAM water distribution by district was calculated proportionally based on population, and the results are presented in Table 7.

Based on Table 7, the estimated PDAM water supply is 48,133,389 m^3/year. There is a supply-demand gap of 31,492,712 m^3/year, which the community meets through alternative sources, primarily groundwater. Table 8 shows the detailed supply-demand differences per district in the study area. The study area's highest estimated groundwater usage levels are in Tamalate District, followed by Tallo District. The plotted map of observation well locations with the distribution of groundwater usage levels in the study area is shown in Figure 9.

SG14 is located in an area with very high groundwater usage (over 5 million m^3/year), relevant to seawater intrusion, while SG22 and SG64 are in high usage areas (1–3 million m^3/year), which also impacts seawater intrusion. The two deep bore wells in Ujung Pandang (SBD04 and SBD06) have moderate groundwater usage at 631,472 m^3/year.

Compared to the groundwater extraction rate of 998.63 liters per second, the groundwater discharge rate in the hydrogeological perspective analysis, at 10.31 liters per second, is considerably lower. Continuous extraction at this rate would significantly reduce the freshwater volume in the aquifer and accelerate seawater intrusion by shifting the interface.

TABLE 6. Population, number of industries, and calculated water demand in the study area.

Districts	Population (peoples)	Number of industries (middle and large-scale company)	Domestic water demand (m^3/year)	Urban water demand (m^3/year)	Industrial water demand (m^3/year)	Total water Demand (m^3/year)
Tallo	147,566	11	8,079,239	2,423,772	138,372	10,641,382
Ujung Tanah	36,764	2	2,012,829	603,849	24,528	2,641,206
Wajo	29,782	5	1,630,565	489,169	11,680	2,131,414
Bontoala	55,444	0	3,035,559	910,668	0	3,946,227
Ujung Pandang	23,011	3	1,259,852	377,956	6,059	1,643,867
Makassar	82,325	1	4,507,294	1,352,188	1,533	5,861,015
Panakkukang	132,600	1	7,259,850	2,177,955	1,533	9,439,338
Mamajang	58,178	2	3,185,246	955,574	5,037	4,145,856
Rappocini	149,945	2	8,209,489	2,462,847	5,037	10,677,372
Mariso	58,501	3	3,202,930	960,879	43,727	4,207,536
Tamalate	167,086	0	9,147,959	2,744,388	0	11,892,346
Manggala	100,178	0	5,484,746	1,645,424	0	7,130,169
Tamalanrea	12,830	0	702,443	210,733	0	913,175
Somba Opu	61,190	0	3,350,153	1,005,046	0	4,355
	1,115,400	29	61,068,150	18,320,445	237,506	79,626,101

TABLE 7. Estimated volume of PDAM water distribution by district.

Districts	Population (peoples)	Population with PDAM access	%	Estimated PDAM water distribution (m^3/year)	Study area Population (peoples)	Coeff.	Estimated PDAM supply (m^3/year)
Tallo	147,566	147,566	10.21	6,492,332	147,566	1.00	6,492,332
Ujung Tanah	36,764	36,764	2.54	1,617,474	36,764	1.00	1,617,474
Wajo	29,782	29,782	2.06	1,310,293	29,782	1.00	1,310,293
Bontoala	55,444	55,444	3.84	2,439,321	55,444	1.00	2,439,321
Ujung Pandang	23,011	23,011	1.59	1,012,395	23,011	1.00	1,012,395
Makassar	82,325	82,325	5.70	3,621,981	82,325	1.00	3,621,981
Panakkukang	132,600	132,600	9.18	5,833,886	132,600	1.00	5,833,886
Mamajang	58,178	58,178	4.03	2,559,607	58,178	1.00	2,559,607
Rappocini	149,945	149,945	10.38	6,596,999	149,945	1.00	6,596,999
Mariso	58,501	58,501	4.05	2,573,817	58,501	1.00	2,573,817
Tamalate	188,432	188,432	13.04	8,290,278	167,086	0.89	7,351,137
Manggala	160,466	160,466	11.10	7,059,882	100,178	0.62	4,407,444
Tamalanrea	106,262	106,262	7.35	4,675,116	12,830	0.12	564,470
Biringkanaya	215,820	215,820	14.93	9,495,244	-	-	-
Sangkarrang	14,981	-	-	-	-	-	-
Subtotal 1	1,460,077	1,445,096	100.00	63,578,624	1,054,210	-	46,381,155
Somba Opu	156,098	156,098		4,470,015	61,190	0.39	1,752,234
Subtotal 2	156,098	156,098		4,470,015	61,190	-	1,752,234
Total					1,115,400		48,133,389

