Identification of seawater intrusion in Gapura Sub-district, Sumenep Regency, East Java, Indonesia

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Abstract. Gapura sub-district is located in the Sumenep Regency, Madura Island, that also recognized as the center of salt production. Due to not availability of a clean water network from the municipal water network (PDAM), the daily water need of the community is provided by groundwater. Local people have reported several brackish waters in the wells since a few years ago. Therefore, the purpose of this research is to identify seawater intrusion potential in this area. The seawater intrusion is analyzed based on the value of electrical conductivity (EC) and groundwater hydrochemistry. From the analysis of EC values, it can be concluded that there are two out of thirty groundwater samples classified as moderately saline water, while in the study of groundwater ion values, both two samples have chloride values that are more than 240 mg/L. However, the Cl and HCO\textsubscript{3} ratio show that the two samples will only have a small effect on seawater. Therefore, it can be concluded that the Gapura sub-district does not have seawater intrusion. High salinity in some wells is mostly coming from salt production in this area.

keywords: Groundwater, intrusion, salt seawater

1. Introduction

Groundwater is one of the essential sources of water in the world. It serves as a crucial source in all regions, especially in an arid area. It is used not only for domestic purposes but also for irrigation and industrial. Groundwater exploitation increases due to its quantity stability, excellent quality, and relatively low development costs [1]. One area with high groundwater susceptibility to the contaminant is the coastal area where all the water will meet the seawater. All surface water and groundwater will be drained in this region with all chemical elements included. Therefore, all pollutants will be carried by the water flow to the coastal zone [2]. The main concern in the many areas is the problems associated with naturally saline groundwater, seawater intrusion, and upcoming saline water due to over-pumping in agricultural and industrial zones. This problem can be caused by natural factors such as water interaction with rocks, hydrodynamic conditions, impacts from adjacent aquifers, and seawater intrusion.
In addition, coastal areas groundwater is also susceptible to contamination by human activities and natural processes such as seawater level rise [4].

Sumenep Regency is located in Madura Island, one of the largest salt producers in Indonesia, based on the Ministry of Maritime and Fisheries Affairs, Indonesia [5]. One of the sub-district that produces salt in Sumenep Regency is Gapura [6]. The groundwater is the primary source of water in this sub-district. The local people use dug well and deep well to abstract the groundwater because the clean water network (PDMA) is not available yet. According to information from local residents, several brackish waters in the wells have been found since a few years ago. Electrical conductivity tends to increase when there are larger salt ions in water [7]. Therefore, it is essential to research groundwater to assess its hydrochemical composition and the impact of pollutants [8]. Therefore, the purpose of this study is to identify the potential of seawater intrusion analyzed based on the value of electrical conductivity (EC) and hydrochemistry of groundwater in this area. Tracing of salinity source is relatively tricky, especially in aquifers with several non-point sources. Other processes, such as water-rock interactions, make it a more complex problem to identify the primary source of salinity [9].

2. **Methodology**

The research area is an area of the coast, the southern side directly adjacent to the strait. The research area is located in the eastern region of Sumenep City, Sumenep Regency, as shown in Figure 1. The lithology of the research area is composed of alluvial deposits, sandstone, and limestone with show karst plains and tidal plains morphology. The research site has a large salt pond, as shown in Figure 2.

![Figure 1. Geological Map of the research area](image)

The research was conducted by field measurements and analysis of the chemical composition of water. First, field measurements were carried out on 50 dug wells, including pH, temperature, electrical conductivity (EC) using Hanna Instrument. Only 30 water samples were taken from the field based on the EC value, as shown in Figure 2. Five hundred milliliters of water samples were taken using...
polyethylene bottles and washed with hydrochloric acid and distilled water. Before its use, the bottle was washed with local water, filled until full, and kept in a cooler for laboratory analysis. The analysis of water samples to determine major elements including Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻ and HCO₃⁻ based on the Indonesia national standard (SNI).

