Subsurface Investigation of Freshwater-Seawater Interface on Gowa-Takalar Coastal Aquifer, Indonesia

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Abstract. Gowa-Takalar Coastal Aquifer is an unconfined aquifer located in the southward of Makassar City. The Gowa-Takalar area has a heavy groundwater exploitation particularly on dry season. In this area, the groundwater is utilized to support water need for agriculture activities, marine tourism facilities, and new settlement development. The highly economic activities in this area, it causes an intensive groundwater exploitation. Since this area is located around coastal area, this area has highly susceptibility to suffer from seawater intrusion. In order to maintain the continuity of groundwater supply, a special study is needed on hydrodynamics of fresh-sea water interface as the basis for the formulation of a sustainable management model. This study as an early step of groundwater management research emphasizing on basic of aquifer and groundwater data. The research method consisting of reconnaissance study for geological & hydrogeological mapping, groundwater chemistry laboratory analysis, and geo-electrical investigation. Geological condition of this area is composed of alluvial and coastal deposits, volcanic deposits, and marine sedimentary rocks interbedded with volcanics. These materials form three hydrogeological characteristics: extensive and moderately productive aquifer, locally productive aquifers, and poorly productive aquifers of local importance. The chemical composition of groundwater from dug wells show the chloride concentration vary from 3.55 ppm to 81.65 ppm, with chloride-bicarbonate ratio is 0.008 – 0.035 indicating aquifer without sea water invasion. However, based on vertical electrical sounding, the resistivity layers vary from 0.02 to 62.50 ohm-m indicating the present of seawater intrusion into coastal aquifer.

1. Introduction
Groundwater plays an important role for the environment and the economy. In many regions, groundwater is exploited in a big volume because ground water has several advantages compared to surface water. However, issues of groundwater quantity and quality have received far less attention than the surface water, particularly in some developing countries. Moreover, due to its existence in subsurface, the issues of groundwater are often not a problem arises until it comes to public attention such as quality and quantity degradation, land subsidence, etc. In the groundwater development area, a heavy groundwater exploitation will result in an uncontrolled decreasing of water table or groundwater piezometric level covering a very large area. This groundwater level change will be followed by number of environmental impacts, which are classified into three main categories; seawater intrusion, land subsidence, and the spread of other contaminants [1]. The seawater intrusion is one of the most common problems in almost all coastal aquifers around the world. It takes place when saline water displaces or mixes with freshwater in aquifers. This phenomenon can be attributed by a variety of
conditions; hydrogeological conditions, hydraulic gradients, tidal and estuarine activity, sea level, infiltration, and groundwater withdrawal.

Coastal area of Gowa-Takalar, which is a buffer zone for Makassar City, has a heavy groundwater exploitation particularly on dry season. In this area, the groundwater is utilized to support water needs for agriculture activities, marine tourism facilities, and new settlement development. The uncontrollable exploitation leads the coastal aquifer to be a highly susceptibility of seawater intrusion. In order to avoid the seawater intrusion problem, it is required assessment activities. The most common methods for assessing seawater intrusion through an aquifer in coastal belts is a periodic analysis of groundwater chemistry [2]. The groundwater chemical composition generally exhibits high concentrations not only in total dissolved solids (TDS) but also in major cations and anions as well accumulation of selective trace elements [3]. Revelle recommended to calculate chloride-bicarbonate ratio (\(\frac{Cl^-}{(CO_3^{2-} + HCO_3^-)}\)) to identify seawater intrusion [4].

The extent of saline water intrusion is influenced by nature of geological settings, hydraulic gradient, rate of groundwater withdrawal and its recharge. In studying the thickness and geometry of depositional systems, a common procedure is to make use of information from geological research, drilling, and exploitation boreholes. However, these methods are expensive and time consuming. In contrast, geophysical measurements can provide a less expensive way to improve the understanding of subsurface geological condition. For this reason, in many cases, geophysical prospecting techniques can provide complementary data that enable geological correlation, even in sectors where there are no data from boreholes. There are a variety of geophysical techniques for which it would be useful to know the subsurface resistivity in order to estimate the saline water intrusion. The large differences between the resistivity of saltwater saturated zones and the freshwater saturated zones have been used by number of investigations for determination of saltwater intrusion in many coastal areas [5].