4.5 Recharge area land use perspective

Groundwater recharge areas play a vital role in replenishing freshwater aquifers. Land-use changes, such as urbanization or conversion to industrial areas in these regions, can reduce rainwater infiltration, contributing to seawater intrusion through lateral encroachment. This study uses a groundwater recharge area map from Nugroho and Taufiq (2025), South Sulawesi Regional Spatial Planning Map

TABLE 8. Detailed data on the supply-demand differences.

Districts	Demand (m^3/year)	Supply (m^3/year)	Deficit (m^3/year)
Tallo	10,641,382	6,492,332	4,149,049
Ujung Tanah	2,641,206	1,617,474	1,023,732
Wajo	2,131,414	1,310,293	821,121
Bontoala	3,946,227	2,439,321	1,506,906
Ujung Pandang	1,643,867	1,012,395	631,472
Makassar	5,861,015	3,621,981	2,239,034
Panakkukang	9,439,338	5,833,886	3,605,452
Mamajang	4,145,856	2,559,607	1,586,250
Rappocini	10,677,372	6,596,999	4,080,373
Mariso	4,207,536	2,573,817	1,633,718
Tamalate	11,892,346	7,351,137	4,541,210
Manggala	7,130,169	4,407,444	2,722,725
Tamalanrea	913,175	564,470	348,705
Somba Opu	4,355,198	1,752,234	2,602,964
Total	79,626,101	48,133,389	31,492,712
			(998.6 liter/s)

