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Surface Groundwater Pollution Dynamics Over 2015-2020 in the Salt Drying Pond of Pademawu Subdistrict, Madura, Indonesia

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ABSTRACT

Pamekasan coastal area is the center of salt production concentrated in the Pademawu subdistrict with the ponds area of 740.96 ha. The sufficiently close distance of salt ponds to settlement areas allows several issues, such as shallow groundwater salinization. This study aimed to determine the salt pond's degradation over five years (2015-2020) and its influence on the salinization issue in Pademawu. We compare groundwater quality parameters (conductivity, TDS, the depth of shallow surface groundwater, and salinity) surveyed in 2015 and 2020, correlated to salt pond area alterations. Over five years of measurement, it was found that conductivity declined, reaching 2779.94 µS/cm. Based on TDS deterioration, groundwater transformed from brackish to freshwater in 2020. By contrast, the depth of shallow groundwater-surface increased by almost one meter. The freshwater area also increased by 22% over five years based on conductivity classification. Groundwater quality dynamics are related to the alteration of the salt pond area. On the other hand, the significant increase in rainfall intensity, which is not beneficial for salt agriculture, results in the salt pond area deterioration, thereby declining surface groundwater salinity in Pademawu due to the less interaction between Cl and groundwater within aquifers. Although the groundwater pollution induced by seawater intrusion and salinization declined in 2020, re-organizing the distance between salt ponds and the settlement area in Pademawu is crucial to minimize further groundwater pollution.

Keywords : Dynamics; pollution; groundwater; salt agriculture; Pademawu

1. Introduction

Groundwater is the most significant resource globally (Huizer et al., 2018). However, freshwater resources in the coastal area are limited due to seawater intrusions induced by over-explored groundwater and sea-level rise (Ferguson & Gleeson, 2012). Coastal groundwater is susceptible to salinization, both developed naturally and induced by anthropogenic activities (Michael et al., 2017). Coastal groundwater salinization due to seawater intrusion becomes the primary concern of safe groundwater utilization (Gopinath et al., 2018). Groundwater salinization and pollution issues critically impact the environment and socio-economic sectors, especially in dense areas (Abu-alnaeem et al., 2018).

Groundwater pollution in the coastal area is mainly caused by seawater intrusion. Moreover, over-explored groundwater also exacerbates the quality of freshwater for daily consumption (Selvam et al., 2018). On the other hand, anthropogenic activities also play a significant role in polluting shallow groundwater aquifers, such as household, agriculture, and husbandry waste directly impacting the low quality of groundwater. The presence of salt agriculture is currently reported to enhance salinity in settlement artesian wells due to infiltration processes of saltwater to the shallow aquifer (Gemilang et al., 2017; Gemilang & Bakti, 2019).

The excellent salt drying pond center is situated in Pamekasan Regency, Madura, Indonesia. Salt productions in the southern Pamekasan Regency are concentrated in Galis, Pademawu, and Tlanakan Subdistricts because these three areas are directly facing the flat beach easing the transfer of seawater to salt ponds by utilizing tidal regimes (Efendy et al., 2014). The Pademawu area is transformed from a spacy area to a center of salt agriculture with 740.96 ha. The main issue is coastal zone management, where salt ponds are too close to the settlement area (Citrayati et al., 2008).

The salt drying pond area that is contiguous with settlement areas in Pademawu results in several environmental issues. Local people reported that artesian wells near the settlement area tend to get saltier (Gemilang et al., 2019). Therefore, systematic identification of salinization zone dynamics is crucial as an initial step to decide how to reduce salinization processes on shallow groundwater in the surrounding salt ponds of the Pademawu Subdistrict.

Salinization on groundwater can be assessed based on conductivity because the more the salt electrolyte is contained in water, the higher the conductivity value. That is why conductivity can reflect the ionized salt in water (Ruseffandi & Gusman, 2020). Assessments of groundwater pollution considering water contamination, topography, geological settings, and pollution sources had been established (Azlaoui et al., 2021; Duraisamy et al., 2019; Ilayaraja & Ambica, 2015; Nas & Berktay, 2010). However, spatial determination of groundwater pollution caused by salt drying pond is rarely studied. Additionally, the temporal correlation between groundwater conductivity and salt pond area alteration should be investigated to figure out the impact of salinization. Therefore, this study aims to determine the influence of salt agriculture on shallow groundwater states in the Pademawu Subdistrict and its surrounding. This study is expected to be a basis for future decision-making of salt pond management to prevent groundwater pollution and salinization in the coastal area of Pademawu.

2. Study Area

The study site is situated in the coastal area of Pademawu Subdistrict, Pamekasan Regency, Madura, Indonesia, conterminous with Galis, Tlanakan, and Larangan Subdistricts (Figure 1). The research location was focused on the settlement areas in the surrounding salt pond of Pademawu Subdistrict, geographically positioned at 7° 14' 18,0" South and 113° 31' 48,5" East. Additionally, the study area is positioned between 0-15° slope with a total area of 7,189 ha.

