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RESEARCH ARTICLE

Predictive numerical modeling of groundwater drawdown impacts in Jakarta

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Abstract An excessive groundwater usage is happening in Jakarta, Indonesia, due to the population growth and industrial development so that it experiences a significant groundwater drawdown which could enhance the risk of seawater intrusion and land subsidence. Existing conditions in 2018 show that seawater intrusion occurred at the Western and Central coastal area and land subsidence happen in the Northern and Central part. This research, a numerical simulation, is conducted by modeling such causality during the critical period, the next 20 years. The result shows that for every groundwater drawdown of 10 m/year, it will cause intrusion 0.7 km/year in the Western and Central and 1.1 km/year in the Eastern area after 2028. The 10 m/year groundwater drawdown also results in land subsidence of 5.7 cm/year in the Northern and 2.5 cm/year in Central Jakarta. This result is useful as an input for groundwater management policies and to prevent the environmental impacts occurred at other large coastal cities.

1. Introduction

A significant groundwater level drawdown in large cities in Indonesia (Wirakusumah & Danaryanto, 2004; Taniguchi, Burnett, & Ness, 2008; Hosono, et al., 2011; Kagabu, et al., 2011, 2012, Taufiq, et al., 2018a), has caused many subsurface issues: land subsidence (Taufiq, 2010; Sarah, et al., 2018; Bandono, 1983; DGTL & Dinas Pertambangan DKI Jakarta, 1996; Ramdhan & Hutasoit, 2007), seawater intrusion (Hehanusa, 1979; Djijono, 2002; Setiawan, et al., 2017, Onodera, et al., 2009), groundwater pollution (Hosono, et al., 2009; Taufiq, et al., 2019), the increase of groundwater temperature (Lubis, et al., 2013), groundwater mixing (Taufiq, et al., 2018b), groundwater age rejuvenation (Kagabu, et al., 2012; Taufiq, et al., 2018a) and others.

Jakarta, the capital city of Indonesia, is one of the largest cities in Southeast Asia. A drastic groundwater drawdown is happening as the consequences of the water resource needs due to a high rate of population and industrial growths (Wirakusumah & Danaryanto, 2004; Delinom, 2008). The groundwater drawdown in Jakarta area has affected the subsurface environment in negative ways, such as seawater intrusion and land subsidence. The seawater intrusion under unconfined aquifers in Jakarta area had been identified from the presence of brackish water which has a $Cl/HCO_3 > 1$ ratio (Setiawan, et al., 2017) and groundwater levels below sea level (Hehanusa, 1979). Soenarto & Widjaya (1985) also found that the intrusion affected not only unconfined aquifers but also confined aquifers. Djaeni, et al. (1986) also reported that the presence of brackish water from a depth of 0 to 100 m has spread up to 6 km from the coastline.

On the other hand, land subsidence in Jakarta area was already known since 1926. At the beginning of the 1980s ,the land subsidence had been caused also by groundwater drawdown, which was analyzed by using leveling survey method, extensometer measurement, and GPS survey (Abidin, et al., 2007) as well as with analytical method and modeling (Marylin & Hutasoit, 2018). Geodetic observation conducted by Dinas Pertambangan DKI Jakarta with LPM-ITB (1999) showed that land subsidence reached 200 cm in the 1982-1999 period. The rate of land subsidence in Jakarta in the period of 1997 - 2005 was 1-10 cm/year and the greatest number was 15-20 cm/year in the northern and central Jakarta. Visually, land subsidence in Jakarta causes damage at the foundation of buildings and flood inundation becomes widespread in several locations (Abidin et al., 2014).

2. The Methods

The analysis method in this study is a numerical groundwater flow model using software MODFLOW v2010 (A modular three-dimensional (3D) finite-difference groundwater flow model and structured rectilinear grid operating system). This tool was applied to simulate the groundwater drawdown condition scenario and its impact on seawater intrusion and land subsidence. Subsurface hydrostratigraphic data and hydraulic parameters (Table 1) used in numerical simulations were obtained from previous studies (Kagabu, et al., 2012; Dirjen SDA dan PT Ganesha Piramida, 2014) and processed result from the Jakarta Groundwater Conservation Agency report, Geology Agency.