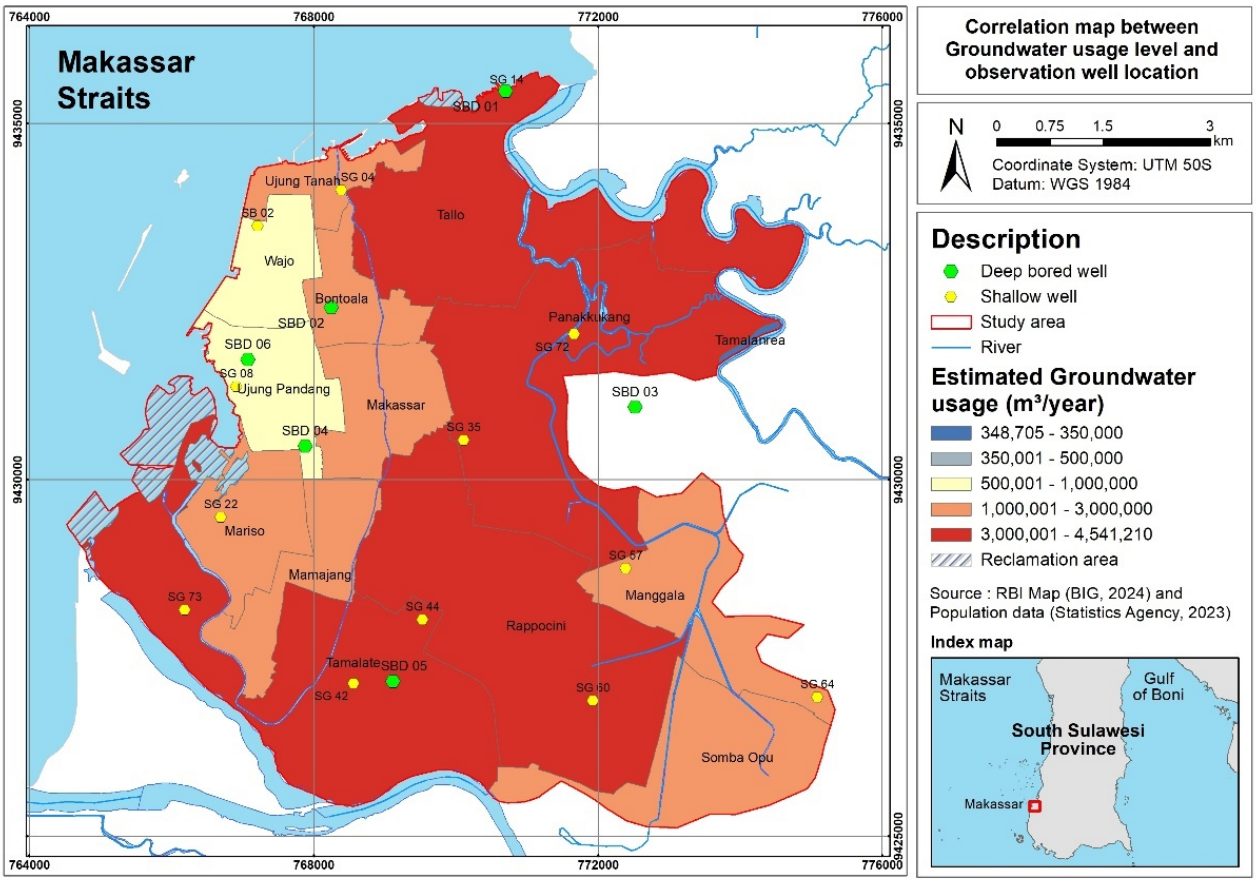

FIGURE 9. Correlation map between groundwater usage level and observation well location compared to the groundwater extraction rate of 998.63 liters per second, the groundwater discharge.

(RTRW) from the Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (ATR/BPN). It analyzes land-use changes through Land-use data (ESRI, 2017-2023).

The elevation of the groundwater recharge area ranges from 4.88 to 49.92 masl for shallow wells and from 20.75 to 37.92 masl for deep bored wells. The estimated recharge area for deep bored wells is between the Tallo and Jeneberang Rivers, specifically near point X. The distribution map of the recharge area is shown in Figure 10.

Seawater intrusion was assessed based on groundwater recharge areas by analyzing land use factors affecting infiltration, such as urbanization, agriculture, and industry. The analysis used the RTRW and ESRI data (2017–2023), with results shown in Figures 11 and 12.

Figures 11 and 12, compared to Figure 10, show that most groundwater recharge areas are classified as residential areas (RTRW) and built-up areas (ESRI, 2017–2023), resulting in low groundwater infiltration potential, especially in shallow well recharge areas. Based on this analysis, the spatial plan (RTRW) data should also consider groundwater recharge areas to support groundwater conservation, particularly for shallow wells still widely used by the community.

According to ESRI land use data, the estimated recharge area for deep bored wells around point X experienced significant changes between 2017 and 2023. Built-up areas increased by 66.30%, while areas covered by trees and bare ground decreased by 40.26% and 50.85%, respectively, as detailed in Table 9. The dominance of the built-up regions in groundwater recharge zones can contribute to seawater intrusion.