Analysis of major ions was used to determine indications of seawater intrusion based on EC value, Cl⁻, sodium chloride ratio, base exchange indices (BEX), and analysis of comparisons of chloride (Cl⁻) and bicarbonate (HCO₃⁻) ions. The classification of EC value is shown in Table 1 and Cl⁻ in Table 2.

Table 1. Classification of saline water according to EC value [11]

| Water class     | EC (μS/cm) |
|-----------------|------------|
| Non-saline      | <700       |
| Slightly saline | 700-2,000  |
| Moderately saline | 2,000-10,000 |
| Highly saline   | 10,000-20,000 |
| Very highly saline | 20,000-45,000 |
| Brine           | >45,000    |

Table 2. Classification of saline water based on Cl⁻ value [12]

| Water class     | Cl value  |
|-----------------|-----------|
| Freshwater      | <280      |
| Slightly brackish | 280-600  |
| Medium brackish | 600-2,800 |
| Brackish        | 2,800-9,000 |
| Strong brackish | 9,000-18,000 |
| Sea water       | >18,000   |

The sodium chloride ratio is used as an indicator for seawater intrusion, with the following equation:

\[
\text{Ca Enrichment} = \frac{\text{Ca}}{\text{Mg}}
\]

A sodium chloride ratio value of less than 0.83 indicates seawater intrusion, where the effect of pollutants from anthropogenic sources will have a value of more than 1 [13].
Another indication of seawater intrusion in an aquifer is used base exchange indices (BEX), with the following equation:

$$BEX = Na + K + Mg - 1.0716 \ Cl$$

(2)

The freshening process was represented by the positive BEX value, which the negative BEX value represents the salinization process, and the BEX value 0 means no base exchange [14].

Analysis of the effect of seawater intrusion was carried out using a comparison of Cl\(^-\) with HCO\(_3\)\(^-\). The effect of seawater intrusion on groundwater is then classified based on Table 3.

| Effect level of saltwater | Comparison of Cl\(^-\) with HCO\(_3\)\(^-\) [15] |
|--------------------------|-----------------------------------------------|
| No effect                | ≤ 0.50                                        |
| Small effect             | 0.51 - 1.50                                   |
| Medium effect            | 1.50 - 3.00                                   |
| Quite large effect       | 3.01 - 6.50                                   |
| Big effect               | 6.51 - 15.50                                  |
| Huge effect              | ≥ 15.50                                       |

3. **Result and Discussion**

According to the groundwater level measurement from the 30 wells, a groundwater level map can be developed in the study area. The depth of groundwater level has a range from 1 to 30 meters from the ground surface. In this area, the groundwater flows from north to south (Figure 3). Table 4 shows the field measurements and analysis results of major ions. Field measurements show that the value of EC of groundwater range from 140 μS/cm to 2,440 μS/cm, the results of the analysis of the EC value can be seen in Figure 4.

![Figure 3. Groundwater flow patterns and directions](image-url)
Table 4. Field measurement and laboratory result of water analysis