Table 1. Hydraulic parameter for groundwater model of Jakarta

Property	Set-Up
Grid size	1 x 1 km2
Number of Grids	43 rows and 60 columns
Layer structure	Zone 1-4
	Zone 1 and 3 is an aquifer
	Zone 2 and 4 is an aquitard
	Zone is basement
Computation period	2018-2038
Hydraulic conductivity	Zone 1 : 5.8 x 10-2 cm/s
(Kx=Ky=Kz x 10-1)	Zone 2 : 1.2 x 10-5 cm/s
	Zone 3 : 1.2 x 10-2 cm/s
	Zone 4 : 5.8 x 10-7 cm/s
Recharge rate	182.55 mm/year
Top boundary condition	Flexible head
Bottom boundary condition	No-flow
Lateral boundary condition against inactive cells	No-flow
Initial condition	2018

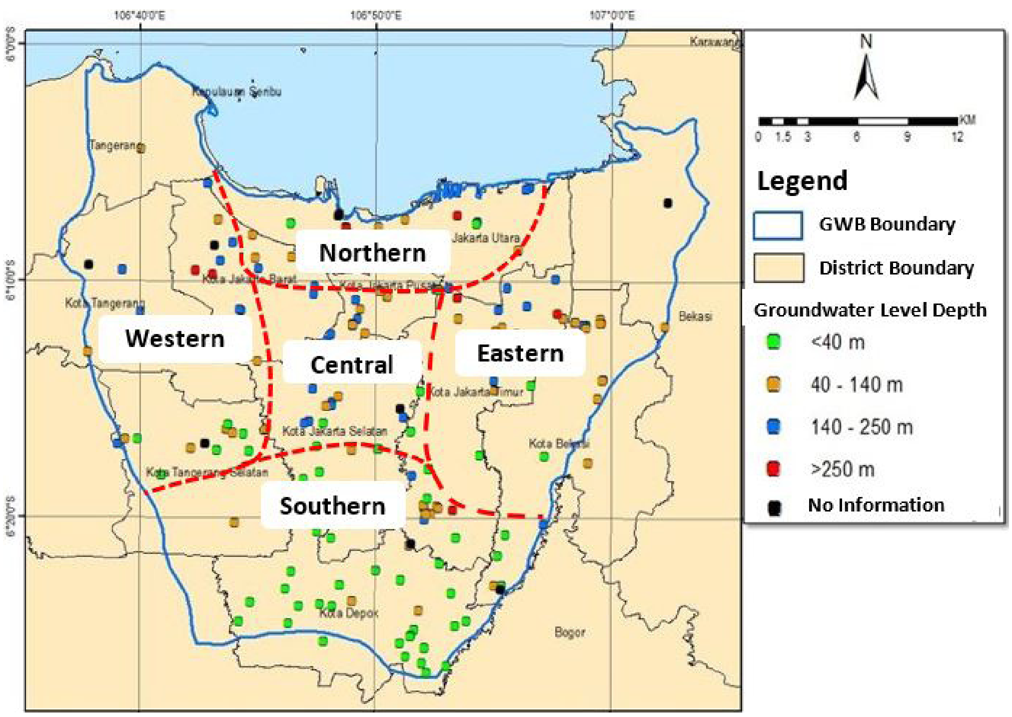

Figure 1. District distribution map in 5 parts of Jakarta area

Data Acquisition

The initial condition for this numerical simulations was acquired from the field hydrogeology survey results: groundwater measurement of monitoring wells, water sampling, in-situ test, and hydrogeochemical analysis. The numerical simulation scenario is the groundwater use for the next 20 years and its impact on the groundwater drawdown. This scenario was chosen based on several previous studies, which conclude that in the next 20-30 years there will be a critical period of subsurface environmental disasters, such as the groundwater drawdown becomes groundwater mining (groundwater below the aquifer level) (Delinom, et al., 2009), a high risk for over-topping seawater against the existing sea wall (Abidin, et al., 2011) and urgent conditions in water resources management (Delinom, 2008; Kagabu, et al., 2011, 2012; Dirjen SDA dan PT Ganesha Piramida, 2014).