4.6 Correlation with previous Vulnerability map

Previous studies on seawater intrusion in Makassar, including the GALDIT (Safitri, 2016) and a modified GALDIT, named G-ALDIT and G-ALDITLcR (Damayanti & Notodarmojo, 2021), produced groundwater vulnerability maps to seawater intrusion for unconfined aquifers. Observation well locations were plotted to assess the correlation between them. The plotting results indicate that, of the three shallow well/unconfined aquifer samples with brackish water types, only SG14 aligns with the high vulnerability zone, according to Safitri (2016) and Damayanti and Notodarmojo (2021). In contrast, SG22 is located in a low-vulnerability zone, and SG64 falls in a non-vulnerable area (Safitri, 2016). In the study by Damayanti and Notodarmojo (2021), both locations lie outside the research area.

Table 10 summarizes the seawater intrusion analysis for five groundwater samples with brackish characteristics. Among these, sample SG14 in Tallo District is confirmed to exhibit seawater intrusion based on multiple parameters. The seawater intrusion distribution map for shallow and deep bored wells at each observation point in the study area is displayed in Figure 13.

5 Conclusion

Based on the results and discussion, it can be concluded that among the groundwater samples with brackish water types, one sample was identified as being affected by seawater intrusion based on geological, hydrogeological, Cl/Br vs Cl graphical analysis, groundwater usage, recharge area land-use, and previous vulnerability mapping in the study area. This well is located in the Tallo district within an unconfined aquifer/shallow wells. Other brackish water samples are not seawater intrusion as they fall into the formation water group (brine basin) and show the influence of anthropogenic contamination resembling landfill leachate, as seen in the Cl/Br vs Cl. It is necessary to implement sustainable groundwater management practices, such as controlling groundwater extraction rates, enhancing surface water usage, and maintaining recharge areas to prevent the expansion of seawater intrusion and the decline in groundwater quality. These strategies can help protect coastal aquifers and mitigate the risks of further seawater intrusion.

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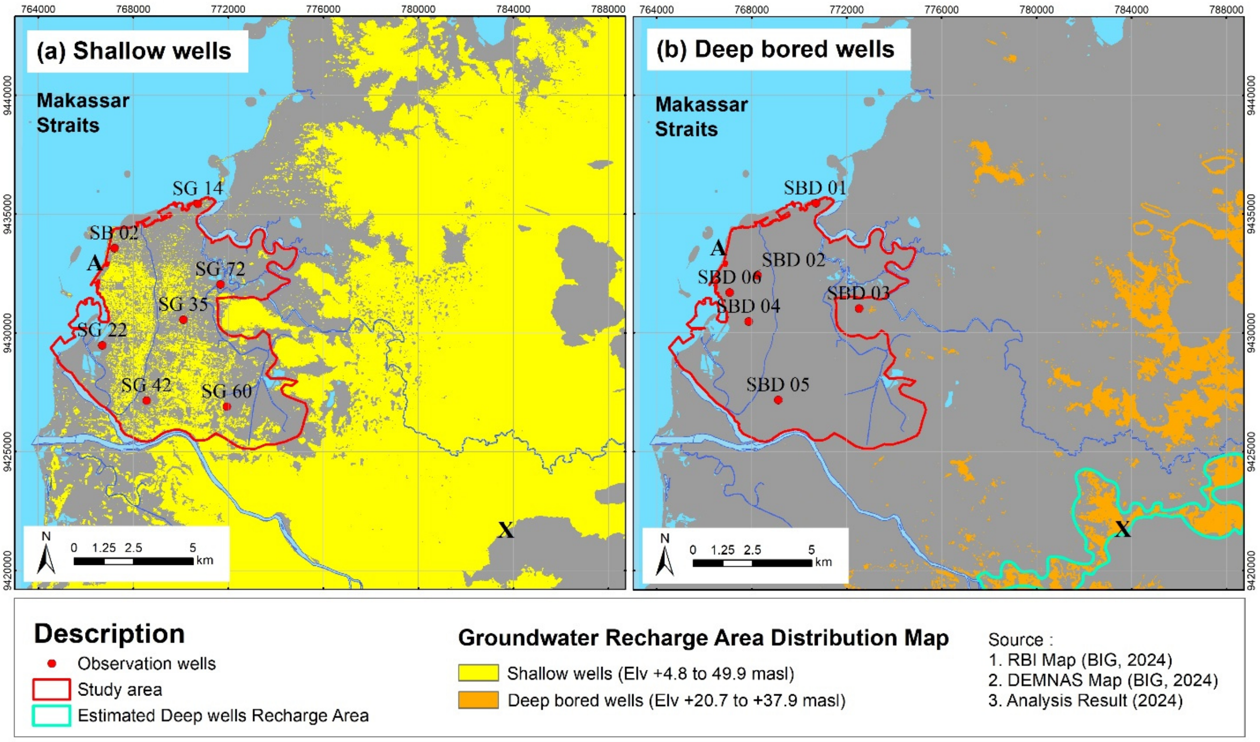