Since the study of seawater intrusion problem in the Gowa-Takalar Coastal Aquifer has not been carried out intensively, this study has been done to provide a basic data of groundwater as interface of fresh-seawater. Therefore, the objective of this study is to provide information of general status of groundwater quality and salinization on unconfined aquifer. To achieve the above objective, the following tasks are to be carried out: (1) mapping of geological and hydrogeological condition; (2) analysis of groundwater hydro-chemical; (3) interpretation of resistivity to estimate position of freshwater-seawater interface.

2. Research Methodology
Reconnaissance of surface geological and hydrogeological mapping was done to have a complete understanding of geomorphology, lithology/stratigraphy, and structural geology of the research area. This reconnaissance mapping was based on regional geological map of Ujung Pandang, Benteng, and Sinjai sheets, South Sulawesi published by the Geological Research and Development Center Bandung [6]. Moreover, the hydrogeological mapping using the Hydrogeological Map of Ujung Pandang, Benteng, and Sinjai Quadrangles, South Sulawesi published by Center for Environmental Geology Bandung [7] was a basic information. In the hydrogeological mapping, it was measured the depth of water table on dug wells and was took groundwater samples. The mapping was carried in August 2018 in which dry season and was collected samples of 25 dug wells. The groundwater samples were analyzed of chemical composition for chloride, carbonate, and bicarbonate element. Result of the chemical analysis is used to predict mixing seawater and freshwater by calculating chloride-bicarbonate ratio.

Overview the groundwater salinity of rock layer beneath surface was investigated by using geoelectrical prospecting. The geoelectrical surface applied Vertical Electrical Sounding (VES) by employing Schlumberger electrode array. The Schlumberger electrode configures current electrode spacing varying between 1 to 400 m. The VES was conducted using the resistivity meter for 10 measurement points. The VES field data was processed to determine layer parameters through 1-D inversion technique of IPI2Win software [8]. This software capable solving resistivity electrical prospecting ID forward and inverse problems for a variety of commonly used arrays for the cross
sections with resistivity contrasts within the range of 0.0001 to 10000. The forward problem is solved using the linear filtering developed at the Near-surface Electrical Prospecting Lab. Geophysical Department, Moscow State University. The inverse problem is solved using a variant of the Newton algorithm of the least number of layers of regularized fitting minimizing algorithm using Tikhonov’s approach to solve incorrect problems. The inverse problem is solved separately for each sounding curve. By using the IPI2win software, it will be estimated number of layers, true resistivity, thickness, depth, and altitude of layer contacts.

3. Geological and Hydrogeological Characteristics
The Gowa-Takalar coastal aquifer stretches from Pappa River in south to Jeneberang River in north with elevation vary from 0 – 25 m above mean sea level. The rainfall analysis was based on rainfall occurrence within the latest 5 years. The monthly rainfall that occurs varies with the lowest value of 0.70 mm in September and the highest value in January is 772.40 mm. Geological condition of the Gowa-Takalar coastal area was described on the published Geological Map of Ujung Pandang, Benteng and Sinjai Quadrangles [6]. The research consists of three rock formations: Alluvial and Coastal Deposits (Qac), Baturape-Cindako Volcanics (Tpbv), and Camba Formation (Tmc).

Alluvial and Coastal Deposits (Qac) is composed of gravel, sand, clay, mud, and coral limestone. Those materials were deposited in rivers, swamps, coast and delta environments. Around the Jeneberang River, the alluvial deposits consist mainly of detritus derived from volcanic materials of Lompobattang Mountain.

Baturape-Cindako Volcanics (Tpbv) consist of lava and breccia, with the intercalation of some tuff and conglomerate. The lava composition is basaltic, mostly porphyritic, with big phenocrysts of pyroxene up to 1 cm, and partly aphanitic, with greenish dark gray to black in color. The lava
commonly displays columnar and sheeted jointing. The breccia consists mostly of coarse components with size of 15 - 60 cm, mainly basaltic with small amounts of andesite mineral, cemented with coarse tuff to lapilli. Diorite intrusive consisting of stock and dyke at vicinity of Baturape-Cindako is thought to be the remnant of eruptive center (Tpbc). The surrounding rocks are highly altered, amygdaloidal with secondary minerals of zeolite and calcite. Ore mineral of galena in Baturape is possibly related to the dioritic intrusive. The area around Baturape and Cindako is dominated with lava (Tpbl).