| Sample | EC (μS/cm) | Na⁺ (mg/L) | K⁺ (mg/L) | Ca²⁺ (mg/L) | Mg²⁺ (mg/L) | Cl⁻ (mg/L) | HCO₃⁻ (mg/L) |
|--------|------------|------------|-----------|-------------|-------------|------------|-------------|
| G 1    | 880        | 27.6       | 29.8      | 109.8       | 12.8        | 24.9       | 326         |
| G 2    | 1070       | 47.1       | 2.71      | 118.5       | 18.3        | 58.6       | 368         |
| G 3    | 2440       | 245.2      | 38        | 118.2       | 39.6        | 432.8      | 391         |
| G 4    | 1200       | 89.2       | 24.4      | 105         | 20.7        | 97.5       | 432         |
| G 5    | 720        | 20.7       | 3.03      | 103.4       | 7.89        | 23.6       | 280         |
| G 6    | 450        | 4.25       | 3.22      | 79.6        | 2.36        | 4.46       | 372         |
| G 7    | 1100       | 59.6       | 33.6      | 121.8       | 8.83        | 63.7       | 336         |
| G 8    | 980        | 50.7       | 1.89      | 91.5        | 13.5        | 99.4       | 405         |
| G 9    | 670        | 11.3       | 6.71      | 97.5        | 8.12        | 3.82       | 345         |
| G 10   | 940        | 21.5       | 1.03      | 113.6       | 23.1        | 22.3       | 349         |
| G 11   | 560        | 27.7       | 4.3       | 72.3        | 7.8         | 35.7       | 345         |
| G 12   | 330        | 9.87       | 0.78      | 49.7        | 7.62        | 3.19       | 340         |
| G 13   | 720        | 8.62       | 1.55      | 110.1       | 3.9         | 6.37       | 299         |
| G 14   | 470        | 46         | 14.1      | 40.5        | 4.25        | 36.3       | 290         |
| G 15   | 190        | 38.1       | 43.7      | 93.6        | 21.6        | 76.5       | 372         |
| G 16   | 1080       | 34.7       | 8.06      | 86.9        | 13.7        | 57.4       | 368         |
| G 17   | 1060       | 49.7       | 1.94      | 92.5        | 16.4        | 116        | 377         |
| G 18   | 2100       | 264.4      | 5.66      | 114         | 32.8        | 247.3      | 322         |
| G 19   | 1060       | 79.6       | 23.3      | 88.7        | 20.2        | 95.6       | 368         |
| G 20   | 1210       | 104.7      | 25.6      | 107.6       | 22.3        | 148.5      | 313         |
| G 21   | 1150       | 82.8       | 23.4      | 110.4       | 15.8        | 70.8       | 294         |
| G 22   | 800        | 26.8       | 6.04      | 95.4        | 16.8        | 33.1       | 303         |
| G 23   | 800        | 20.3       | 1.47      | 94.1        | 18.5        | 8.92       | 331         |
| G 24   | 600        | 11.9       | 2.32      | 99.4        | 2.51        | 12.1       | 299         |
| G 25   | 430        | 19.6       | 3.17      | 63.6        | 4.17        | 7.65       | 276         |
| G 26   | 600        | 18         | 0.54      | 68          | 10.3        | 16.6       | 345         |
| G 27   | 540        | 8.19       | 1.28      | 73.6        | 3.89        | 6.37       | 391         |
| G 28   | 1040       | 26.3       | 6.22      | 115.4       | 28.7        | 38.2       | 336         |
| G 29   | 310        | 3.92       | 4.45      | 69.8        | 4.63        | 6.37       | 349         |
| G 30   | 960        | 52.7       | 29.4      | 92.4        | 14.1        | 70.1       | 278         |

Figure 4. Groundwater EC value distribution map
Based on measurements of 30 samples taken, the EC value shows three types of saltwater influence levels, non-saline, slightly saline, and moderately saline. Only two samples are classified as moderately saline water, G3 and G18, while the other twenty-eight samples belong to non-saline and slightly saline classification. The distribution classification of groundwater EC values can be seen in Table 5.

| Sample | EC (μS/cm) | Water category | Sample | EC (μS/cm) | Water category |
|--------|------------|----------------|--------|------------|----------------|
| G1     | 880        | Slightly saline | G16    | 1080       | Slightly saline |
| G2     | 1070       | Slightly saline | G17    | 1060       | Slightly saline |
| G3     | 2440       | Moderately saline | G18    | 2100       | Moderately saline |
| G4     | 1200       | Slightly saline | G19    | 1060       | Slightly saline |
| G5     | 720        | Slightly saline | G20    | 1210       | Slightly saline |
| G6     | 450        | Non-saline      | G21    | 1150       | Slightly saline |
| G7     | 1100       | Slightly saline | G22    | 800        | Slightly saline |
| G8     | 980        | Slightly saline | G23    | 800        | Slightly saline |
| G9     | 670        | Non-saline      | G24    | 600        | Non-saline      |
| G10    | 940        | Slightly saline | G25    | 430        | Non-saline      |
| G11    | 560        | Non-saline      | G26    | 600        | Non-saline      |
| G12    | 330        | Non-saline      | G27    | 540        | Non-saline      |
| G13    | 720        | Slightly saline | G28    | 1040       | Slightly saline |
| G14    | 470        | Non-saline      | G29    | 310        | Non-saline      |
| G15    | 190        | Non-saline      | G30    | 960        | Slightly saline |