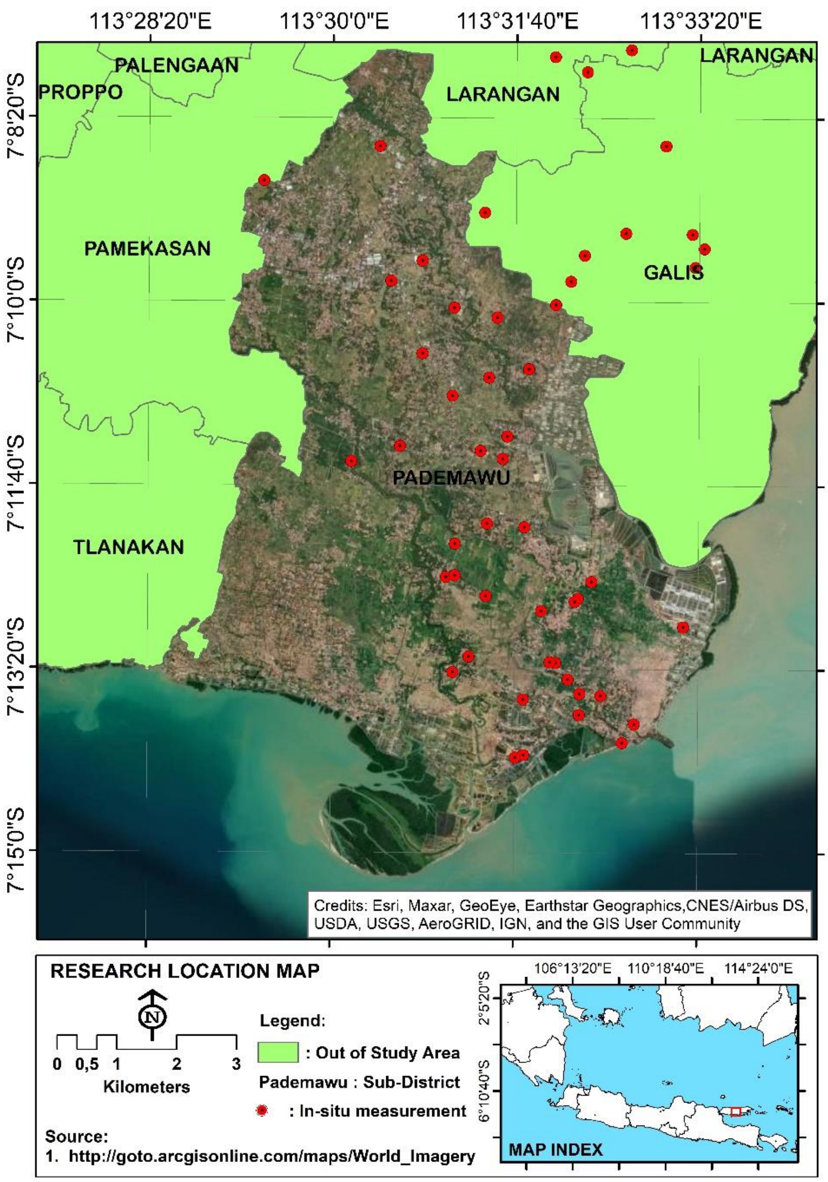

Figure 1. Study area and sampling site in Pademawu Subdistrict

3. Methods

Mapping and sampling groundwater were conducted on 37 observation stations in artesian and production wells (unconfined aquifer). Physical parameters measured were the depth of surface groundwater, conductivity, pH, and temperature, surveyed using *handy water checker Toax*, a portable instrument equipped with sensitive censors for measuring pH, conductivity, temperature. This technique is generally used for various environmental-related studies, diminishing the possibility of other contaminations of water samples while sampling (Gemilang et al., 2017; Kusumaningtyas et al., 2014; Nagano et al., 2003).The positions were also recorded using a GPS and mapped using *ArcGIS 10.10.* Data were collected in situ measuring shallow groundwater in Pademawu and its surrounding with the well's depth of approximately 1.9-23.9 meters. Several surveys were conducted in March 2015 and December 2020. Sampling stations were chosen based on geological settings, surface groundwater, and the distance from the coastline (Martin et al., 2007; Yusuf & Abiye, 2019).

Groundwater quality analysis was done by comparing the modified conductivity classifications gained from previous studies (Cahyadi et al., 2017; Moayedi et al., 2019), TDS (Kumar et al., 2015) (Table 1 and Eq. 1), and pH (Permenkes RI, 2010). In contrast, seawater intrusion was approached from standardized conductivity and temperature values because every 1°C increase in temperature, conductivity will enhance by 2% (Razeghi, 2018). The standard temperature used in this study was 25°C because, according to the environmental health standard, ionized water will become a conductor at 25°C temperature (Permenkes RI, 2010). Thus, groundwater conductivity surveyed in the field was converted using the Eq. 1 :

$$DHL_{25} = DHL_t + (\Delta t + 0.02 x DHL_t) \quad (1)$$

Where:

DHL_{25} = Conductivity within 25°C temperature

DHL_t = Conductivity within °C temperature

Δt = water temperature in °C

Table 1. Groundwater classification based on TDS value

Category	TDS (mg/l)
Freshwater	0 – 1000,00
Brackish	1000,01 – 10.000
Saline water	10.000.01 – 100.000

Source: Kumar et al. (2015)

The distribution of groundwater salinization was interpolated using *Inverse Distance Weighted* (IDW) method based on seawater intrusion classification against conductivity (Muchamad et al., 2017) (Table 2) and salinity (Todd, 1981) (Table 3). Groundwater salinization and surface elevation were statistically analyzed using regression analysis to determine a correlation between conductivity, coastline distance, and surface groundwater depth. The conductivity distribution was overlayed with the salt agriculture area alteration over five years (2015-2020).

Table 2. Groundwater classification based on conductivity

Category	Conductivity (µS/cm, 25°C)
Freshwater	<1.500
Slightly brackish water	1.500 – 5.000
Brackish water	5.000 – 15.000
Saline water	15.000 – 50.000
Brine (connate)	>50.000

Source : Klassen et al. (2014) ; Muchamad et al. (2017)

Table 3. Groundwater classification based in salinity (Todd, 1981)

Salinity (‰)	Category
<0.05	Freshwater
0.05-3.00	Brackish water
3.00-5.00	Saline water
>5	Brines

4. Results and Discussion

4.1 Geological and hydrogeological settings

Geomorphologically, the study area is composed of flat relief morphology and an alluvial area directly facing the ocean (Madura Strait) (BPS, 2018). The arranging lithology consists of several rock formations; alluvial deposits (Qa), Pamekasan formation (Qpp), Madura formation (Tpm), and Ngrayong formation (Tmtn) (Figure 2) (Situmorang et al., 1992).

The study area is predominated by alluvium sediment deposits (Qa) consisting of coarse sand, clay-gravel, and pebble materials. These compositions are found in the southern study area nearby the coastline. There are 12 main rivers in the study area, ranging from 1-16 km. According to hydrogeological map sheet VIII Surabaya (Java), the study area is composed of alluvium deposits lithology consisted of clay and sand deposits, containing organic materials in the form of coralline limestone with poorly medium sortation (Poespowardoyo, 1986).