Camba Formation (Tmc) is generally marine sedimentary rocks interbedded with volcanics. The formation consists of tuffaceous sandstone interbedded with tuff, sandstone, and claystone; with intercalation of marl, limestone, volcanic conglomerate and breccia, and coal. The rocks has varies in color from white, brown, red, light to dark grey. The materials are mostly well consolidated. Tuffs are fine to lapilli in size. Red clayey tuff contains abundant biotite. Conglomerate and breccia composed of andesite and basalt pebbles of 2 – 30 cm in size. Sandy limestone contains fragment of coral and mollusca. Dark gray claystone and marl contain small forams.

The hydrogeological conditions of Gowa-Takalar coastal area and its surroundings have been published by the Bandung Center for Environmental Geology on a Hydrogeological Map of Indonesia, Ujungpandang, Benteng, and Sinjai Quadrangles [7]. Hydrogeological conditions based on rocks properties are categorized into 3 categories, namely:

1. Extensive and moderately productive aquifer. The aquifer has low to moderate transmissivity. Water table on this aquifer lies at depth less than 5 meter below land surface, with wells yield is less than 1.0 liter/second.
2. Locally productive aquifers. The material is mostly incoherent aquifers of low thickness and transmissivity. The position of water table is 1 – 5 meter below land surface, and wells yield is less than 1.0 liter/second.
3. Poorly productive aquifers of local importance. Generally, aquifier has very low transmissivity, local, limited shallow groundwater resources. The aquifer can be obtained in weathered zones of solid rocks or in the valleys.

4. Freshwater and Seawater Interface

4.1. Chloride-bicarbonate ratio

The chemical composition of ground water is related to the soluble products of rock weathering and decomposition and changes with respect to time and space. Geochemical study can provide a complete knowledge of water resources of a hydrogeological system. Therefore, several hydro-chemical approaches have been published regarding different uses. To investigate seawater enroachment into coastal aquifer, Revelle, 1941 recommended to calculate chloride-bicarbonate ratio (Cl– (CO3²⁻ + HCO⁻))₂. Chloride is the dominant ion in seawater and it is only available in small quantities in groundwater while bicarbonate which is available in large quantities in groundwater occurs only in very small quantities in seawater [4]. An appropriate assessment of salt water intrusion aspect requires establishing the levels of Cl–, CO3²⁻ & HCO⁻ quantitatively [9].

On hydrogeological mapping, Groundwater samples were collected from 25 dug wells in August 2018 (dry season). The well’s locations are shown on Figure 3. The sampling objectives to provide information groundwater quality laterally within the aquifer, so that the samples were taken from water table. The samples were sent to Laboratory of Water Quality, Faculty of Marine Science and Fisheries, Universitas Hasanuddin for chemical composition analysis. The analysis was carried for major chemical constituents; cations (Na⁺, K⁺, Mg²⁺, and Ca²⁺), and anions (Cl–, HCO₃⁻, SO₄²⁻, and CO₃²⁻). The sum of the cations and anions when expressed in milliequivalents per liter will be equal and may expected as total dissolved solid. The ionic balance was determined for the results of the major cations and anions calculated by Balance = ((Cations – Anions)/(Cations + Anions))^100. Where Cations is the total cation milliequivalents per liter. Anions is the total anions milliequivalents per liter.

Since this paper describes fresh-sea water interface, result of chemical quantity analysis of groundwater samples focuses on chloride (Cl–), bicarbonate (HCO₃⁻), and carbonate (CO₃²⁻). Table 1
shows the concentration values for carbonate (CO$_3^{2-}$), bicarbonate (HCO$_3^-$), and chloride (Cl$^-$) and calculated of chloride-bicarbonate ratio. The results of the analysis show that concentration of chloride ion vary from 3.55 - 81.5 ppm, carbonate ion vary 588.0 - 2256.0 ppm, and bicarbonate ion vary from 434.0 - 2839.6 ppm. The calculated chloride-bicarbonate ratio varies from 0.001 to 0.045. All the samples showed the ratio less than 0.5 indicating that there is no salt water intrusion in the groundwater of the study area.