Data Processing

Recorded groundwater abstraction in Jakarta area from Dinas Sumberdaya Air in 2018 revealed that the groundwater discharge from wells is only around 2,950.08 L/sec (distributed in 5 parts of Jakarta area, see Figure. 1 and Table 2) or only 12% of the assumption of total groundwater usage (24,353.12 L/sec). The southern part of Jakarta is an area with the most groundwater discharge, accounted for 1.458 L/sec or 50% of the total Jakarta use, which is due to the highest number of recorded wells (1613 wells). It is because the southern part of Jakarta is an area where many industries operate, especially Bekasi City and Depok City.

The groundwater discharge abstracted for numerical simulations is following the previous research (Braadbaart & Braadbaart, 1977; Kagabu, et al., 2012) that an unrecorded and or unmeasurable amount of total groundwater reaches 8-12 times greater than the recorded discharge. In this modeling, the number of assumptions ranged from 8-10 times from the recorded data and follows a distribution pattern of regional wells. The scenario carried out in this study is the discharge of groundwater abstraction for the next 20 years in every 3-4 years, as shown in Table 3. with a predicted trend of increasing usage debit around 10% every year (Dirjen SDA dan PT Ganesha Piramida, 2014).

Table 2. Official groundwater discharge abstracted during 2018

Section of Jakarta Area	Administration City	Recorded Groundwater Abstraction Debit (Lt/second)	Total of Well (Unit)
Southern Part	Depok, South Bekasi, South Tangerang, South Jakarta	1,458.00	1613
Eastern Part	East Jakarta and Bekasi	570	981
Central Part	South Jakarta, West Jakarta, Central Jakarta	310.8	641
Western Part	Tangerang dan West Jakarta	414	745
Norther Part	North Jakarta, West Jakarta, Central Jakarta	197.28	426
	Total	2,950.08	4406

Table 3. Prediction of groundwater discharge abstraction for the next 20 years

Year	Prediction of groundwater discharge (L/s) Jakarta part					Total
	South	East	Central	West	North	(L/s)
2018	12,150.00	4,750.00	2,590.00	3,450.00	1,644.00	24,584.00
2021	13,230.00	5,240.00	2,826.00	3,818.00	1,789.00	26,903.00
2025	14,580.00	5,700.00	3,108.00	4,140.00	1,970.00	29,498.00
2028	15,790.00	6,175.00	3,367.00	4,485.00	2,137.00	31,954.00
2031	17,010.00	6,650.00	3,626.00	4,830.00	2,301.00	34,417.00
2034	18,350.00	7,113.00	3,899.00	5,234.00	2,502.00	37,098.00
2038	19,440.00	7,600.00	4,144.00	5,520.00	2,630.40	39,334.40

The most recent groundwater contour condition in 2018 was measured from several representative monitoring wells for unconfined aquifers and confined aquifers during the dry season period (**Figure. 2**). In this initial condition, the groundwater contour pattern moves from the highest part (southeast, south, and southwest) in unconfined aquifers (Zone 1), while in confined aquifers (Zone 3) there is a cone depression due to a groundwater drawdown in the middle, southeast and southwest regions.