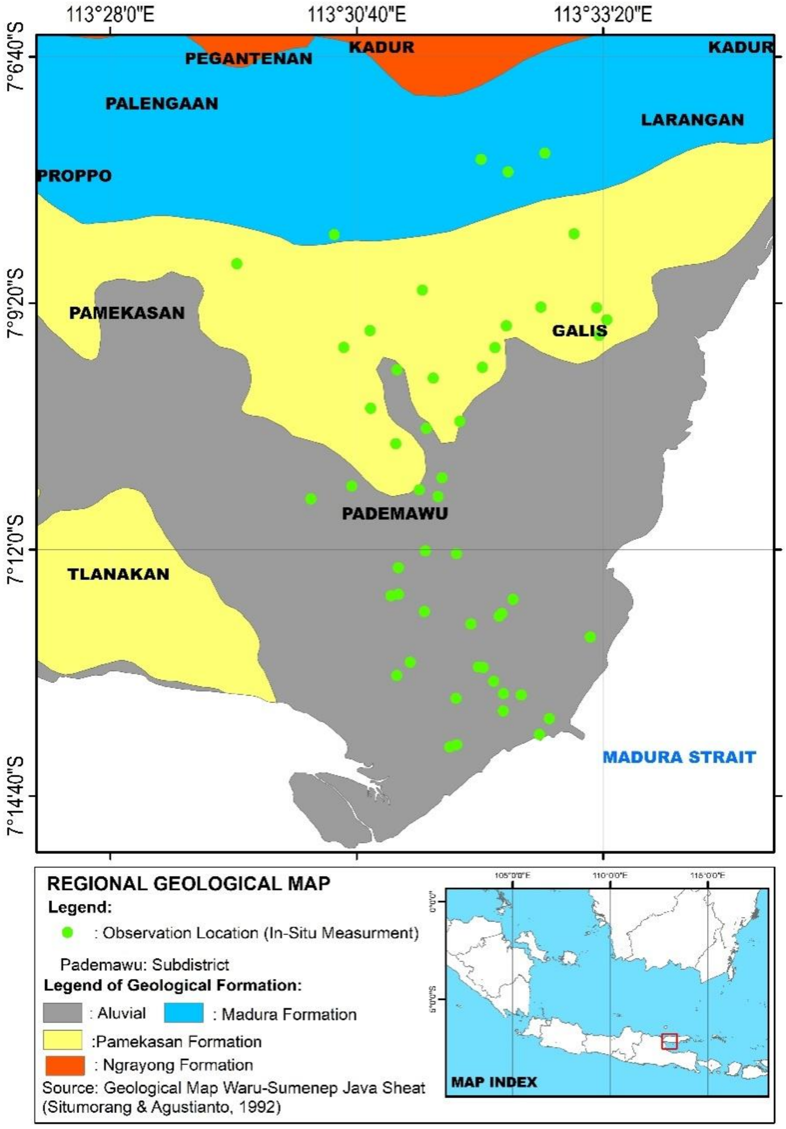

Figure 2. Regional geological map of study area

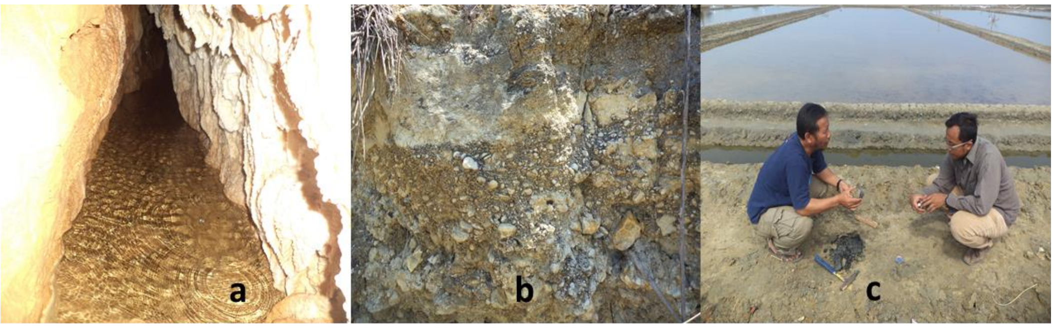

Figure 3. Lithology-arranged aquifer of study area, A. Madura formation,
B. Pamekasan formation, C. Alluvial deposits
Source: Gemilang et al. (2019)

In Pademawu Subdistrict, the aquifer is categorized to small productivity with a rare groundwater source. Caves in the northern study area become a media of dissolved limestone flow. Moreover, in the north of Pademawu, several artesian wells exist located right underneath the high-productivity underground river. In the trough and compacted rock zones, groundwater resource is also limited to be gained (Krishnamurthy et al., 2000).

Based on the arranging lithology, the depth of surface groundwater in the study area varies considerably. In the area arranged by alluvial deposits lithology, the depth of surface groundwater ranges from 1.98 to 7.2 m. While in the area arranged by Pamekasan formation (Qpp), the depth ranges from 7.26 to 15.95 m. Toward the north, the depth of surface groundwater is gradually getting deeper with a limestone lithology in Madura formation (Tpm) approximately 15.95-27 m. In the south, the lowland morphology was identified. In contrast, the highland morphology is a hilly, mountainous area (Figure 3a).

Several water sources and artesian wells in the north are utilized for production wells. Above the limestone aquifer, there are deposits of Pamekasan formation in the form of sandstone and limestone yielded from older rock weathering (Figure 3b). Alluvial deposits can be found in the coastal area, predominated by river or coastal deposits and weathered sandstone, silt, and clay (Figure 3c). Brackish and saltier groundwater couldbe found in the surrounding alluvial deposits, while in the higher elevation area, the groundwater tended to be categorized as freshwater (Yusuf & Abiye, 2019).

4.2 Shallow groundwater quality dynamics in Pademawu and its surroundings

The area is arranged by alluvial deposits, composed of 1.8-10 m depth of surface groundwater. While for Pamekasan formation-dominated area (Qpp), the depth ranged from >5 to <15 m. In the north, limestone lithology was predominant in the Madura formation (Tpm) with a depth of >10- >15 m. It was found that in the north, the depth of shallow groundwater measured in the sampled artesian wells significantly decreased over five years (2015-2020) and vice versa for the southern area with an enormity of around one meter (Figure 4).A previous study (Gemilang et al., 2019), defined the depth of surface groundwater in the south (alluvial) of Pademawu ranged from 1.98 to <8 meters, in the middle (Qpp) and in the north (Tpm) ranged from 7.26 to15.95 meters and 15.95 to 27 meters, respectively, indicating the deeper surface groundwater level in the south of Pademawu deteriorated over times.