Table 1. Chemical analysis results of collected groundwater samples.

| No | SAMPLE CODE | CHEMICAL CONC. (ppm) | MOLARITY (m.eq/ltr) | CHLORIDE-BICARBONATE RATIO |
|----|-------------|----------------------|---------------------|---------------------------|
|    |             | HCO$_3^-$          | CO$_3^{2-}$           | Cl$^-$ | HCO$_3^-$ | CO$_3^{2-}$ | Cl$^-$ |                    |
| 1  | OW-01       | 2021.2             | 1956.0               | 53.25  | 0.033     | 0.033      | 0.0015 | 0.023             |
| 2  | OW-02       | 2070.8             | 2004.0               | 56.80  | 0.034     | 0.033      | 0.0016 | 0.024             |
| 3  | OW-03       | 1190.4             | 1152.0               | 24.85  | 0.020     | 0.019      | 0.0007 | 0.018             |
| 4  | OW-04       | 1959.2             | 1896.0               | 39.05  | 0.032     | 0.032      | 0.0011 | 0.017             |
| 5  | OW-05       | 1438.4             | 1392.0               | 28.40  | 0.024     | 0.023      | 0.0008 | 0.017             |
| 6  | OW-06       | 818.4              | 792.0                | 24.85  | 0.013     | 0.013      | 0.0007 | 0.026             |
| 7  | OW-07       | 434.0              | 420.0                | 7.10   | 0.007     | 0.007      | 0.0002 | 0.014             |
| 8  | OW-08       | 1500.4             | 1452.0               | 14.20  | 0.025     | 0.024      | 0.0004 | 0.008             |
| 9  | OW-09       | 1562.4             | 1512.0               | 81.65  | 0.026     | 0.025      | 0.0023 | 0.045             |
| 10 | OW-10       | 2331.2             | 2256.0               | 3.55   | 0.038     | 0.038      | 0.0001 | 0.001             |
| 11 | OW-11       | 1971.6             | 1908.0               | 39.05  | 0.032     | 0.032      | 0.0011 | 0.017             |
| 12 | OW-12       | 731.6              | 708.0                | 14.20  | 0.012     | 0.012      | 0.0004 | 0.017             |
| 13 | OW-13       | 942.4              | 912.0                | 17.75  | 0.015     | 0.015      | 0.0005 | 0.016             |
| 14 | OW-14       | 2170.0             | 2100.0               | 42.60  | 0.036     | 0.035      | 0.0012 | 0.017             |
| 15 | OW-15       | 2157.6             | 2088.0               | 49.70  | 0.035     | 0.035      | 0.0014 | 0.020             |
| 16 | OW-16       | 1748.4             | 1692.0               | 28.40  | 0.029     | 0.028      | 0.0008 | 0.014             |
| 17 | OW-17       | 1426.0             | 1380.0               | 39.05  | 0.023     | 0.023      | 0.0011 | 0.024             |
| 18 | OW-18       | 942.4              | 912.0                | 17.75  | 0.015     | 0.015      | 0.0005 | 0.016             |
| 19 | OW-19       | 669.6              | 648.0                | 10.65  | 0.011     | 0.011      | 0.0003 | 0.014             |
| 20 | OW-20       | 607.6              | 588.0                | 24.85  | 0.010     | 0.010      | 0.0007 | 0.035             |
| 21 | OW-21       | 2839.6             | 2748.0               | 49.70  | 0.047     | 0.046      | 0.0014 | 0.015             |
| 22 | OW-22       | 1103.6             | 1068.0               | 14.20  | 0.018     | 0.018      | 0.0004 | 0.011             |
| 23 | OW-23       | 1860.0             | 1800.0               | 49.70  | 0.030     | 0.030      | 0.0014 | 0.023             |
| 24 | OW-24       | 1450.8             | 1404.0               | 28.40  | 0.024     | 0.023      | 0.0008 | 0.017             |
| 25 | OW-25       | 1624.4             | 1572.0               | 49.70  | 0.027     | 0.026      | 0.0014 | 0.027             |
4.2. Groundwater resistivity