To investigate the initial condition of seawater intrusion, a result of hydrogeochemical laboratory analysis was processed from 12 groundwater samples around the coast of northern Jakarta. The sampling places were similar with previous studies for comparison. The laboratory results were then analyzed and plotted in an indicator chart: Sea Water Intrusion (SWI). The SWI indicator analysis conducted in this study was carried out in 5 indicators of SWI (Table 4): (1) Na / Cl ratio (Bear, 1999), (2) Cl ratio and Electro-Conductivity (EC) (Kelly, 2005), (3) ratio of Cl / Br (Panno, et al., 2006), (4) main ion-exchange index (Stuyfzand, 2008), and (5) value of TDS (Total Dissolved Solid) (Allen & Liteanu, 2008).

The data from Table 4 were then plotted on a map and then compared with the results from previous studies (Setiawan, et al., 2017). The similar seawater intrusion occurs in the Jakarta area in the western and central part of the coast, but it is relatively invisible in the eastern part. In the western and central part, there are intrusion indications within 3 km from the coastline (Figure. 3). This spatial distribution is used for the basis of the research area of intrusion into 2 regions: the western and central area and the eastern part.

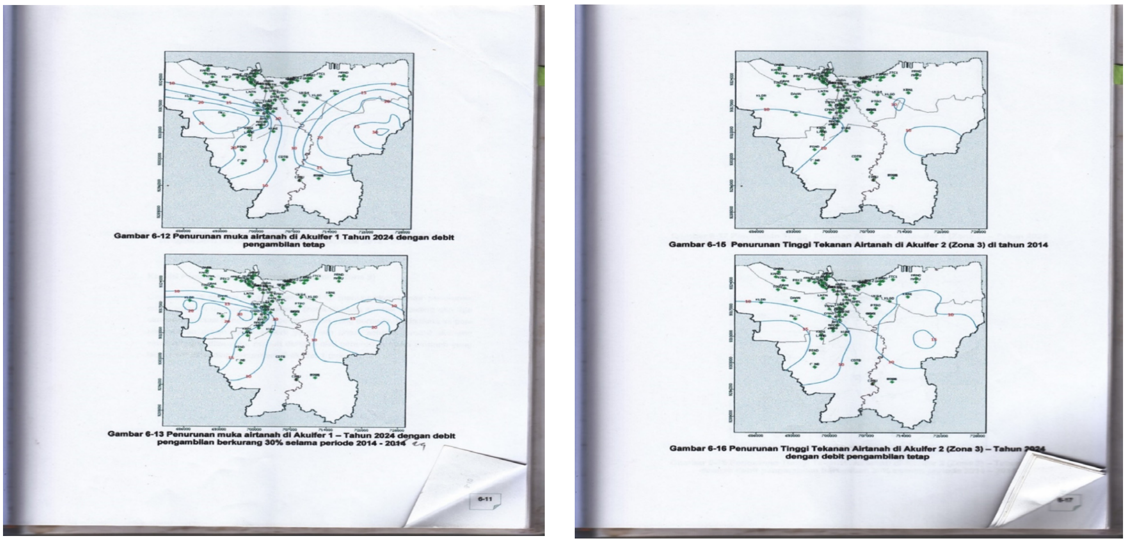

Figure 2. Groundwater potential maps on (a) unconfined aquifers and (b) confined aquifers

Table 4. Value of 5 SWI Indicators

Identity	(1)Na/Cl	(2)Cl/EC	(3)Cl/Br	(4)BEX	(5)TDS
(1) Sunter U	1.44	3.97	45.16	-123.61	909
(2) Sunter S	-	10.53	-	105.067	500
(3) BKAT 150	0.73	3160.10	13.08	-64.48	145
(4) BKAT 250	1.25	2.44	100.44	-1026.34	1510
(5) Kapuk 150	-	3.98	469.66	-19044.20	14500
(6) Kapuk 50	1.09	3691.47	63.61	-266.36	406
(7) Kapuk U	0.87	-	92.80	-485.92	1200
(8) Kapuk S	-	5776.63	-	-17.22	273
(9) KBN 50	0.73	3.71	87.57	-514.73	780
(10) KBN 150	-	28.29	56.17	-134.72	950
(11) Tongkol U	1.51	-	17.29	-17.58	1300
(12) Tongkol S	1.57	6486.31	18.15	-16.95	554

