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Estimation of groundwater potential and aquifer hydraulic characteristics using resistivity and pumping test techniques in Makassar Indonesia

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Abstract:

In this study, groundwater potential and aquifer characteristics were analysed and investigated for the first time in an integrated manner using pumping test and resistivity method in all areas within Makassar City, Indonesia. It is identified that the soil layer in Makassar consists of alluvial sediment, clay sand, sandy clay, tuff, and volcanic breccia. Productive aquifers were found at a depth of 15 to 50 m in the northern, southern, and eastern areas of the city and at a depth of 51 to 120 m in the central areas. The storativity values showed that the type of aquifer in Makassar is dominated by unconfined and semi-confined. The largest optimum pumping discharge was identified in Panakkukang and Manggala Districts with values of 0.102 and 0.061 m^3/min, respectively. It was found that the distribution of aquifer transmissivity corresponds to the distribution of the optimum pumping discharge where the largest transmissivity values are located in Panakkukang and Manggala Districts. Among all districts in Makassar City, Panakkukang and Manggala Districts have the greatest groundwater potential. This is most likely due to the position of these two areas which are situated in a groundwater discharge zone identified in the previous study.

KEYWORDS aquifer characteristics; groundwater potential; pumping test; resistivity method

INTRODUCTION

Clean water is one of the important elements of nature which is currently difficult to obtain due to the increasing needs of community and the deterioration of its quality due to water pollution (Dwivedi, 2017). The availability of an adequate amount of clean water is very important in supporting public health and also to support agricultural and industrial activities (Flörke *et al.*, 2018). Currently, the issue of sufficient clean water availability has received great attention from people around the world (Larsen *et al.*, 2016). Water obtained from underground aquifers is presently considered as one of the important natural resources that can be renewed and may support the sustainability of human life and ecosystems (Gleeson *et al.*, 2020). This occurs as a result of the lack of surface water reliability in supplying clean water since it is more susceptible to pollutants (Dwivedi, 2017).

Resistivity method is one of the most promising geophysical techniques used for groundwater surveys. It is non-destructive, cost-effective, and has the ability to provide useful information about the subsoil at a sufficient depth (Mehmood *et al.*, 2020). For example, geo-electric techniques are very efficient in mapping aquifer systems, boundary layers, aquifer depth and thickness, and groundwater quality (Manu *et al.*, 2019). Vertical electrical sounding which is a type of geo-electrical engineering tool, together with other hydrogeological techniques, can be combined to give a rational result and a clear picture of the formations below the ground surface (Manu *et al.*, 2019). This is important for good management of groundwater resources, especially in coastal areas (Sonkamble *et al.*, 2016). In terms of groundwater potential, hydraulic conditions which include transmissivity, storativity, and specific capacity are important keys in developing groundwater flow models to determine quantity and availability of water resources in the future (Bateni *et al.*, 2015). The pumping test is one of the techniques that can be used in determining the hydraulic parameters of the aquifer (Ha *et al.*, 2020). This is one of the most accurate methods that can provide information about the hydraulic parameters of aquifers in general (Ha *et al.*, 2020).

Makassar City, which is the location of this research, is one of the metropolitan cities in Indonesia that is directly adjacent to the Sulawesi Sea. From the results of population census, it is known that the population of Makassar City in 2020 was 1.42 million people (Surya *et al.*, 2020). The increasing population and economic growth continues to increase the need for clean water in Makassar City, both in terms of water for daily needs as well as for industrial and agricultural requirements. The use of groundwater by the community is increasing due to ineffectiveness of the local water company (i.e. Perusahaan Daerah Air Minum) in providing drinking water for the community (Santosa, 2020). However, little information is available on groundwater availability and there is no data related to the local aquifer's

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capability in supplying water to meet this demand. To date, there is no research available explaining in detail about groundwater potential and also the depth of the groundwater aquifer across the city. The continuous rise of groundwater exploitation is considered to have resulted in seawater intrusion in aquifers in the coastal area of Makassar City, especially in Ujung Pandang and Wajo Districts. This is indicated by the growing number of resident wells whose water has turned brackish (Badaruddin *et al.*, 2020). This will trigger some negative impacts, such as seawater intrusion, decreased groundwater quality, and land subsidence in the region (Badaruddin and Mehdizadeh, 2021).