The surface electrical resistivity method is a useful tool in determining seawater intrusion in coastal areas for its capability to discriminate the large resistivity contrast between the presence of seawater that strongly reduces the resistivity values and saturated freshwater layers [10]. The Vertical Electrical Sounding (VES) survey reported in this paper was carried out with the primary objective of obtaining information on the hydrogeological behavior of the aquifers, the subsurface lithology and groundwater salinity. Surface Schlumberger electrode array with electrode spacing varying between 1 to 400 m was applied for the VES survey to investigate subsurface condition for maximum depth of 150 – 200 m. Location and distribution of the VES stations are shown on Figure 4, for 10 VES using the resistivity meter.

The electrical resistivity of sediments depends on lithology, water content, clay content and salinity. Variations in rock type resistance values at a sounding point can be used to predict; (1) the position of the water bearing layer, (2) the thickness of the water bearing layer, (3) the quality of ground water, (4) the lateral spread of the water bearing layer, (5) the condition of the material below the surface. Some interpretation problems for the VES can occur when mapping subsurface salinity, since resistivity for salt water, saturated clay and sand overlaps. Both groundwater saline and saturated

Figure 3. Map of chloride-bicarbonate ratio
clay has low resistivity. It is, therefore, important to correlate the VES results with the lithological and hydrological information.

Figure 4. Matching field data curve with calculated IPI2Win curve.

Owing to the differing character of features in the apparent resistivity curves, the VES stations show different types of curves. The interpretation results reveal significant variations in subsurface resistivity of the coastal rock units in the study area. The types of VES curves were defined in terms of the number of geoelectrical layers and their resistivity relationship. If the lateral variations in resistivity in the shallow subsurface units as a result of heterogeneity of lithology and soil moisture content are ignored, most of the VES resistivity curves show two types of resistivity curve showed in
Figure 3. The first type with a trend of decreasing resistivity until about 5 ohm-m and then increasing in the last part of the curve (ρ1 > ρ2 < ρ3) for VES-1, VES-2, VES-3, VES-8, and VES-9. The second type is decreasing curve to end of the curve (ρ1 < ρ2 < ρ3) for VES-4, VES-5, VES-6, VES-7, and VES-10. In general, the type of data obtained varies from 0.02 ohms-m to 62.50 ohms-m.

Table 2. Interpretation of resistivity layers into groundwater quality.