According to Cl- concentration, only one sample has a value more than the freshwater standard, G3 classified as slightly brackish water, shown in Table 6.

| Sample | Cl- (mg/L) | Water category | Sample | Cl- (mg/L) | Water category |
|--------|------------|----------------|--------|------------|----------------|
| G1     | 24.9       | Freshwater     | G17    | 57.4       | Freshwater     |
| G2     | 58.6       | Freshwater     | G17    | 116        | Freshwater     |
| G3     | 432.8      | Slightly brackish | G18    | 247.3      | Freshwater     |
| G4     | 97.5       | Freshwater     | G19    | 95.6       | Freshwater     |
| G5     | 23.6       | Freshwater     | G20    | 148.5      | Freshwater     |
| G6     | 4.46       | Freshwater     | G21    | 70.8       | Freshwater     |
| G7     | 63.7       | Freshwater     | G22    | 33.1       | Freshwater     |
| G8     | 99.4       | Freshwater     | G23    | 8.92       | Freshwater     |
| G9     | 3.82       | Freshwater     | G24    | 12.1       | Freshwater     |
| G10    | 22.3       | Freshwater     | G25    | 7.65       | Freshwater     |
| G11    | 35.7       | Freshwater     | G26    | 16.6       | Freshwater     |
| G12    | 3.19       | Freshwater     | G27    | 6.37       | Freshwater     |
| G13    | 6.37       | Freshwater     | G28    | 38.2       | Freshwater     |
| G14    | 36.3       | Freshwater     | G29    | 6.37       | Freshwater     |
| G15    | 76.5       | Freshwater     | G30    | 70.1       | Freshwater     |

Meanwhile, from the calculation of the Sodium Chloride Ratio, all samples are still classified as freshwater, shown in table 7.
Table 7. Water classification of groundwater based on the Sodium Chloride Ratio value

| Sample | Sodium Chloride Ratio | Water class | Sample | Sodium Chloride Ratio | Water class |
|--------|-----------------------|-------------|--------|-----------------------|-------------|
| G1     | 8.57                  | Freshwater  | G16    | 6.34                  | Freshwater  |
| G2     | 6.48                  | Freshwater  | G17    | 5.64                  | Freshwater  |
| G3     | 2.98                  | Freshwater  | G18    | 3.48                  | Freshwater  |
| G4     | 5.07                  | Freshwater  | G19    | 4.39                  | Freshwater  |
| G5     | 13.11                 | Freshwater  | G20    | 4.83                  | Freshwater  |
| G6     | 33.73                 | Freshwater  | G21    | 6.99                  | Freshwater  |
| G7     | 13.79                 | Freshwater  | G22    | 5.68                  | Freshwater  |
| G8     | 6.78                  | Freshwater  | G23    | 5.09                  | Freshwater  |
| G9     | 12.01                 | Freshwater  | G24    | 39.60                 | Freshwater  |
| G10    | 4.92                  | Freshwater  | G25    | 15.25                 | Freshwater  |
| G11    | 9.27                  | Freshwater  | G26    | 6.60                  | Freshwater  |
| G12    | 6.52                  | Freshwater  | G27    | 18.92                 | Freshwater  |
| G13    | 28.23                 | Freshwater  | G28    | 4.02                  | Freshwater  |
| G14    | 9.53                  | Freshwater  | G29    | 15.08                 | Freshwater  |
| G15    | 4.33                  | Freshwater  | G30    | 6.55                  | Freshwater  |

However, there were some irregularities in the result of the BEX calculation. For example, it can be seen in Table 8, samples classified as experiencing salinization occurred in samples G3, G8, G16, G17, and G20.