In the south, a low productive aquifer-induced groundwater extinction is predominated and categorized to brackish-saline groundwater type (Poespowardoyo, 1986). It sources from shallow groundwater in the surrounding settlement and salt drying pond area, intensively influenced by rainfall, riverine water, and the other anthopogenic activities (Gemilang et al., 2019; Gemilang & Kusumah et al., 2017). The depth of surface groundwater is the most significant parameter to determine the aquifer vulnerability level induced by salinization and the presence of salt drying pond (Gemilang et al., 2017).

The alteration of surface depth relates to salt infiltration to groundwater. Twenty-two observation points showed the decline in surface depth (getting shallower) with an average of -0.806 meters, while the remnant 27 observation points showed an opposite condition whereby the surface depth is getting deeper with an average of 0.974 meters. Overall, the sampled artesian wells showed an increasing depth of approximately 0.312 meters. A significant increase in surface depth was observed in the north, reaching 1.61 meters. However, several stations were getting shallower, approximately -1.78 meters.

The spatial comparison of surface groundwater depth between 2015 and 2020 is shown in Figure 5. The depth of surface groundwater in the south, where salt ponds-surrounded coastline does exist, decreased over five years (2015-2020) with an enormity of 1.9 meters. In contrast, the depth of surface groundwater ranging from 5-10 meters expanded in the middle and north of the study area.

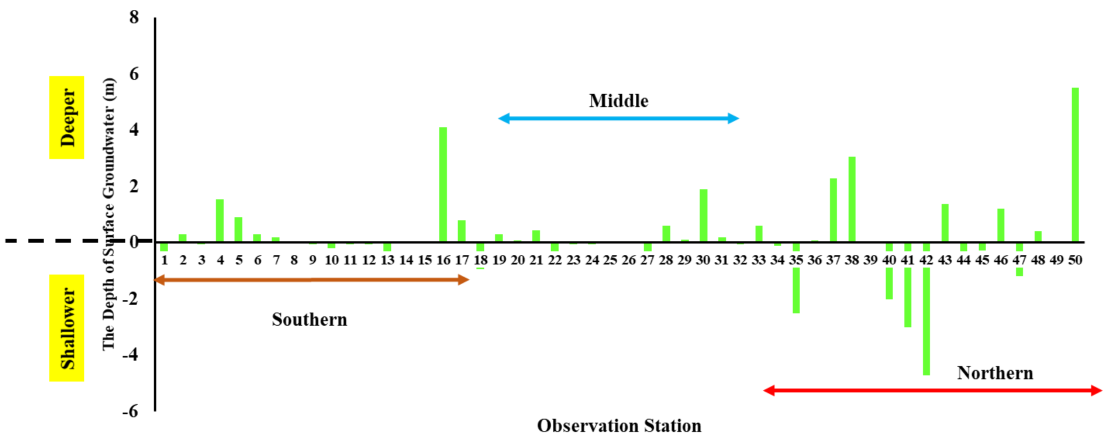

Figure 4. The dynamics of gorundwater surface in 2015 and 2020

The depth of surface groundwater >10 meters found in the northern study area is supported by the hilly mountainous topography characteristics, which is higher than the south area. Higher topography could reduce the retaining ability of contaminants polluting groundwater aquifer, even though the arranging rock is good in porosity. Furthermore, due to the depth of surface groundwater >10 meters, the depth of local artesian wells should be more profound, resulting in more retained contaminants within aquifers (Putranto, 2019).

The rate of contaminant-polluted shallow groundwater relies on elevation and the depth of surface groundwater. Deeper surface of groundwater results in the less contaminated groundwater and vice versa for the shallower surface of groundwater. It relates to groundwater pollution issues in the study area where the shallow surface groundwater allows salt content from salt ponds to infiltrate into the unconfined groundwater aquifer.

Salinity concentration in the study area ranged from 0.03 to 3.32% in 2015 and 0.003 to 2.13% in 2020, respectively. The average enormity of salinity values over five years (2015-2020) was 0.12%, with a higher deviation of 1.64% found in the south of the study area. Over the southern Pademawu Subdistrict, the salinity level generally lowered by 0.25%. While in the middle and north, the alteration of salinity was not too significant, only 0.01-0.02%. The increase in groundwater salinity is induced by mixing pollutants and freshwater contained in aquifers. By contrast, the decrease in salinity level in 2020 showed the decline in groundwater pollution in aquifers (Pinder, 2011).

According to groundwater classification based on salinity values, 17% of groundwater samples were freshwater, while the remnant samples were brackish water (Todd, 1981). The freshwater indication was observed in the north of the study area. In contrast, brackish water was identified in the southern study area (nearby salt ponds and coastline).