FIGURE 10. The distribution map of the groundwater recharge area.

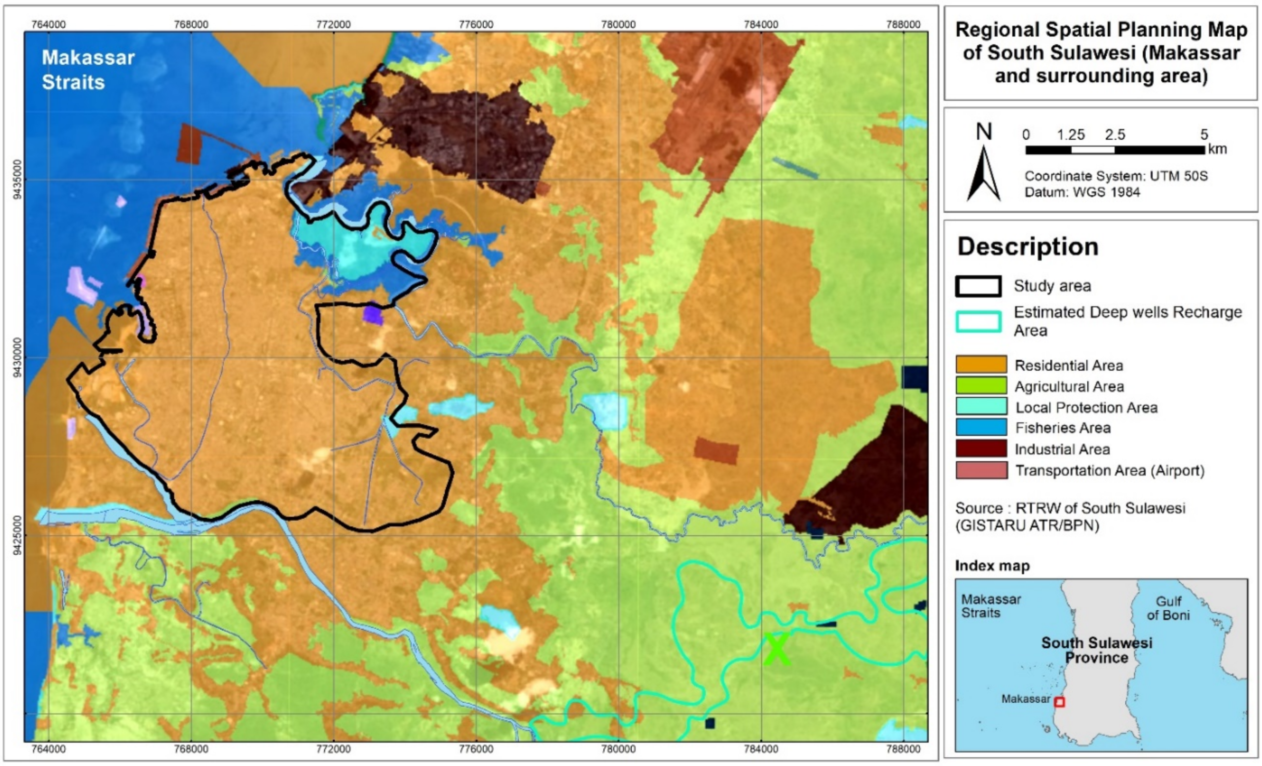

FIGURE 11. Regional spatial planning map of South Sulawesi (GISTARU ATR/BPN) .