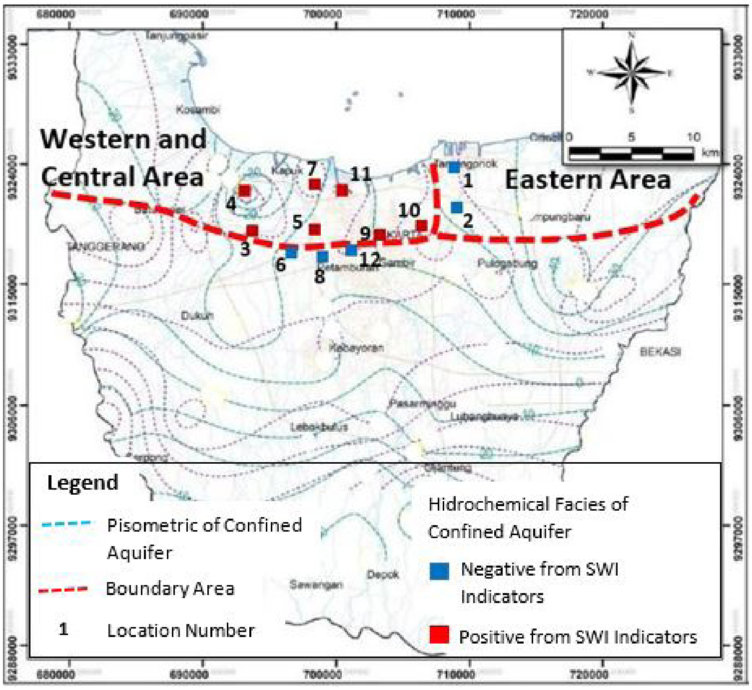

Figure 3. Seawater intrusion map in Jakarta area (plotted on the map from Setiawan et al, (2017))

Meanwhile, the initial conditions for land subsidence were obtained by comparing Dirjen SDA dan PT Ganesha Piramida (2014) and Abidin, et al. (2011). It shows that the rate of land subsidence data varies from 0-10 cm/year in the Jakarta area, especially in the northern and central Jakarta. For the purpose of this study, the Jakarta area was divided into two regions with a different rate of land subsidence: the northern part of Jakarta and Central Jakarta. The northern part of Jakarta has a land subsidence rate >5 cm/year, which covers Kalideres, Cengkareng, Ancol to Tanjung Priok, whereas, in the central part, the rate is 1-5 cm/year, including Kebayoran Lama area, Cikini, Pancoran and Grogol (Figure. 4).

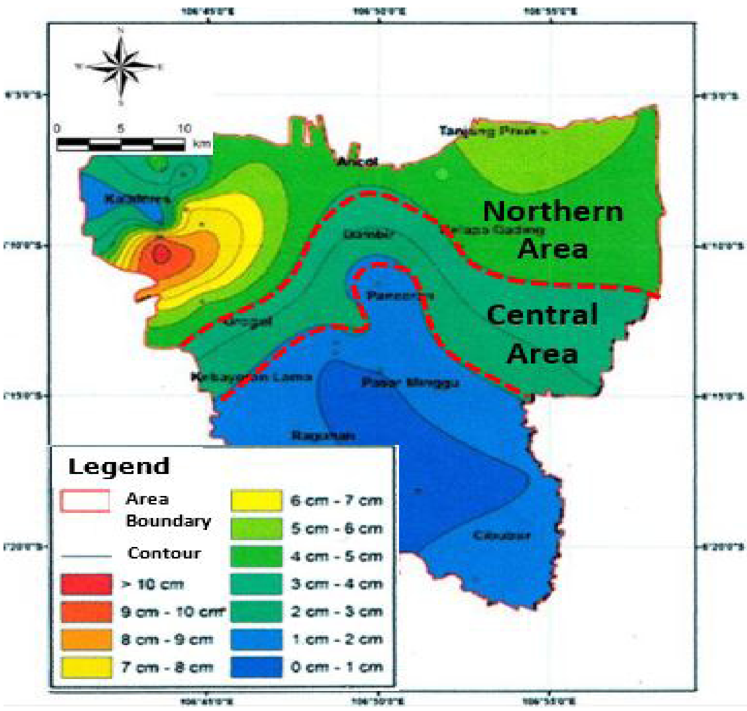

Figure 4. Land subsidence map in Jakarta area (modified from Dirjen SDA dan PT Ganesha Piramida (2014))