| No | VES CODE | True Resistivity (ohm-m) | Layer Depth (m) | Groundwater Condition |
|----|----------|--------------------------|-----------------|----------------------|
| 1  | VES_01   | 18.00                    | 0.00 – 1.80     | -                    |
|    |          | 5.85                     | 1.80 – 20.71    | Brackish water.      |
|    |          | 1.76                     | 20.71 – 106.90  | Saline water         |
|    |          | 7.14                     | >106.90         | Brackish water       |
| 2  | VES_02   | 12.90                    | 0.00 – 0.80     | -                    |
|    |          | 62.50                    | 0.80 – 3.59     | Fresh water          |
|    |          | 3.97                     | 3.59 – 16.53    | Brackish water       |
|    |          | 1.89                     | 16.53 – 79.04   | Saline water         |
|    |          | 7.90                     | >79.04          | Brackish water       |
| 3  | VES_03   | 50.20                    | 0.00 – 1.74     | -                    |
|    |          | 15.20                    | 1.74 – 10.52    | Fresh water          |
|    |          | 2.44                     | 10.52 – 56.50   | Saline water         |
|    |          | 19.90                    | >56.50          | Fresh water          |
| 4  | VES_04   | 14.30                    | 0.00 – 0.90     | -                    |
|    |          | 37.60                    | 0.90 – 9.54     | Fresh water          |
|    |          | 9.56                     | 9.54 – 100.30   | Brackish water       |
|    |          | 4.86                     | >100.30         | Brackish water       |
| 5  | VES_05   | 13.90                    | 0.00 – 1.98     | -                    |
|    |          | 47.30                    | 1.98 – 9.51     | Fresh water          |
|    |          | 19.30                    | 9.51 – 24.37    | Fresh water          |
|    |          | 5.37                     | >24.37          | Brackish water       |
| 6  | VES_06   | 6.91                     | 0.00 – 0.53     | -                    |
|    |          | 53.70                    | 0.53 – 2.03     | Fresh water          |
|    |          | 26.50                    | 2.03 – 22.31    | Fresh water          |
|    |          | 3.73                     | >22.31          | Brackish water       |
| 7  | VES_07   | 9.19                     | 0.00 – 0.68     | -                    |
|    |          | 40.40                    | 0.68 – 2.79     | Fresh water          |
|    |          | 19.00                    | 2.79 – 15.41    | Fresh water          |
|    |          | 3.43                     | >15.41          | Brackish water       |
| 8  | VES_08   | 10.40                    | 0.00 – 0.48     | -                    |
|    |          | 45.40                    | 0.48 – 4.39     | Fresh water          |
|    |          | 11.60                    | 4.39 – 24.37    | Fresh water          |
|    |          | 2.48                     | 24.37 – 93.50   | Saline water         |
|    |          | 6.14                     | >93.50          | Brackish water       |
| 9  | VES_09   | 4.95                     | 0.00 – 0.97     | -                    |
|    |          | 1.22                     | 0.97 – 5.74     | Saline water         |
|    |          | 0.33                     | 5.74 – 59.18    | Saline water         |
|    |          | 1.36                     | >59.18          | Saline water         |
| 10 | VES_10   | 9.51                     | 0.00 – 0.88     | -                    |
|    |          | 34.10                    | 0.88 – 2.65     | Fresh water          |
|    |          | 2.94                     | 2.65 – 136.1    | Saline water         |
|    |          | 0.02                     | >136.10         | Saline water         |

The results from the analysis of VES data is combined with the lithology data to interpretate the groundwater condition on the aquifer. The interpretation of the value of the prisoner into the condition of groundwater can be explained that:
a. Overburden/top soil layer: Layer with a resistivity value of 4.95 ohm-m - 50.20 ohm-m. This layer lies at a depth from 0.0 m to varies bottom layer at depth of 0.30 - 1.98 m from the top surface. This layer is the result of weathering of the rock beneath it which is clay-glazed material without groundwater.

b. The layer of fresh groundwater carrier with resistivity value varies from 11.60 ohm-m - 62.50 ohms-m. This layer composed of sandstones to sandstone-gravel layers. This layer lies at a very varied depth. In coastal areas found at a depth of 0.80 m - 20.71 m from the top surface, while in the areas far from the coast can be found deeper than 100 meters.

c. Brackish ground water is indicated with resistivity value of 3.0 ohm-m - 10 ohm-m. This layer presents at variable depths depending on the VES distance from coastline. Contact between brackish – saline water is shown in Figure 5 assumed as a fresh-sea water interface.

d. Saline groundwater carrier layer with a resistivity value of less than 3.00 ohm-m. This layer was found at all VES measurement points except in VES-05, VES-06, and VES-07.

5. Conclusions
Geological condition of the Gowa-Takalar Coastal Aquifer, mainly, consists of Alluvial and Coastal Deposits (Qac) with material size of sand to boulder. Those materials form unconfined aquifer categorized as moderately productive aquifer. Water table on this aquifer lies at depth less than 5 meter below land surface leading to an easy condition to extract ground water form aquifer.

![Figure 5. Interpreted fresh-sea water interface based on true resistivity of rock layers.](image-url)
chemical analysis of ground water samples collected from water table of 25 dug wells shows the calculated chloride-bicarbonate ratio is far less than 0.50. The result indicates that here the shallow ground water aquifer has not contaminated yet with sea water intrusion. However, the VES results demonstrate that only three geoelectrical measurement location (VES-05, VES-06, and VES-07) have not indicated the existence of saline water. All VES has low resistivity value indicating the present of brackish water into aquifer.

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