Groundwater Pumping Management in Controlling Seawater Up-Coning in The North Coastal Area of Makassar

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Abstract—In big cities, communities generally consume clean water from local water supply company which uses surface water sources. However, due to the limitations of the company in supplying water, particularly in the dry season, an alternative is required, such as using groundwater without causing over-exploitation. This study aims to determine the optimal rate of groundwater pumping in the coastal aquifer to avoid seawater up coning using SEAWAT V.4 numerical model. The research method was carried out using a GEO-7X GPS device to obtain coordinate's location, land elevation and observation well distance from the coastline. Secondary data in the form of aquifer thickness data and geological map of the site were obtained from previous studies. The salinity test results show that the average salinity value of the ten water samples from observation wells is 36.8 mg/l, which means that the water is categorized as non-saline water (freshwater). These data are in line with the groundwater utilization monitoring activity report of Makassar City Environment Office in 2018, which reported that Ujung Tanah and Wajo Districts were found to be free from seawater intrusion. Even so, the potential for seawater intrusion is still considered high because of the location of community groundwater wells are near from the coast. One of the efforts to prevent seawater up coning is by limiting groundwater pumping. From the numerical modeling results, it is found that the maximum groundwater discharge in the research site, namely P3 is 20% of total flow rate(0.3 m³/day), P5 is 20% (1.32 m³/day), P6 is 40% (0.52 m³/day) and P10 is 20%(0.63 m³/day).

Keywords—*Seawater Up-coning; Groundwater Pumping; Numerical Modelling*

I. Introduction

Water is a basic need to support human life. Water is used for daily purposes such as drinking water, irrigation, industry, and others. One source of water is groundwater. In general, groundwater is water that is contained in layers of soil or rocks below the soil surface. Groundwater is formed or flows from the recharge area, immediately when it rains, so it requires a significant amount of time to be in the aquifer layer before finally reappearing naturally at the discharge point, depending on the position of the saturated zone, topography, climatic conditions and aquifer hydraulics [1].

One of the objectives of groundwater management in coastal areas is to maximize groundwater use without causing an invasion of seawater into pump wells. Some management questions can arise regarding this consideration. For existing pump wells, for example, what is the maximum pumping discharge that can be done? For new pump wells, where should the well be located? How to maximize groundwater recharge in coastal aquifers? This question can be answered by using a seawater intrusion simulation model [2]-[4].

One of the problems arising from excessive groundwater pumping in coastal aquifers is up-coning. Up-coning is the vertical movement of seawater towards the pump well, and this is a global problem [5]. Previous studies have explained that groundwater pollution due to up-coning will usually cause the pump wells to no longer be used because groundwater quality has been degraded [6]. So far, up-coning seawater has been studied more theoretically because of limited field data about the dynamics of seawater under the pump well.

The most widely used solution regarding up-coning is the solution from [7]. They provide transient solutions for interface movement under pump wells in a coastal aquifer that is unlimited in size. They compared the results obtained from the analytical solution with the results from the sand tank experiments. There is a fairly good fit between the results of the analytical solution and the results of the experiment. [8] was the first to carry out numerical modeling for up-coning under pump wells involving variable-density and the effects of dispersion. They found that the up-coning process was strongly influenced by the dispersion parameters and this result was confirmed by [9] who carried out the same modeling and found that seawater transport was strongly influenced by longitudinal dispersion.

Currently, in the north coastal area of the city of Makassar, the use of groundwater has been very intensive. Because of its location near the coastline, there is a possibility of a significant seawater infiltration in the area. In addition, uncontrolled groundwater uptake in the area can cause a decrease in the groundwater level and cause emptiness in the pores of the soil in the aquifer layer. This decrease in groundwater level causes seawater to move into the aquifer and cause pollution of groundwater.

In this study, numerical modeling is used to determine the condition and description of salinity distribution as a reference parameter for groundwater quality in people's wells around the north coast of Makassar while evaluating the optimal pumping discharge that can be done to control the up-coning around the north shore of the city. Numerical modeling is done by using 2-dimensional models at several observation locations.