3. Results and Discussion

Numerical simulation was performed according to the groundwater drawdown scenario for the next 20 years and was monitored from groundwater level data from the well that was thought to be the representative of each area: the Northern area and Southern area, and then were analyzed for two impacts: seawater intrusion and land subsidence (Figure. 5). In 2018, the hydraulic simulation result shows that the seawater intrusion process occurred only in the western and central parts, which is similar to the spatial conditions of SWI results, as the initial condition. The condition in the next 3 years, in 2021, is the same. The seawater intrudes farther, but there is no yet intrusion occurred in the Eastern part. Thicker clay layers or thinner aquifers condition below the Eastern part might become a 'barrier' from the intrusion. The intrusion process could be understood from the graph of the relationship between the discharge of groundwater abstraction (Figure. 6) and groundwater level drawdown (Figure. 7) to the distance of seawater intrusion and its area.

Figure. 6 shows that the intrusion distance is farther away from the coastline in each year for all parts. In 2018, on the Western and Central areas, intrusion reaches 7 km from the coast and then increases every 3 years around 2-5 km, or around 1.5 km per year. Meanwhile, in the Eastern part, intrusion starts in 2025, which then moves with a rate of around 2.5 km per year. Notably, in 2028, it moves at the same rate in all parts, 1.5 km per year due to since 2028 the intrusion interface contour connects from West to East in 1 line (**Figure. 8**).