In this study, groundwater potential and aquifer characteristics within the area of Makassar City were investigated in an integrated way by combining pumping test and resistivity method. Since there is a lack of research available related to groundwater potential and aquifer properties in Makassar City, the present study aims to be the first to provide comprehensive information of groundwater conditions and also aquifer characteristics in the form of a map which covers the entire area of the city. It is expected that the results can be used as the basis for a future groundwater model of the respected region and also as preliminary data to give new insight for the local community in exploiting groundwater in a sustainable manner.

Location and geology of the study area

The research location is in Makassar, the capital city of South Sulawesi Province, Indonesia. Makassar City is located at a latitude of 5°03′44.53″ to 5°13′1.61″ S and a longitude of 119°22′44.40″ to 119°32′33.48″ E and is a lowland area with an altitude varying from 1 to 25 m above sea level. The city is directly adjacent to Maros Regency in the north, Gowa Regency in the south, Makassar Strait in the west, and Maros Regency in the east. The area of Makassar City is around 175.77 km^2 which consists of 14 districts, namely Mariso, Mamajang, Tamalate, Rappocini, Makassar, Ujung Pandang, Wajo, Bontoala, Ujung Tanah, Tallo, Panakukkang, Manggala, Biringkanaya and Tamalanrea. The entire area of the city is covered in this study (see Figure 1).

From a geological perspective, the research area is regionally located in the Lompobattang volcanic rock formation which is mostly in the form of volcanic breccia, lava, and tuff (Sigit, 1965). Makassar City itself is located in rock formations, including (1) alluvium deposits in the form of gravel, sand, clay, mud and clay materials, (2) the Lompobattang volcanic rock formation, which consists of volcanic rocks in the form of agglomerates, lava, volcanic breccia, lava deposits and tuff rocks of fine, medium to coarse material size, even in the form of Lapili tuff rock, and (3) volcanic rock consisting of volcanic breccia material, lava and tuff rock of medium to coarse size, and also compact and fresh Lapili tuff rocks.

METHODS

Resistivity survey

Geo-electric measurements were carried out in 10 districts in Makassar City, both in residential and non-residential areas. In each of these districts, a minimum of one measurement point is placed using the code of GLP 01 to GLP 16. The location of the resistivity measurement points can be seen in Figure 2.

The resistivity measurement method used in this study is the Schlumberger method (Bhatnagar *et al.*, 2022) with a span length of AB/2 up to 500 m. This method places the potential electrode MN at a certain span, while the current electrode AB is moved according to the selected span. The total span distance of AB as a whole reaches a distance of 500 m. The placement of the span of the potential electrode MN and the current electrode AB must meet the condition that the distance MN/2 is 1/5 of AB/2 (Vasantrao *et al.*, 2017). The equipment used for resistivity measurements in the entire research area is the Naniura NRD 300 HF (Kalilu *et al.*, 2022) using the Schlumberger method, as previously mentioned. The relationship between resistivity values and