II. Methodology

A. Conceptual model

Figure 1 shows a schematic picture of an unconfined coastal aquifer, following the conceptual model used in [10]. Three different salinity contours were measured in evaluating the interface configuration (i.e., 5, 50, and 95% of seawater salinity), and both the interface toe at the aquifer base x_{toe} [L] and the interface tip at the watertable x_{tip} [L] were evaluated. In Figure 1, the right and the left sides represent the coastal and the inland boundaries, respectively, with hs the depth of the horizontal aquifer base below sea level [L], and hf the inland freshwater head [L].
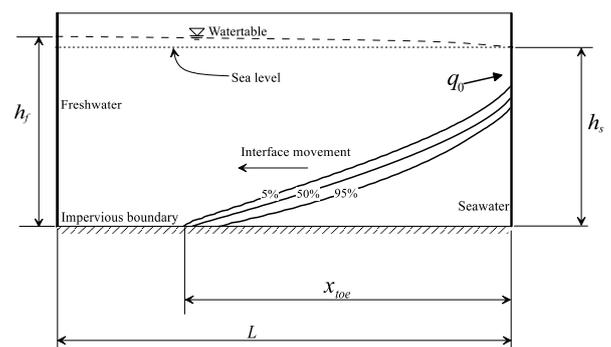
Figure 1. Conceptual model of an unconfined coastal aquifer subjected to SWI and q_0 is freshwater discharge to the sea [L2/T] (adopted from [10]).

B. Research Site and Time Frame

The location of this research is located on the north coast of Makassar City, namely Ujung Tanah District and Wajo District (See Figure 2). The study was conducted in January 2019 to August 2019.

Figure 2. Research site

C. Materials

The tools and materials used in this study are as follows:

1. Conductometer for measuring the salinity of well water samples.
2. GPS Geo 7X to mark the location point of salinity measurement, measure elevation and distance.
3. 600 ml Sample Bottle for storing water samples.
4. Cooler Box to preserve water samples.
5. Water bucket to take samples from the bucket to the bottle.
6. Roll Meter to measure the height of the top of the well.
7. Water Level to measure the level of water in the well.
8. Stationery for recording measurement and test results.
9. Laptops that have Microsoft Excel, ArcGIS 10.4 and SEAWAT V.4 software installed to process data.
10. Camera to document activities.
11. Aquades for cleaning the conductometer.

The types of data used include primary and secondary data. Primary data include well water salinity data, well coordinates, well water level, distance between wells to shoreline, and well surface elevation. Secondary data includes data obtained from previous studies and related institutions namely aquifer thickness data in the Makassar area collected from the Department of Energy and Mineral Resources of South Sulawesi Province, porosity and soil permeability values obtained from the literature [11] and [12] and other related resources (i.e., [13]).

Data such as soil porosity, soil permeability, well water level, distance between wells to the coastline and other data will be inputted to software called SEAWAT V.4 [14]. These data can be seen in Table 1. Through SEAWAT V.4, numerical modelling will be performed for pumping simulations on each well sample so that it may predict the maximum pumping depth, maximum discharge and the exact pumping location so that there is no up-coning in the future.

Table1. Hydrogeological data used in numerical modelling.

Parameter	Case			
	P3	P5	P6	P10
K (m/day)	10	10	10	10
Z_0 (m)	80	200	200	80
MAT (m)	2,72	2,41	1,80	2,96
n	0,35	0,35	0,35	0,35
δ	0,025	0,025	0,025	0,025
Q_{tot} (m³/day)	1,51	3,31	2,58	3,13

Figure 3 is an example of pumping modelling using SEAWAT V.4 software. X is the distance of the well from the coastline which is represented by a uniform vertical line, while Z is the thickness of the aquifer which is represented by a uniform horizontal layer. The red dot is the groundwater pumping point. The red line is the 1% isochlor concentration line with a concentration value of 500 mg/l, the blue line is the 50% isochlor concentration line with a concentration value of 17,500 mg/l and the black line is the 95% isochlor concentration line with a concentration value of 33,250 mg/l. Each case will be modelled with a pumping distance of 3/4 Xt and a pumping depth of 2/5 Z.
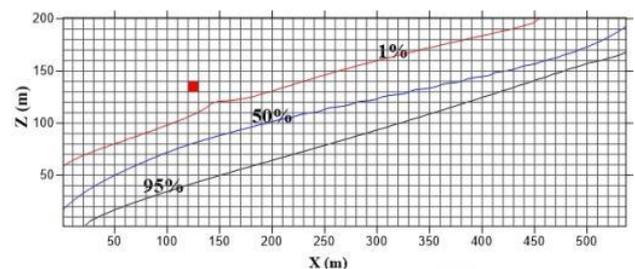
Figure3. Description of pumping modelling with SEAWAT V.4