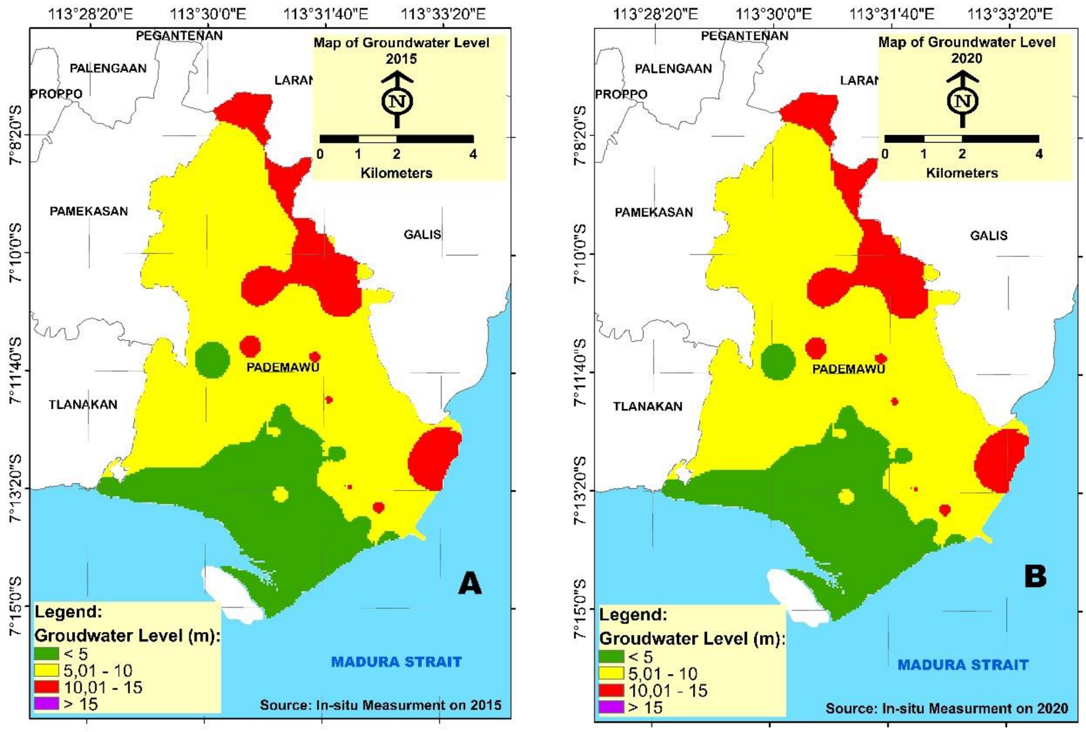

Figure 5. Spatial distribution of the depth of surface groundwater in 2015 (a) and 2020 (b)

In addition to pH parameter, it ranged from 6.88 to 8.21 in 2015 and 6.56 to 7.49 in 2020, respectively. According to the standard established by Ministry of Health No.492/MENKES/PER/IV/2010 (Permenkes RI, 2010) about water quality for drinking, pH states in the study area are still allowed for daily consumption. However, the decrease in pH of around 0.3 could be caused by the lack of instrument accuracy more/less 0.05. Therefore, a slight decline in pH could not indicate water pollution. Another consideration is due to the nature of the study area where anthropogenic and natural states could possibly determine pH values (Wisha et al., 2017). Over five years, the highest decrease in pH was 0.42, observed in the south, while in the middle and north of the study area, the decline was approximately 0.15-0.37.

4. 3 The alteration of spatial salinization in Pademawu

Higher concentration of dissolved salt that could be ionized, triggers the increase in conductivity, resulting in more brackish-saline water predomination in groundwater (Ruseffandi & Gusman, 2020). The average conductivity value surveyed from artesian wells in 2015 was 6303.5 µS/cm, while in 2020, it lowered by around 2780 µS/cm. In several artesian wells, the conductivity declined over five years with an average of 2779.94 µS/cm. Spatially, brackish, and saline water distribution showed an alteration over five years (Figure 6). An extensive brackish area was observed in the south in 2015, while in 2020, the area was narrowed and altered, becoming a slightly brackish groundwater area.

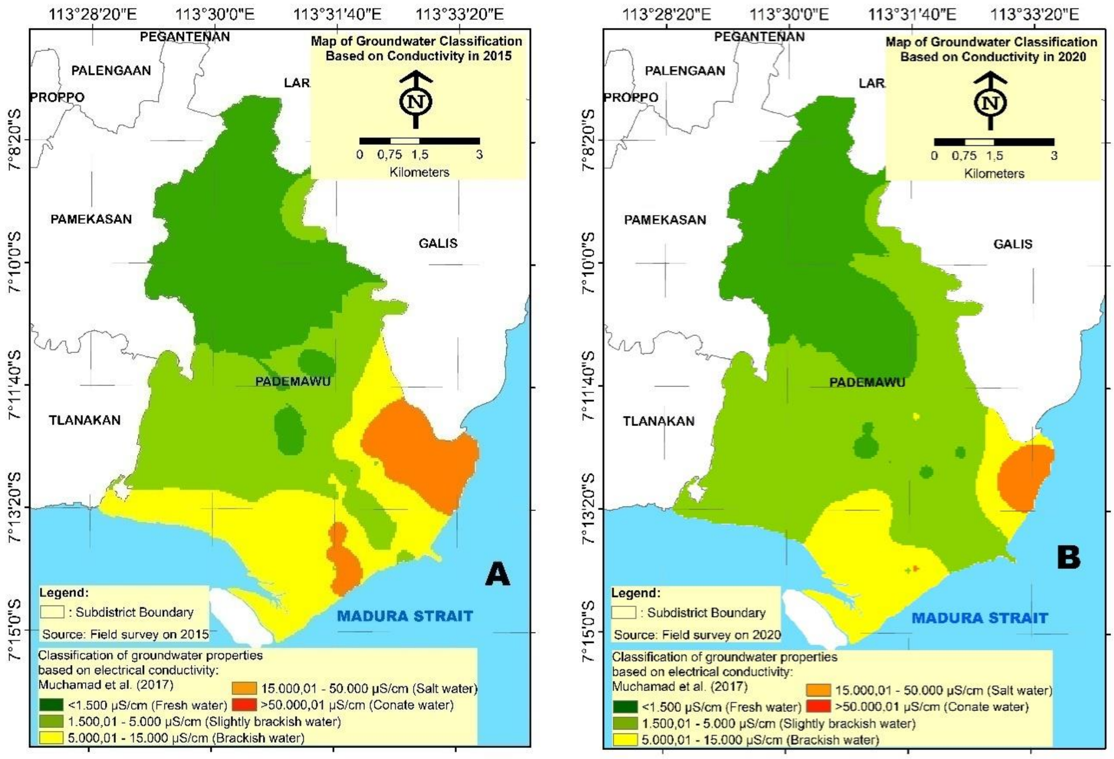

Figure 6. The spatial degradation of groundwater characteristics in 2015 (a) and 2020 (b)

Groundwater classification based on conductivity showed that slightly brackish water was predominant in the south of 63% in 2015 and 2020. In contrast, groundwater is composed of freshwater in the middle and north of the study area. A significant increase in freshwater predomination was identified in the middle of the study area, approximately 22%. However, in 2020, an anomaly was observed in the south of Pademawu, where the domination of freshwater lowered by 20%, becoming a slightly brackish water (Figure 7).