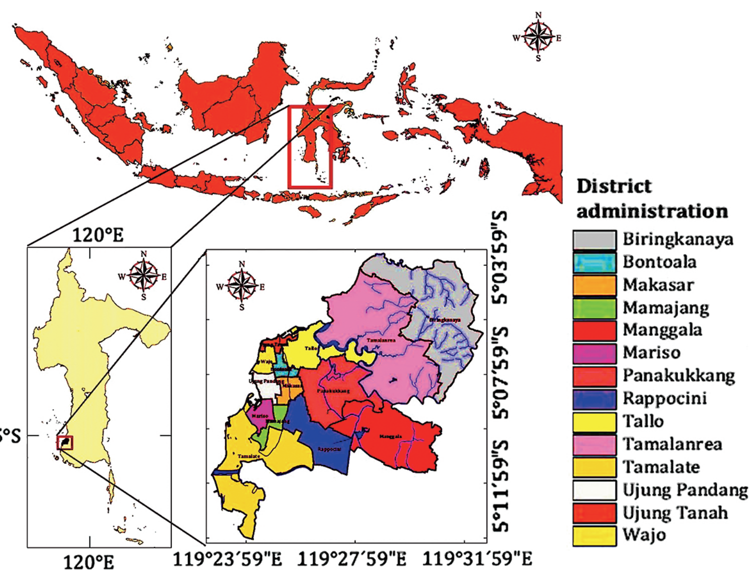

Figure 1. Locality map of study area and division of its administrative area

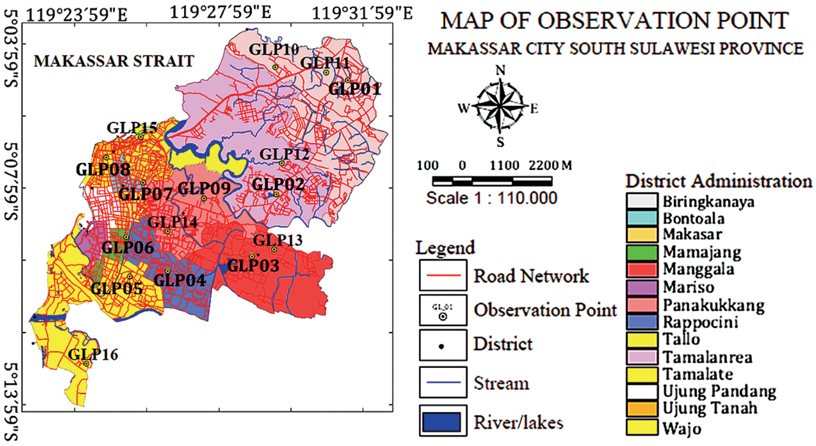

Figure 2. Map of survey point locations in each district

rock types was determined using the results of research from Vingoe (1972) which are provided in the Supplements section (see Tables SI and SII).

The pumping test was also used in this study. Pumping test is a method of measuring water discharge in order to observe the continuity of groundwater sources and the availability of water from the source itself. The essence of this pumping test is the comparison between the decreasing rates of water level during pumping to the increasing rate of water level during recovery (Ha *et al.*, 2020). Using the interpolation technique between pumping discharge and the rate of change of groundwater level in the well during pumping and recovery, the optimum discharge value from the aquifer can be determined. In addition to determining the groundwater potential, another purpose of the pumping test is to determine the characteristics of aquifer capabilities such as transmissivity, specific capacity, and storativity. In this study, the pumping wells at each observation point were pumped with a different constant pumping discharge, with discharges at points GLP 01, GLP 02, GLP 03, GLP 04, GLP 05, GLP 06, GLP 07, GLP 08 and GLP 09 being 0.037, 0.013, 0.062, 0.025, 0.053, 0.043, 0.017, 0.021 and 0.066 m^3/min, respectively. The change in groundwater level in the well at the time of pumping is measured at a certain time using a water level meter and then the change is plotted against the pumping time using a logarithmic scale. The decrease in groundwater level in one logarithmic time phase and pumping discharge were then substituted into the straight-line equation of Cooper Jacob to determine the value of transmissivity (T) [L^2/T], specific capacity (S_y) [L^2/T], and storativity (S) [–] (Anomohanran *et al.*, 2021; Dana and Jwan, 2016). The Cooper-Jacob formula used to calculate these parameters is as follows:

$$T = \frac{2.3 \times Q}{4 \times \pi \times \Delta s} \tag{1}$$

$$Sy = \frac{Q}{\Delta s} \tag{2}$$

and

$$S = 2.25 \times T \times \left(t_0/r^2\right) \tag{3}$$

where Q [L^3/T] is the pumping discharge, Δs [L] is the drawdown in one logarithmic time phase, and (t_0/r^2) [T/L^2] is the intersection of the straight line drawn through the drawdown data in the field with the pumping time, t_0 [T] is the time since pumping began, and r [L] is radius of the pumping well.