III.   Results and Discussion

A. Distribution of Water Quality in Pumping Well

From the results of measurements of shallow well samples conducted on the north coast of Makassar City using GPS Geo 7X, obtained the coordinates of the sampling points as in Table 2.

Table 2. Pumping well point coordinates

Sample point	Coordinates		District
	X	Y	
P1	767338	9433000	Wajo
P2	767730	9432893	Wajo
P3	767868	9432722	Wajo
P4	768517	9434178	Ujung Tanah
P5	767679	9433984	Ujung Tanah
P6	768385	9434002	Ujung Tanah
P7	768239	9433630	Ujung Tanah
P8	768210	9434289	Ujung Tanah
P9	767377	9433580	Wajo
P10	767424	9432733	Wajo

Primary data obtained from the results of measurements of shallow well samples conducted on the north coast of Makassar City using GPS Geo 7X, water level and roller meters can be seen in Table 3.

Table 3. Measurement results at pumping well sample points.

Sample points	Groundwater level	Soil elevation	Distance
	m	m	m
P1	0,79	3,46	494,04
P2	1,09	4,63	900,34
P3	0,81	3,53	937,69
P4	1,08	3,54	194,33
P5	1,37	3,49	460,67
P6	1,22	3,02	537,15
P7	1,14	6,25	868,56
P8	1,27	3,32	209,18
P9	1,21	7,32	405,79
P10	1,11	4,07	519,66

Salinity testing for well water samples was conducted at the Environmental Laboratory of South Sulawesi Province with parameters in the form of chloride content found in water samples. Laboratory test results obtained can be seen in Table 4.

Table 4. Laboratory test results of pumping well water samples

Sample point	Coordinate		Salinity
	X	Y	mg/l
P1	767338	9433000	36,9
P2	767730	9432893	22,0
P3	767868	9432722	69,0
P4	768517	9434178	23,5
P5	767679	9433984	12,7
P6	768385	9434002	52,8
P7	768239	9433630	5,4
P8	768210	9434289	53,3
P9	767377	9433580	57,2
P10	767424	9432733	35,2

Based on the salinity test results from 10 well water samples on the north coast of Makassar City, the salinity values obtained were classified based on the amount of salinity in the water according to [15]. All well water samples included in the category of non-saline (freshwater) with a salinity value <500 mg/l. Freshwater is water that does not taste and does not contain much salt or other mineral solutions, so it is safe to be used as drinking water for humans.

Based on the Groundwater Utilization Monitoring Activity Report by the Makassar City Environment Office in 2018, observations of seawater infiltration based on alkalinity concentration (R values) are estimated to occur around Ujung Pandang District, Biringkanaya District, Rappocini District, Tallo District and Panakkukang District. So that the Ujung Tanah and Wajo Districts are expected to have not experienced seawater infiltration so that the well water in both districts is still classified as freshwater. Judging from the chemical parameters namely Hardness, Chloride, Nitrite, BOD, DO, Salinity and pH that exceed the quality standards can be seen in the area around the District of Ujung Based on chemical parameters, Ujung Tanah District and Wajo District have not exceeded the quality standard so they are still classified as safe for use as