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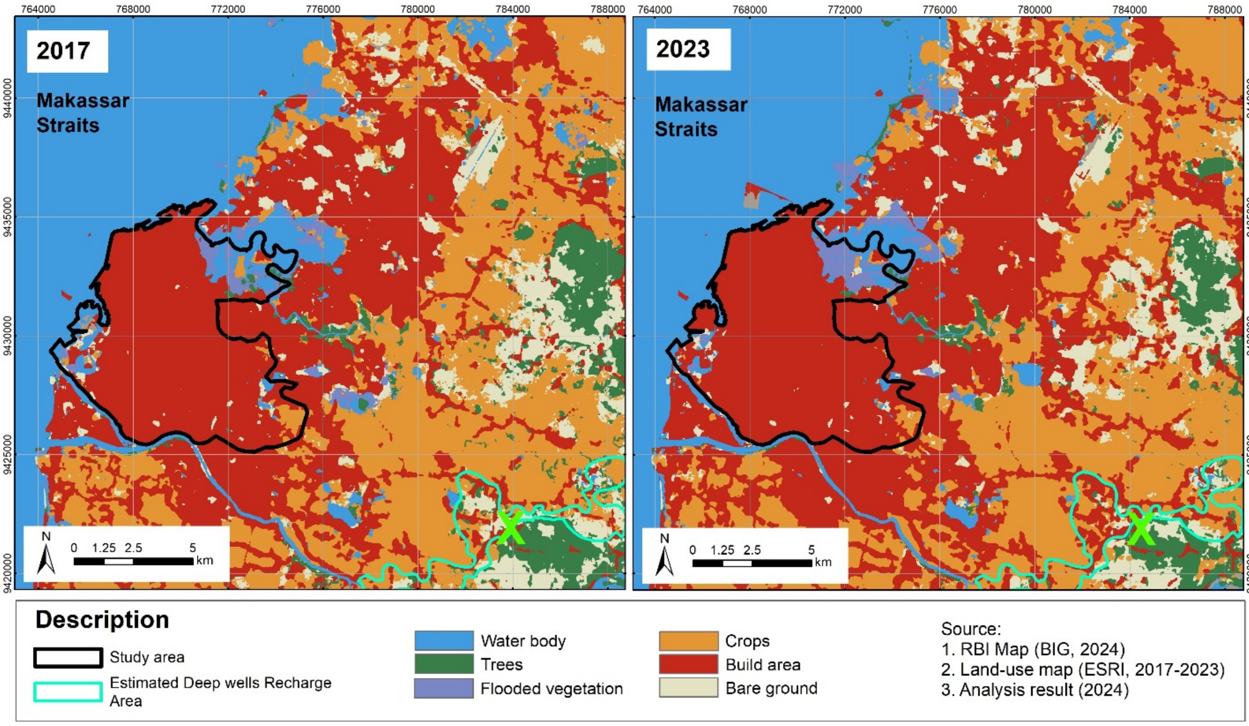

FIGURE 12. Analysis of land use change in groundwater recharge area.

TABLE 9. Summary of seawater intrusion analysis result.