RESULTS AND DISCUSSION

Resistivity survey results

As mentioned previously, geo-electric measurements in Makassar City were carried out at 16 points, namely points GLP 01 to GLP 16. In addition to physical aspects (apparent resistivity), geological conditions are also considered in the analysis. The results of geo-electric data processing which include lithological type, layer thickness, layer depth and resistivity value range are shown in Figure 3. For brevity and clarity of the figure, only five interpretation results from five of the observation points are selected and presented in Figure 3. These five observation points are chosen since their positions are distributed evenly throughout the area of Makassar City (see Figure 2). The complete interpretation results are provided in the Supplements section (see Figure S1 to S4 and Table SIII).

From the results of inversion and interpretation of geo-electric data based on the results of Vingoe (1972), it is noticed that the number of subsurface layers at the observation points range from three to six layers with a maximum depth of 40 to 195 m. Three layers were identified in GLP 05, GLP 06, GLP 09, GLP 11, GLP 12, GLP 13 and GLP 16. Four layers were found in GLP 01, GLP 03, GLP 08, GLP 14 and GLP 15, five layers in GLP 10, and six layers in GLP 02, GLP 04 and GLP 07. The subsurface layers are dominated by top soil (i.e. alluvial deposits), clay sand, sandy clay, tuff/sandstone and volcanic breccia. Potential groundwater aquifers are generally located in tuff/sandstone layers with depths ranging from 15 to 120 m. From the inversion results of geo-electric data, it is found that freshwater which has the potential as a source of groundwater is generally in the tuff/sandstone layer with resistivity values ranging from 5.6 to 164.0 Ωm (Palacky, 1987; Riwayat *et al.*, 2018; Vingoe, 1972) with aquifer thicknesses ranging from 15 to 70 m. In addition, it is also discovered in this research that there is brackish to salty water in the subsurface soil layers with resistivity values lower

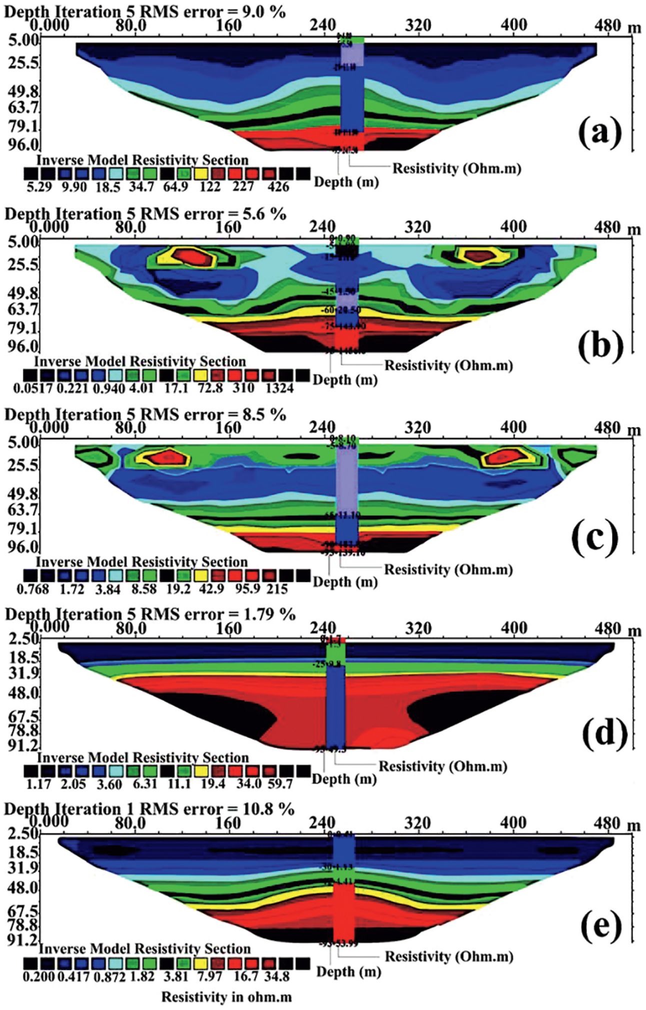

Figure 3. The cross-section of resistivity value from the geo-electric survey and the depth of each layer at point (a) GLP 01 (b) GLP 04 (c) GLP 08 (d) GLP 12 (e) GLP 16