drinking water. Although at present, the condition of well water in the north coastal area of Makassar City is still in fresh condition so it is safe for consumption but groundwater pollution due to seawater intrusion in the area is very likely to occur because of the location of shallow wells of communities that are very close to the sea, precisely to the north of Makassar City which is directly adjacent to the sea. If groundwater extraction is carried out irregularly with large discharges at certain depths and locations that are less strategic, it can trigger up-coning so that well water becomes salty and no longer suitable for consumption as drinking water. The results of measurements in the field and the results of water salinity laboratory tests in the Environmental Laboratory unit of South Sulawesi Province are shown in Figure 4.
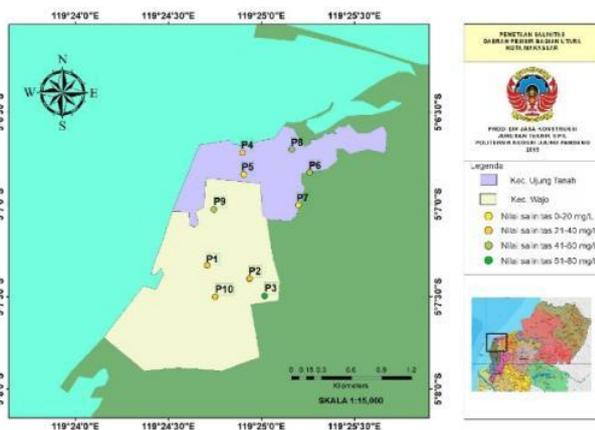
Figure 4. Map of salinity distribution in the north coastal region of Makassar City.

B. Groundwater Pumping Settings Numerical Model

Groundwater pumping modelling in the north coastal area of Makassar City was carried out using SEAWAT V.4 application by adjusting the position, depth and discharge of the pumping. Modelling is presented in 2 dimensions with an estimated time of the next 100 years. The sample points that are modelled are P3, P5, P6 and P10. Aquifer conceptualization of the four research location points used in numerical models and modelled in 2 dimensions and cross-sections perpendicular to the coast. Each point is modelled in 1 pumping position with a certain pumping point and

discharge depth until it reaches a maximum flow that is safe to pump before reaching up-coning.

a. **Case P3**

Xt   = 334 m
3/4 Xt   = 250,5 m
Pumping distance for Case P3 is 250,5 m from the coastline
Z   = 80 m
2/5 Z   = 32 m
Pumping depth for Case P3 is 32 m.

Figure 5 is a steady-state condition before pumping. This case is modeled in two dimensions, and the cross-section is perpendicular to the beach. The domain model is uniformly discredited in carrying out "steady-state" simulations. For aquifers at Case P3 use 469 vertical columns with a width of 2 m and 42 horizontal layers with a thickness of 2 m.
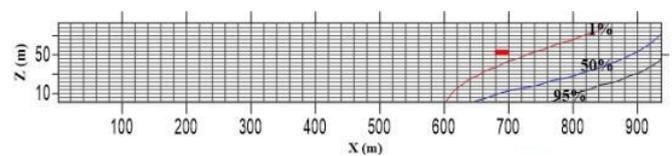
Figure5. P3 condition before pumping

Table5. Modelling results for Case P3.

No	Flow rate		Distance (Xt)	Depth	Period	Indicator
	m³/day		m	m	(years)	
1	Q10%	0.15	250,5	32	-	Up-coning has not happened, wells have not contaminated
2	Q20%	0,30	250,5	32	10	Up-coning is started, wells have not contaminated
3	Q30%	0,45	250,5	32	10	Up-coning is started, wells have not contaminated
4	Q40%	0,60	250,5	32	16	Up-coning has occurred, Wells have been contaminated

Thus from Table 5, for the position of P3 in the pumping position of 250.5 m from the coastline with a pumping depth of 32 m, the maximum safe discharge for use in pumping is 20% of the total Q (0.30 m³/day).

b. **Case P5**

Xt   = 462 m
3/4 Xt   = 346,5 m
Pumping distance for Case P5 is 346,5 m from the coast line
Z   = 200 m
2/5 Z   = 80 m
Pumping depth for Case P5 is 80 m.
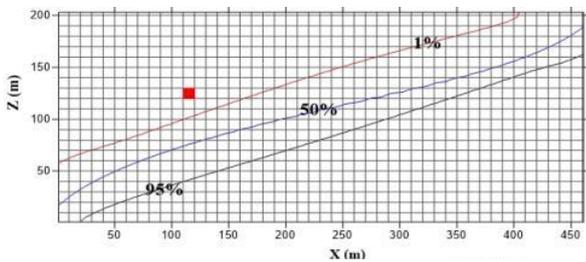
Figure 6. P5 Condition before pumping

Figure 6 shows a steady-state condition before pumping. This case is modeled in two dimensions and the cross-section is perpendicular to the beach. The domain model is uniformly discretized in carrying out "steady-state" simulations. For aquifers in the case of P6 used 231 vertical columns with a width of 2 m and 102 horizontal layers with a thickness of 2 m.