Type of landuse	2017 area (km^2)	2023 area (km^2)	Change area (km^2)	%
Waterbody	0.10	0.11	0.01	7.68
Trees	1.72	1.03	-0.69	-40.26
Crops	6.19	6.69	0.50	8.08
Build area	3.75	6.23	2.48	66.30
Clouds	0.02	-	-0.02	-
Bare ground	4.47	2.20	-2.27	-50.85

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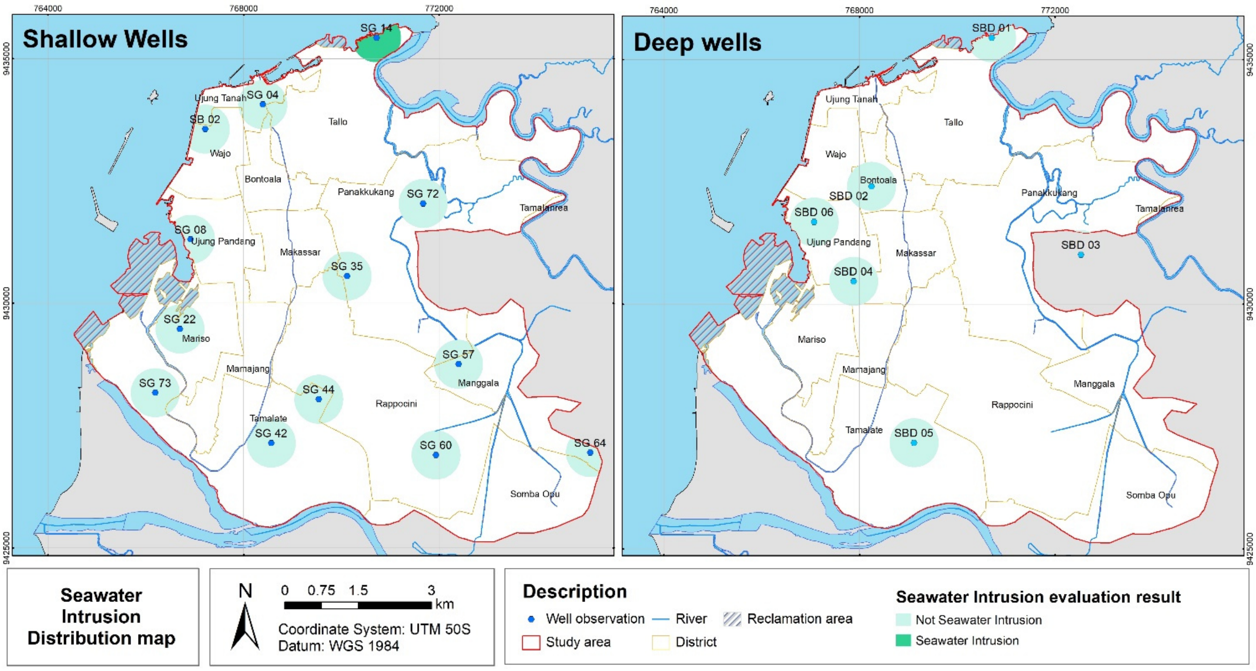

FIGURE 13. Seawater intrusion distribution map.

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TABLE 10. Summary of seawater intrusion analysis result.

Brackish sample	Geological perspective	Hydro-geological perspective	Cl/Br vs Cl Graphical Analysis	Ground-water usage	Recharge area land use	Previous vulnerability map	Analysis result
SG14 (Tallo)	-	The local groundwater flow pattern is not related to the indication of a shallow sea.	Seawater	Very High	Most of the land use in recharge areas for unconfined and semi-confined aquifers con-sists of built-up areas, reducing infiltration and leading to lateral seawater intrusion.	High vulnerable	SWI[a]
SG22 (Mariso)	Trapped marine sediment (delta evolution)	The local groundwater flow pattern indicates shallow sea	Landfill Leachate	High		Low vulnerable	Not SWI
SG64 (Manggala)	Trapped marine sediment (ancient lagoon)	The local groundwater flow pattern indicates shallow sea	Brine Basin				
(air format)	High	Not vulnerable	Not SWI				
SBD04 (Ujung Pandang)	-	-	Landfill Leachate	Moderate		-	Not SWI
SBD06 (Ujung Pandang)	-	-	Landfill Leachate	Moderate		-	Not SWI

[a]SWI = Seawater intrusion