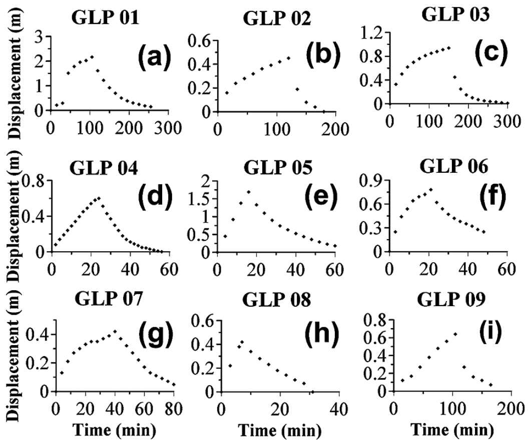

Figure 4. Pumping and recovery test graphs on (a) GLP 01 (b) GLP 02 (c) GLP 03 (d) GLP 04 (e) GLP 05 (f) GLP 06 (g) GLP 07 (h) GLP 08 and (i) GLP 09

than 7 Ωm (Islami, 2011; Singh *et al.*, 2004), namely in GLP 04, GLP 06, GLP 07, GLP 10, GLP 12, GLP 14, GLP 15 and GLP 16. This is in good agreement with the results of Meyke *et al.* (2020) that identified higher groundwater salinity in Untia Village in Biringkanaya District (near GLP 10) where the optimum groundwater discharge in this area is relatively small. This is most likely due to the influence of seawater intrusion or saltwater trapped for a long period of time. Further research is required to investigate this phenomenon.

Pumping test results

Figure 4 shows the results of pumping and recovery tests from pumping wells at points GLP 01 to GLP 09. Each well sample studied gave quite varied results in terms of drawdown velocity during pumping and groundwater level increment velocity during recovery. This shows the differences in the ability of each observed aquifer in responding to the groundwater abstraction through the pumping process.

Figure 4 indicates that in general, there are three conditions of the rate of change of the groundwater level during pumping and recovery. The first is the condition where the rate of change of groundwater level during pumping is greater than during recovery occurred in GLP 01, GLP 04, GLP 05, GLP 06, GLP 07 and GLP 08. The second is the condition where the rate of change of groundwater level during pumping is smaller than during recovery which occurred in GLP 02 and GLP 09. The third is the condition where the rate of change of groundwater level during pumping is the same as during recovery only which occurred in GLP 03. Using interpolation it is known that the optimum pumping discharge in the points of GLP 01, GLP 02, GLP 03, GLP 04, GLP 05, GLP 06, GLP 07, GLP 08 and GLP 09 are 0.024, 0.026, 0.061, 0.019, 0.023, 0.023, 0.015, 0.002 and 0.102 m^3/min, respectively. From all measured pumping points, the largest optimum pumping discharge was found in GLP 09, which is around the Panakkukang District with an optimum pumping discharge of 0.102 m^3/min, and the smallest pumping optimum discharge was found in GLP 08 which is around the Wajo District with an optimum pumping discharge of 0.002 m^3/min.

Hydraulic characteristics of the aquifer

Using the drawdown data outlined in a semi-logarithmic graph (see Figure S5 in the Supplements section), the groundwater aquifer parameter values in the form of transmissivity (T), specific capacity (S_y) and storativity (S) can be determined using Equations (1), (2) and (3). In detail, the values of T, S_y and S are shown in Table I. Based on the value of S in Pongmanda and Suprapti (2020) which is not written here for brevity, the type of aquifer at the observed point can be determined.

From Table I, it is shown that the highest transmissivity values were noticed at points GLP 03 in Manggala District and GLP 09 in Panakkukang District with T of 0.024 m^2/min and 0.019 m^2/min, respectively. Meanwhile, the smallest transmissivity value was found at points GLP 08 in Wajo District and GLP 01 in Biringkanayya District with T of 0.007 m^2/min and 0.003 m^2/min, respectively. Based on the storativity values obtained from the pumping test, it can be seen that the type of aquifer found at points GLP 01, GLP 02, GLP 03 and GLP 09 is unconfined, and

Table I. Aquifer hydraulic characteristic values calculated from Cooper-Jacob's straight line equation (Dana and Jwan, 2016)