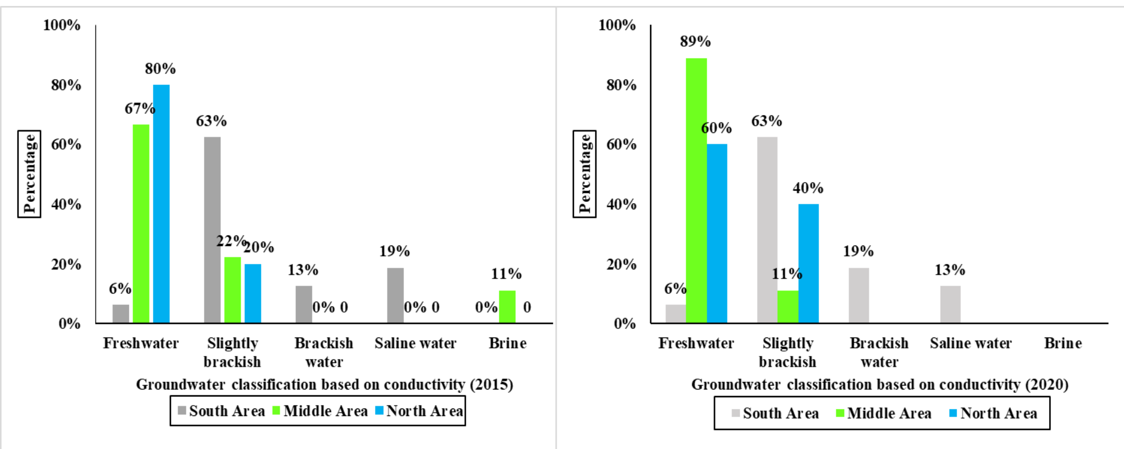

Figure 7. The dynamic of groundwater characteristics in Pademawu Subdistrict

Each type of groundwater has a specific adaptation to TDS in solid materials, ions, compounds, and colloids contained in water. TDS value relies on ion concentrations in water (Kumar et al., 2015). In 2015, TDS ranged from 1013.11 to 1587.58 mg/L with an average of 1065.22 mg/L, categorized as brackish water. In the surrounding salt drying ponds area, the TDS value was >1300 mg/L, while TDS ranged from 1013 to 1020 mg/L in the middle and north of the study area. These indicate that the presence of salt drying ponds area played a role in influencing groundwater quality in the study area.

In 2020, TDS was found in two categories: freshwater and brackish water (Figure 8). In the south of the study area, TDS was >100 mg/L and gradually decreased by <1000 mg/L in the north. TDS value measured in 2020 ranged from 17.7 to 4420 mg/L with an average of 1043.27 mg/L. Based on spatial interpolation, brine water category was found in the south up to the middle of the study area. On the other hand, in 2015, the TDS value exceeded the standard allowed for drinking, however, in 2020, 26% of groundwater met the quality standard (Permenkes RI, 2010).

The solid material contamination of groundwater depends on several factors, such as environmental condition, lithology, and rock formation in aquifers. TDS concentration is supposed to be linear with conductivity (Matahelumual, 2010). The interpolation results of conductivity and DHL in 2015 and 2020 showed the same groundwater characteristic zones where brackish-saline and brackish water can be found in the south of Pademawu.

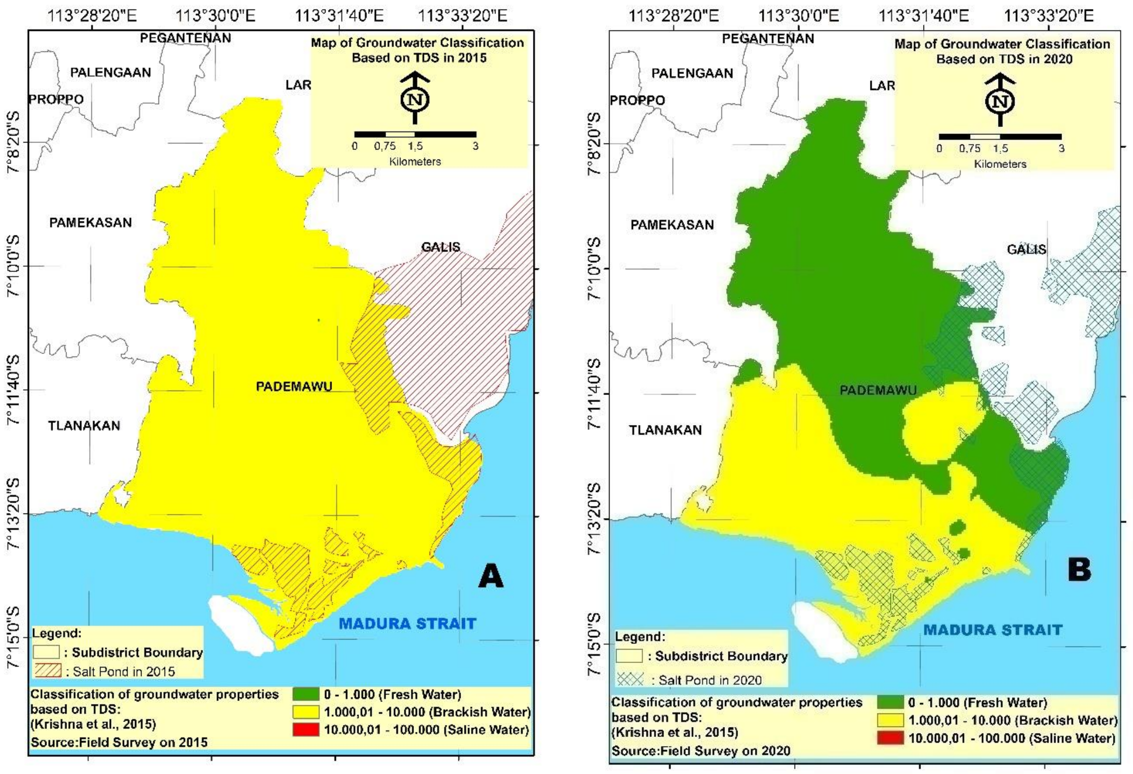

Figure 8. Spatial distribution of groundwater salinization zone in Pademawu in 2015 (a) and 2020 (b)

4.4 Land-use changes in the salt agriculture area

The alteration of the salt pond area in 2020 was observed in the southeastern coastal area of Pademawu (Figure 9). The salt pond's subtraction positively impacts groundwater, whereby groundwater pollution and salinization should decline. The presence of salt drying ponds in Pademawu tremendously relates to the state of shallow groundwater, which previously became a local strategic issue in reducing groundwater pollution in Pademawu. The relation of land use changes to groundwater pollution could also be approached from conductivity states.