Table 6. Modelling results For Case P5.

No	Flow rate		Distance (Xt)	Depth	Period	Indicator
		m³/day	m	m	(years)	
1	Q40%	1,32	346.5	80	10	Up-coning has started, wells have not contaminated
2	Q60%	1,99	346.5	80	1	Up-coning has started, wells have not contaminated
3	Q80%	2,65	346.5	80	1	Up-coning has started, wells have not contaminated
4	Q100%	3,31	346.5	80	23	Up-coning has occurred, wells have been contaminated

Thus from Table 6, for the position of the P5 case at the pumping position 346.5 m from the shoreline with a pumping depth of 80 m, the maximum safe discharge for use in pumping is 40% of Q total (1.32 m³/day).

c. **Case P6**

Xt   = 528 m
3/4 Xt   = 403,5 m
Pumping distance for Case P6 is 403,5 m from the coast line
Z   = 200 m
2/5 Z   = 80 m
Pumping depth for CaseP6 is 80 m.
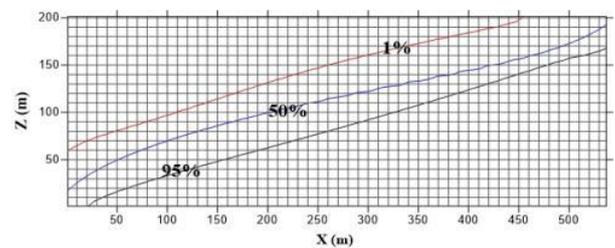
Figure 7. P6 condition before pumping

Figure 7 shows a steady-state condition before pumping. This case is modelled in two dimensions and the cross-section is perpendicular to the beach. The domain model is uniformly discretized in carrying out "steady-state" simulations. For aquifers in the case of P6 using 269 vertical columns with a width of 2 m and 102 horizontal layers with a thickness of 2 m.

Table 7. Modelling Results for Case P6

No	Flow rate		Distance (Xt)	Depth	Period	Indicator
		m³/day	m	m	(years)	
1	Q20%	0,52	403.5	80	10	Up-coning has started, wells have not contaminated
2	Q40%	1,03	403.5	80	1	Up-coning has started, wells have not contaminated
3	Q60%	2,07	403.5	80	1	Up-coning has started, wells have not contaminated
4	Q100%	2,58	403.5	80	2	Up-coning has occurred, wells have been contaminated

Thus from Table 7, for the position of the P6 case at the pumping position of 403.5 m from the coastline with a pumping depth of 80 m, the maximum safe discharge

for use in pumping to avoid contamination under sustainable conditions is 0.52m³/day.

d. **Case P10**

Xt   = 182 m
3/4 Xt = 136,5 m
Pumping distance for Case P10 is 136,5 m from the coast line
Z   = 80 m
2/5 Z= 32 m
Pumping depth for Case P10 is 32 m.
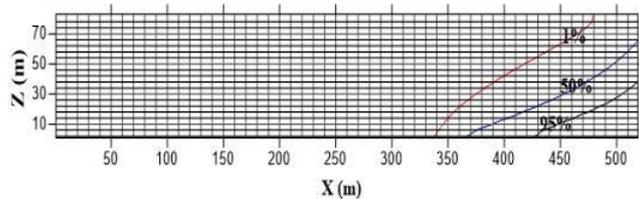
Figure 8. P10 condition before pumping

Figure 8 shows the steady-state conditions before pumping. This case is modelled in two dimensions and the cross-section is perpendicular to the beach. The domain model is uniformly discretized in carrying out "steady-state" simulations. For aquifers in Case P6 use 260 vertical columns with a width of 2 m and 42 horizontal layers with a thickness of 2 m.