Station	Transmissivity (*T*) (m^2/min)	Specific capacity (S_y) (m^2/min)	Storativity (*S*) (–)	Type of aquifer based on storativity values
GLP 01	0.003	0.015	0.090	Unconfined
GLP 02	0.008	0.044	0.099	Unconfined
GLP 03	0.024	0.134	0.240	Unconfined
GLP 04	0.009	0.048	0.017	Semi Confined
GLP 05	0.005	0.026	0.027	Semi Confined
GLP 06	0.012	0.069	0.033	Semi Confined
GLP 07	0.011	0.062	0.035	Semi Confined
GLP 08	0.007	0.038	0.017	Semi Confined
GLP 09	0.019	0.105	0.380	Unconfined

the type of aquifer found at points GLP 04, GLP 05, GLP06, GLP 07 and GLP 08 is semi-confined.

Figure 5a reveals that the deepest position of the groundwater aquifer is in Tallo District which is in the mid-west of the Makassar City area with a depth of 120 m. The depth of the groundwater aquifer is decreasing towards the north, south and east of Makassar City with a minimum depth of 15 m. This means that for people living in Tallo District, Ujung Tanah District and parts of Panakkukang and Tamalanrea Districts, to access a good groundwater source they have to drill deeper to reach the groundwater aquifer.

From Figure 5b, it can be seen that the largest value of the optimum pumping discharge is in the central part of the Makassar City area, namely in the Panakkukang District with a value of 0.102 m^3/min, then it decreases in all directions to the outskirts of the city with the smallest value of 0.001 m^3/min at the northwest of Makassar City, namely in Districts of Wajo and Ujung Tanah whose territory is directly adjacent to the Makassar Strait. These values are considered reasonable compared to the results of Amah *et al.* (2012) which obtained values ranging from 0.036 to 1.833 m^3/min for the optimum groundwater discharge in Calabar coastal aquifers, Nigeria. A larger value of optimum pumping discharge in Panakkukang District is most likely because the area is situated in a groundwater discharge zone whose source is partly from precipitation that infiltrates around the city of Makassar, mainly from the eastern part of the city (Caronge and Mardyanto, 2019). Caronge and Mardyanto (2019) determined the area of groundwater recharge and discharge in Makassar City using ArcGIS based on distribution of several parameters including soil permeability, slope of soil surface, geological condition, rainfall, and land cover. They found that recharge areas are mostly located in the eastern part of the city i.e. Biringkanaya and Manggala Districts, while discharge areas are located mainly in the central part of the city i.e. Panakkukang, Tamalanrea and Tallo Districts.

The results of the transmissivity shown in Figure 5c indicate a good agreement with the optimum groundwater pumping discharge data shown in Figure 5b. It can be observed that the highest transmissivity value is in the central part of the Makassar City area, namely in the Manggala and Panakkukang Districts with transmissivity ranging from 0.014 to 0.022 m^2/min and then the transmissivity

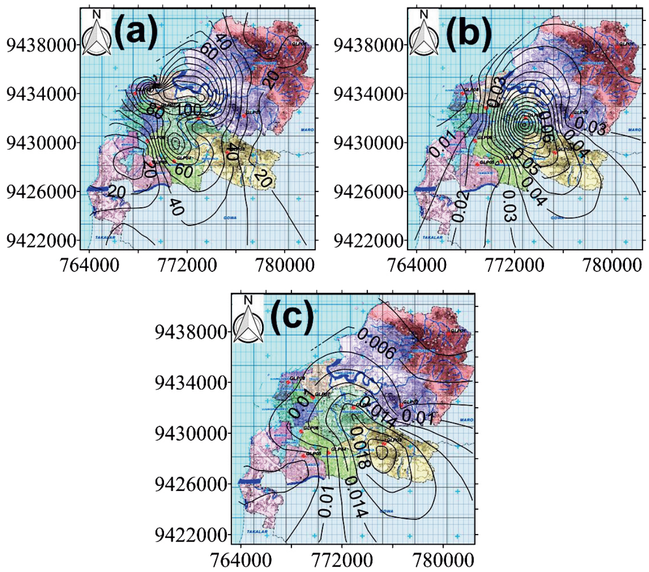

Figure 5. Map of (a) the depth of groundwater aquifer in Makassar City (units in m), (b) the optimum groundwater pumping discharge in Makassar City (units in m^3/min), and (c) the groundwater aquifer transmissivity in Makassar City (units in m^2/min)