According to conductivity overlay in Figure 9, the conductivity in 2015 showed a brackish up to saline water predomination (Figure 10a) (Gemilang et al., 2019).The southern study area is the widest salt drying pond in 2015 with the water conductivity ranging from 15,000 to 50,000 $\mu S/cm^2$ (saline water). The ratio of Na/Cl <1 was caused by salt pond-polluted groundwater in the surrounding shallow artesian wells (Gemilang et al., 2019). The alteration of salt drying pond area in 2020, based on Na/Cl ratio and conductivity correlation in 2015, indicated that the deterioration of salt pond area could control the conductivity states in Pademawu. Higher conductivity shows the amount of organic materials and minerals infiltrating as the waste for shallow groundwater (Ruseffandi & Gusman, 2020).

In contrast, groundwater zonation has changed in the area predominated by a slightly brackish water category in the southern Pademawu (Figure 10b). The degradation of these groundwater categories interprets that the changes in the area of salt ponds played a significant role in reflecting groundwater salinization. Additionally, the area of salt pond decreased in 2020 compared to 2015. Theoretically, seawater should have a higher conductivity due to a plethora of chemical compounds. The decrease in the salt pond area results in the less the conductivity level, clearly shown in the overlaid salt pond area of 2015-2020.

According to the recorded weather data, compared to a record in 2015, a significant increase in rainfall intensity was observed in 2020, reaching 640.48 mm/year, while the rainfall intensity was 90.75 mm/year in 2015, with dry period was commonly occurred in May to November (Figure 11). Higher rainfall intensity occurred in 2020, forcing salt farmers to substitute salt pond's activities to become vegetable gardens or deactivate the salt ponds instead. That is why the area of salt drying ponds in Pademawu generally decreased in 2020.

The increase in rainfall in the study area correlates with the decrease in land use for salt drying pond in 2020. Moreover, higher intensity of rainfall causes salt pond water dilution containing a high concentration of Cl, so interactions between Cl and groundwater will also decline. That is why the conductivity and salinity tended to get lower in 2020 compared to 2015. The value of Cl determined the anion compound predominating the study area with an average of 453.84 mg/L in 2015. The maximum Cl concentration was observed throughout Pademawu coastline where salt drying pond area does exist (Gemilang & Bakti, 2019). This makes a consideration that the origin of Cl is yielded from salt deposit infiltrating groundwater and caused by other anthropogenic activities (Selvam et al., 2018).

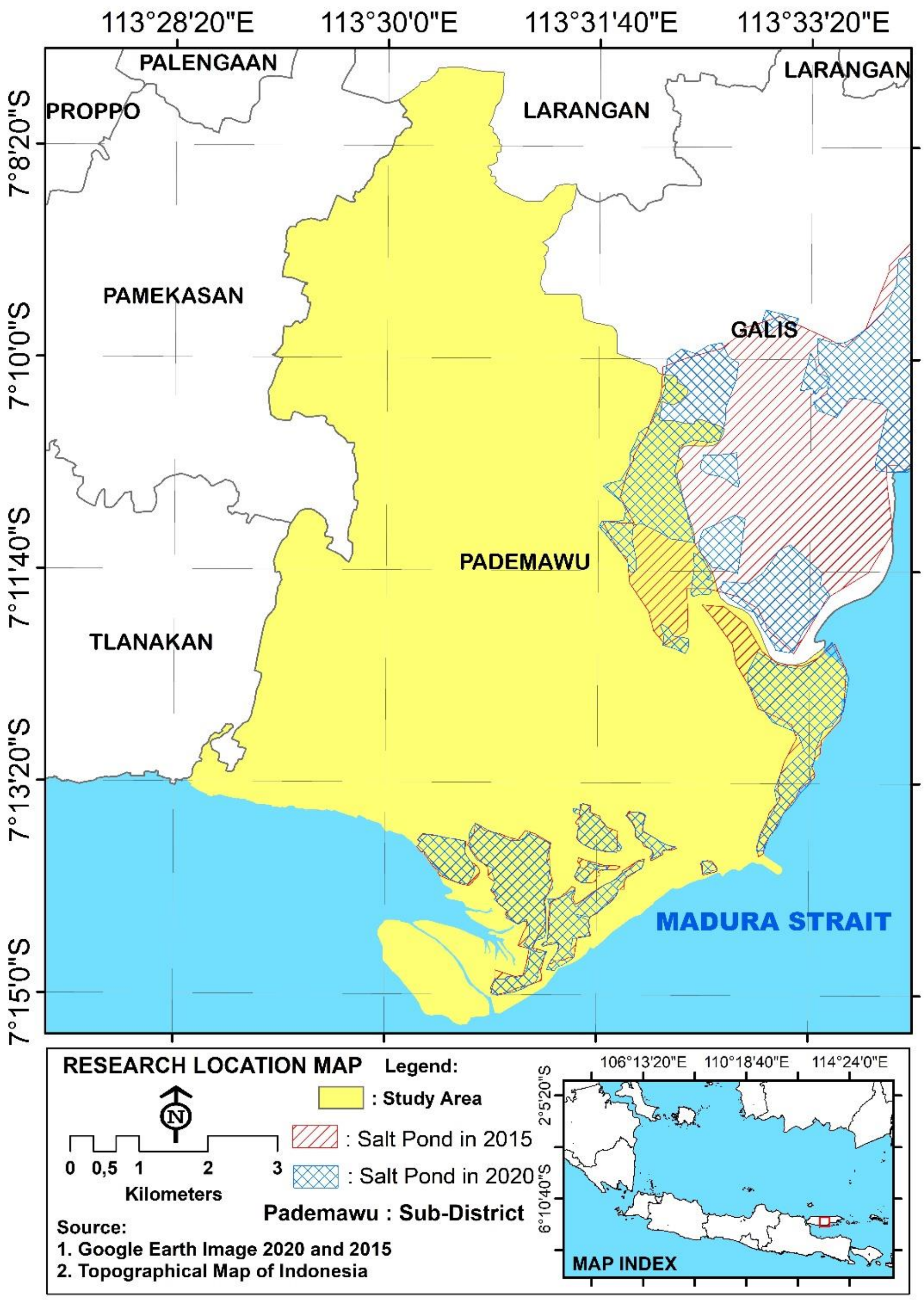

Figure 9. Salt drying pond area changes over five years (2015-2020)

The interpolation map of conductivity and TDS in 2015 and 2020 showed the same groundwater characteristics zonation where brackish-saline and brackish water were predominant in the south. Furthermore, the salt drying pond area changes impacted the spatial distribution of conductivity and TDS in the study area. Based on the correlation between TDS vs Cl, TDS vs HCO_3, and Na vs Cl, it showed a strong relationship with a correlation value almost 1. Therefore, it is interpreted that the groundwater in the study area is highly influenced by seawater yielded from salt pond infiltration (Gemilang & Bakti, 2019).