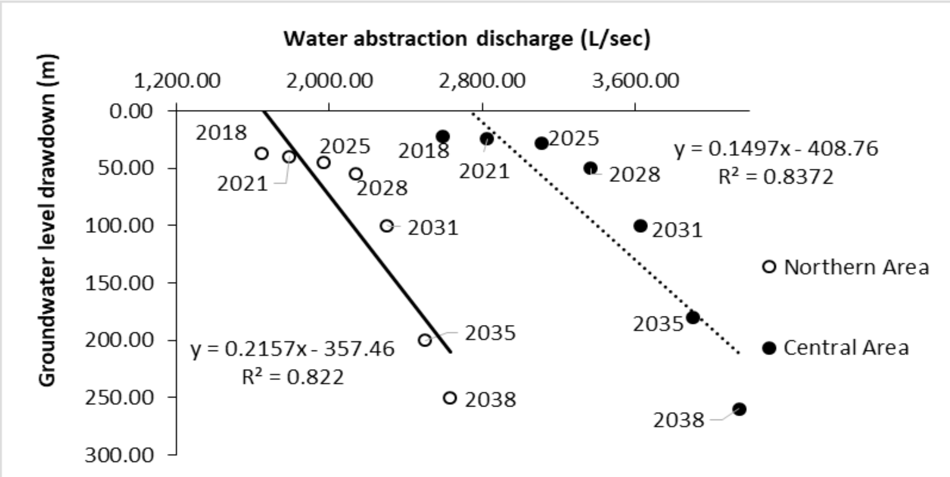

Figure 5. Graph of water extraction discharge to groundwater level drawdown

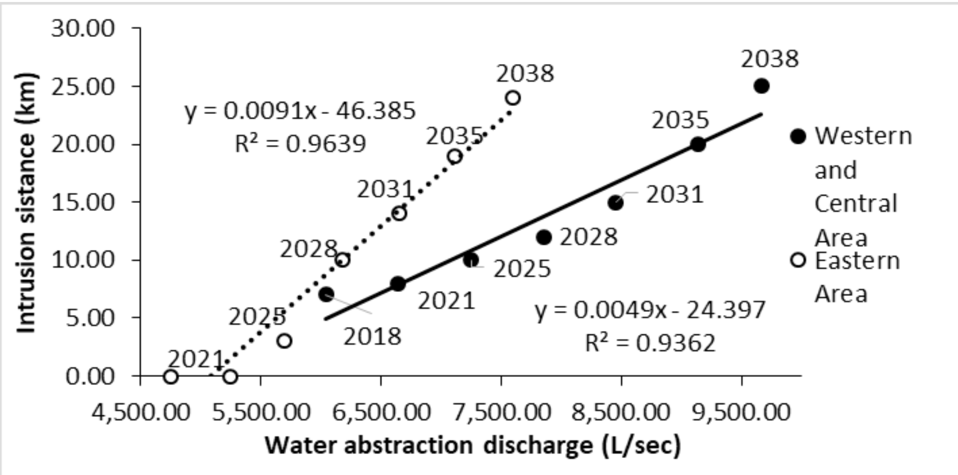

Figure 6. Graph year relationship to intrusion distance

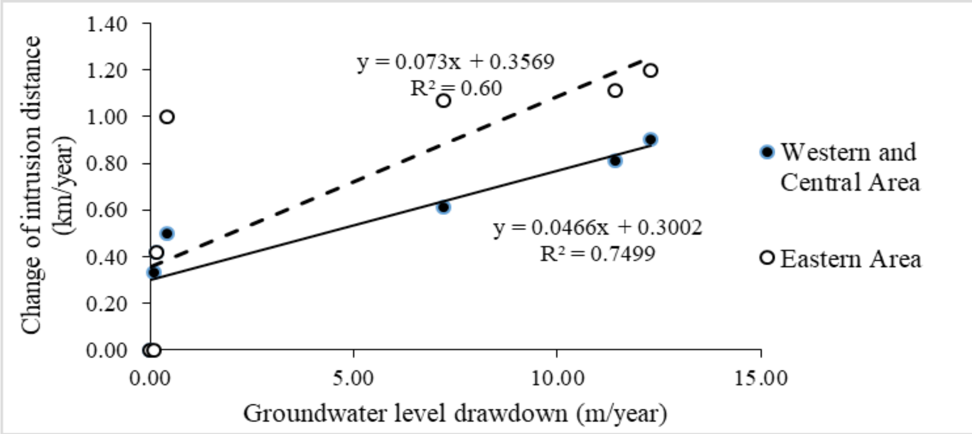

Figure 7. Graph of groundwater drawdown (m/year) to rate of intrusion distance (km/year)

Figure. 7 shows a non-linear positive correlation in the relationship between the groundwater drawdown (in m) from the representative regional monitoring wells and the intrusion distance from the coast (in km) from numerical simulation modeling. The groundwater drawdown impacts on the seawater intrusion have different equations different rate for two parts area. For Western and Central Jakarta, the equation is y = 0.0466x + 0.3002, with R^2 = 0.75, or rate 0.7 km / year; meanwhile for Eastern Jakarta, the equation is y = 0.073x + 0.3569, with R^2 = 0.60) or rate 1.1 km / year, after 2028.

This intrusion rate in Jakarta is far greater than the intrusion rate in California, which only reaches 100 to 200 feet per year (equal to 30.48 m to 60.96 m per year) (Martin, 2014). The intrusion rate in Jakarta is alarming because, in no more than 20 years, the intrusion can reach more than 25 km landward, affecting millions of people. Even though the intrusion is quite severe, that is only one-fourth of the expected intrusion in Egypt, with the seawater from Mediterranean Sea intrude 100 km landward (Sherif et al., 2012 in Post et al., 2018). Other than Egypt, the effect of over-exploitation of groundwater could also be found in other Mediterranean countries (e.g. Greece, Spain, and Morocco to name a few) with the majority of the coastline in Mediterranean are affected by seawater intrusion (Mediterranean Groundwater Working Group, 2007).