Table 8. Modelling results for Case P10

No	Flow rate		Distance (Xt)	Depth	Period	Indicator
	m³/day		m	m	(years)	
1	Q20%	0,63	136.5	32	-	Up-coning has started, wells have not contaminated
2	Q40%	1,25	136.5	32	10	Up-coning has started, wells have not contaminated
3	Q60%	1,88	136.5	32	5	Up-coning has happened, wells have been contaminated

Thus from Table 8, for the position of the P10 case at the pumping position of 136.5 m from the coastline with a pumping depth of 32 m, the maximum safe discharge for use in pumping to avoid contamination under sustainable conditions is 0.63 m³/day. The maximum pumping rates that can be done for each observation well is shown in Table 9.

Table 9. Maximum pumping rates obtained from the numerical model for all cases.

No	Case	Max Flowrate m³/day
1	P3	0,30
2	P5	1,32
3	P6	0,52
4	P10	0.63

Based on the simulation results of groundwater pumping with SEAWAT V.4, it can be seen that the length of seawater intrusion that occurred in steady-state conditions in the P3 case for 1% isochlor concentration is 324 m, 50% is 294 m and 95% is 174 m. In the case of P5 the concentration of 1% isochlor is 462 m. In the case of P6 for a concentration of 1% it was 538 m. Whereas in the P10 case for 1% isochlor concentration was 182 m, 50% was 154 m and 95% was 94 m.

To get a sustainable condition, it was found that at position P3 (distance of 250.5 m from the coastline and pumping depth of 32 m) the maximum discharge that can be used to prevent contamination is Q20% (0.30 m³/day). For position P5 (a distance of 346.5 m from the coastline and pumping depth of 80 m) the maximum discharge that can be used is Q40% (1.32 m³/day). For position P6 (a distance of 403.5 m from the coastline and pumping depth of 80 m) the maximum discharge that can be used is Q40% (1.03 m³/day). As for the position of P10 (distance 136.5 m from the coastline and pumping depth 32 m), the maximum discharge that can be used is Q20% (0.63 m³/day).

In the case of P3 with a Q20% discharge (0.3 m³/day), if pumping is carried out on an ongoing basis, then up-coning will occur in the 10th year. For the case of P5 with a Q40% discharge (1.32 m³/day) there will be an up-coning in the 10th year. For the P6 case with a Q20% discharge (0.52 m³/day) there will be an up-coning in the 10th year. Whereas in the case of P10 with a Q40% discharge (1.25 m³/day) there will be an up-coning in the 10th year.

In the case of P3 with a Q40% discharge (0.60 m³/day), if pumping is carried out on an ongoing basis, then contamination will occur in the 16th year. For the case of P5 with Q100% discharge (3.31 m³/day),

contamination will occur in the 23rd year. For P6 cases with Q100% discharge (2.58 m³/day) contamination will occur in the 2nd year. Whereas in the case of P10 with a Q60% discharge (1.88 m³/day) contamination will occur in the 5th year.

IV. Conclusion

From the results of research in the north coastal area of Makassar City, it was concluded that based on the salinity test in the laboratory, the average salinity value in the ten samples tested was 36.8 mg / l. The results showed that all well water samples located in Ujung Tanah and Wajo Districts were included in the non-saline (freshwater) classification. Based on groundwater pumping simulation using SEAWAT V.4, to obtain a sustainable condition, it was found that at position P3 (distance 250.5 m from the coastline and pumping depth 32 m) the maximum discharge that can be used to prevent up-coning is Q20 % (0.30 m³/day). For position P5 (a distance of 346.5 m from the coastline and pumping depth of 80 m) the maximum discharge that can be used is Q40% (1.32 m³/day). For position P6 (a distance of 403.5 m from the coastline and pumping depth of 80 m) the maximum discharge that can be used is Q40% (1.03 m³/day). As for the position of P10 (distance 136.5 m from the coastline and pumping depth 32 m), the maximum discharge that can be used is Q20% (0.63 m³/day).

Acknowledgement

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