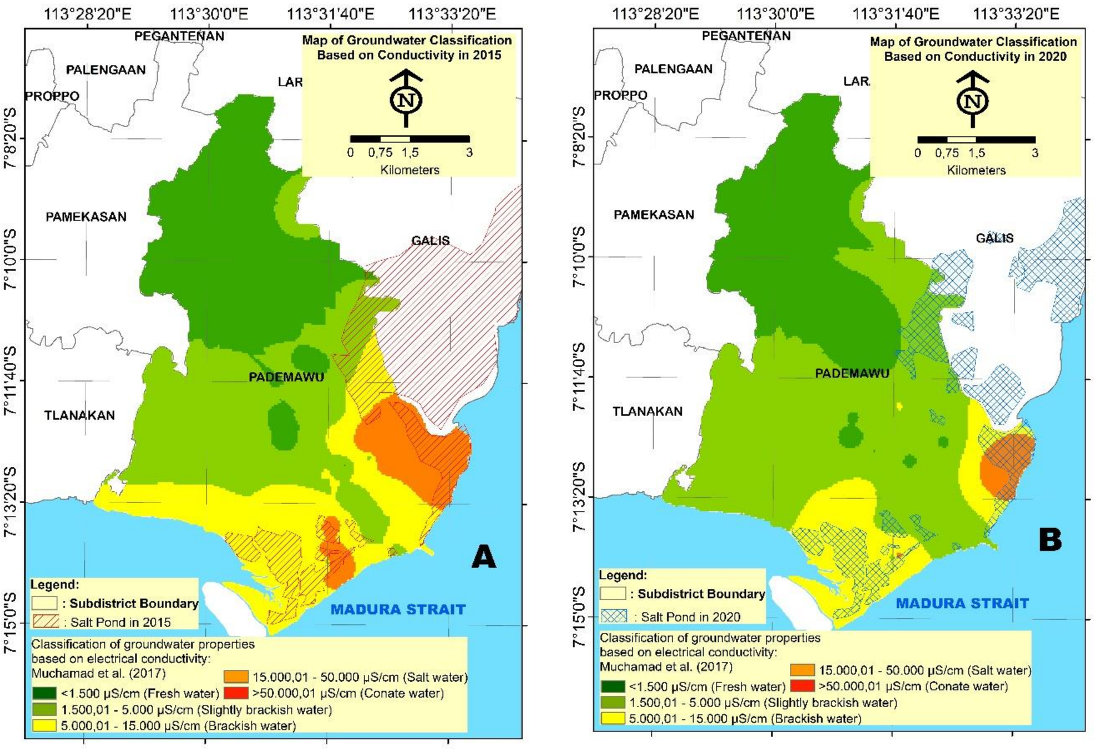

Figure 10. Conductivity distribution overlaid map in salt drying ponds area of Pademawu in 2015 (a) and 2020 (b)

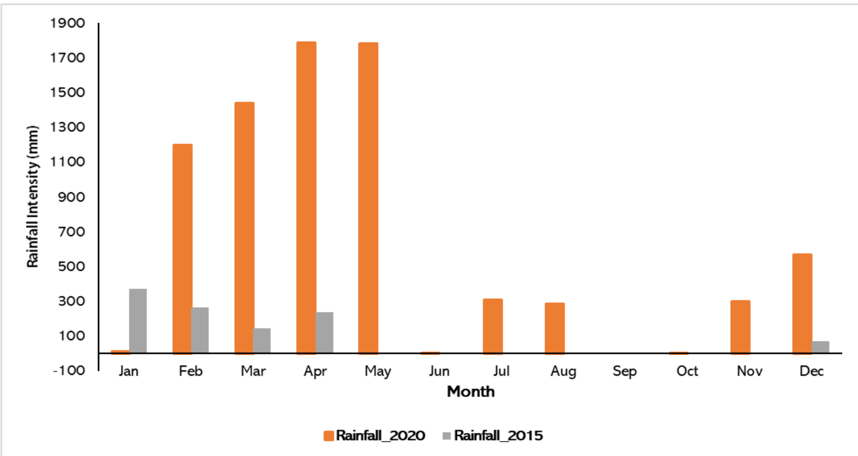

Figure 11. Monthly average of rainfall intensity in 2015 and 2020

Source: (BMKG, 2015 & 2020)

The amount of adsorbed water to the surface of earth mainly relies on rainfall intensity, soil permeability, and land use type (Gopinath et al., 2021). However, rainfall intensity becomes a media to accelerate the pollutant to contaminate the aquifer. Rainfall also influences percolation and contaminant transport toward the groundwater zone.

5. Conclusion

The dynamic of groundwater quality commonly decreased over five years. However, the general water quality parameters meet the quality standard established by the Ministry of Health in 2020. The depth of shallow groundwater-surface increased by 0.974 meters in 2020. This state played significant a role in reducing the groundwater pollution caused by seawater infiltration from salt ponds. Slightly brackish water zone expanded in 2020, replacing the brackish water zone in 2015 based on conductivity distribution. In 2020, the overall groundwater type was categorized as freshwater and brackish. Higher rainfall intensity is correlated with the decrease of salt drying pond area, resulting in degraded groundwater type zones in the south and southeast of the study area. These current states could be beneficial for managing and mitigating land use for salt drying pond to reduce groundwater contaminations. Sea water intrusion and salinization induced by the presence of salt pond are the main factors triggering groundwater pollution in Pademawu. To be more modern for further research and development, we recommend organizing the distance between the salt pond and artesian wells and evaluating the salt pond management system, so groundwater pollution could be diminished.

Conflict of interest

The authors declare that there is no conflict of competing interests regarding the publication of this article.

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