Table 8. Water classification of groundwater BEX value

| Sample | BEX  | Water process | Sample | BEX  | Water process |
|--------|------|---------------|--------|------|---------------|
| G1     | 43.52| Freshening    | G16    | -5.05| Salinization  |
| G2     | 5.31 | Freshening    | G17    | -56.27| Salinization  |
| G3     | -140.99| Salinization| G18    | 37.85| Freshening    |
| G4     | 29.82| Freshening    | G19    | 20.66| Freshening    |
| G5     | 6.33 | Freshening    | G20    | -6.53| Salinization  |
| G6     | 5.05 | Freshening    | G21    | 46.13| Freshening    |
| G7     | 33.77| Freshening    | G22    | 14.17| Freshening    |
| G8     | -40.43| Salinization| G23    | 30.71| Freshening    |
| G9     | 22.04| Freshening    | G24    | 3.76 | Freshening    |
| G10    | 21.73| Freshening    | G25    | 18.74| Freshening    |
| G11    | 1.54 | Freshening    | G26    | 11.05| Freshening    |
| G12    | 14.85| Freshening    | G27    | 6.53 | Freshening    |
| G13    | 7.24 | Freshening    | G28    | 20.28| Freshening    |
| G14    | 25.45| Freshening    | G29    | 6.17 | Freshening    |
| G15    | 21.42| Freshening    | G30    | 21.08| Freshening    |

Analysis of the seawater on groundwater is also shown by the value of the ratio of Cl\(^-\) and HCO\(_3^-\). Based on the calculation results in Table 9, only two samples show that they are classified as a small effect. G3 and G18 have a value greater than 0.5, other samples classified as no effect.

The EC value analysis and several groundwater hydrochemical indicators show that the indications of seawater intrusion are small and can only be seen at two sampling locations. Two water samples that have high salinity with a brackish taste are located close to the salt ponds. Therefore, a source of salinity in the wells mainly comes from the salt ponds, not from seawater intrusion.
Table 9. Classification of the effect of seawater intrusion on groundwater conditions

| Sample | Cl/HCO₃ | Level of effect | Sample | Cl/HCO₃ | Level of effect |
|--------|---------|----------------|--------|---------|----------------|
| G1     | 0.08    | No effect      | G16    | 0.16    | No effect      |
| G2     | 0.16    | No effect      | G17    | 0.31    | No effect      |
| G3     | 1.11    | Small effect   | G18    | 0.77    | Small effect   |
| G4     | 0.23    | No effect      | G19    | 0.26    | No effect      |
| G5     | 0.08    | No effect      | G20    | 0.47    | No effect      |
| G6     | 0.01    | No effect      | G21    | 0.24    | No effect      |
| G7     | 0.19    | No effect      | G22    | 0.11    | No effect      |
| G8     | 0.25    | No effect      | G23    | 0.03    | No effect      |
| G9     | 0.01    | No effect      | G24    | 0.04    | No effect      |
| G10    | 0.06    | No effect      | G25    | 0.03    | No effect      |
| G11    | 0.10    | No effect      | G26    | 0.05    | No effect      |
| G12    | 0.01    | No effect      | G27    | 0.02    | No effect      |
| G13    | 0.02    | No effect      | G28    | 0.11    | No effect      |
| G14    | 0.13    | No effect      | G29    | 0.02    | No effect      |
| G15    | 0.21    | No effect      | G30    | 0.25    | No effect      |

4. Conclusion
The EC, chloride, and seawater intrusion indicators of groundwater shows that there are only two samples of groundwater classified as moderately saline water. However, Cl and HCO₃ ratio show that those two samples will only have a small effect from seawater. Those samples could not meet the requirement as seawater intrusion categories. Therefore, it cannot be categorized as seawater intrusion. It can be concluded that the Gapura sub-district does not have seawater intrusion. Salt production and salt ponds activity is the primary source of high salinity in the groundwater in this area.

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