value decreases in all directions out of the Makassar City area with the smallest value towards the northeast, namely in Biringkanayya District with a value of 0.003 m^2/min. Based on the results of research from Krásný (1993), in general, the value of transmissivity of aquifers in the Makassar City area is dominated by aquifers with category 2, namely aquifers that can be used to supply water for medium-scale residents, both for industrial and domestic purposes. Aquifers with category 3 which are considered good enough by Krásný (1993) to supply water for small-scale residents are also found in some areas at northeast of Makassar City, such as in Biringkanayya District and southwest of Makassar City, namely in Tamalate District with transmissivity values less than 0.006. These results inform that in general, groundwater aquifers in Makassar City have good potential to become a source of clean water and in detail, it can be seen that among all districts in

Makassar City, Panakkukang and Manggala Districts have the most potential to be utilized as a source of clean water for residents of Makassar City. The aquifers in these two areas can be used as an alternative water source to accompany surface water sources that are already in use today.

CONCLUSION

In this study, a combination of resistivity survey and pumping test was carried out to determine the subsurface lithology and hydraulic parameters of groundwater aquifers in the Makassar City of Indonesia. The results showed that the subsurface layer of Makassar City consists of top soil in the form of alluvial deposits, clayey sand, sandy clay, tuff/sandstone, and volcanic breccia/bedrock. Based on the storativity value, aquifers in the Makassar City area are dominated by unconfined and semi-confined aquifers. Productive aquifer layers are generally found at a depth of 15 to 50 m in the northern, southern and eastern parts of Makassar City and at a depth of 51 to 120 m in the central part. The resistivity value of the productive aquifer from the resistivity survey results ranges from 5.6 to 164.0 Ωm with a thickness ranging from 15 to 70 m. Based on the results of the pumping test, it is known that the optimum groundwater pumping discharge in the Makassar City area ranges from 0.002 m^3/min to 0.102 m^3/min. The highest optimum groundwater pumping discharge is in Panakkukang and Manggala Districts. From the value of the hydraulic characteristics of the aquifer obtained from the pumping test analysis which includes transmissivity, specific capacity and storativity, it is known that the aquifers in the Panakkukang and Manggala Districts are aquifers with the most potential to be used as sources of clean water. The aquifer transmissivity values in Panakkukang and Manggala Districts ranged from 0.019 and 0.024 m^2/min, respectively. These values indicate that the aquifers in the Panakkukang and Manggala Districts have sufficient water to supply clean water for industrial and domestic needs in areas with a medium-scale population. In this case, it is highly recommended to create a groundwater utilization scheme in these two areas.

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SUPPLEMENTS

Figure S1. The cross-section of resistivity value from the geo-electric survey and the depth of each layer at point (a) GLP 01 (b) GLP 02 (c) GLP 03 (d) GLP 04

Figure S2. The cross-section of resistivity value from the geo-electric survey and the depth of each layer at point (a) GLP 05 (b) GLP 06 (c) GLP 07 (d) GLP 08

Figure S3. The cross-section of resistivity value from the geo-electric survey and the depth of each layer at point (a) GLP 09 (b) GLP 10 (c) GLP 11 (d) GLP 12

Figure S4. The cross-section of resistivity value from the geo-electric survey and the depth of each layer at point (a) GLP 13 (b) GLP 14 (c) GLP 15 and (d) GLP 16

Figure S5. Drawdown vs. time of pumping with the drawdown per log circle of time and the time intercept in (a) GLP 01 (b) GLP 02) (c) GLP 03 (d) GLP 04 (e) GLP 05 (f) GLP 06 (g) GLP 07 (h) GLP 08 dan (i) GLP 09

Table SI. Resistivity values of some rock minerals (Vingoe, 1972)

Table SII. Relationship between resistivity values and type of water (Vingoe, 1972)

Table SIII. Results of interpretation from resistivity survey

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