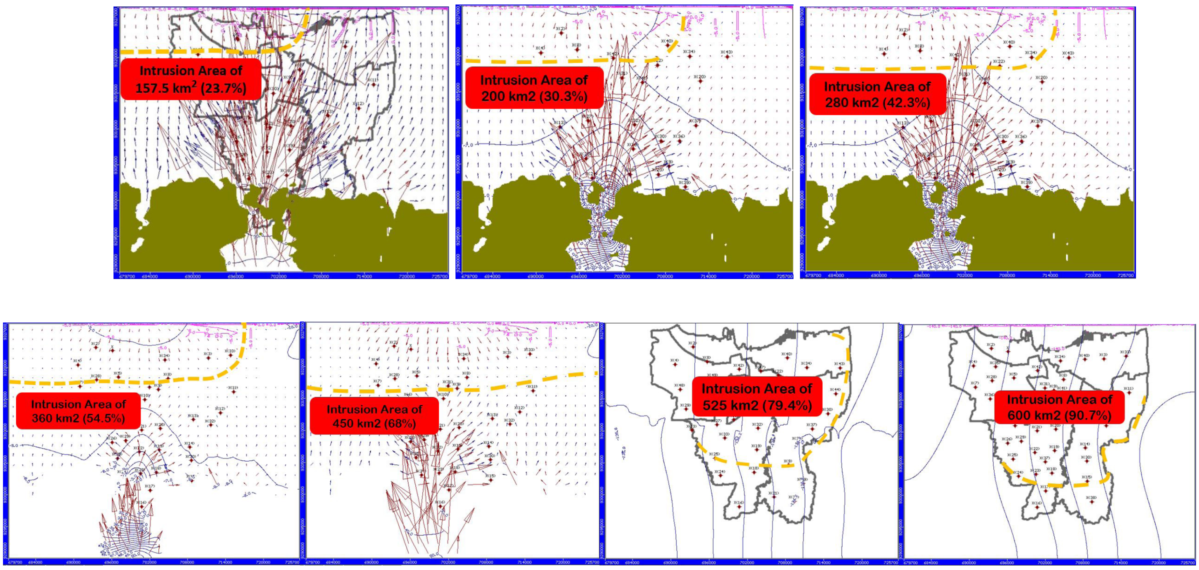

Figure 8. Prediction seawater intrusion map result from modeling a) 2018, b) 2021, c) 2025, d) 2028, e) 2031, f) 2035, and g) 2038

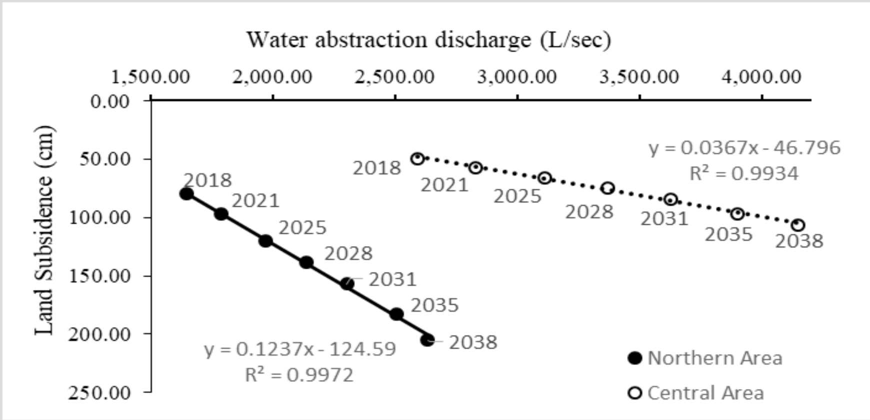

Figure 9. Graph of the relationship between water abstraction discharge (L/sec) and land subsidence (m)

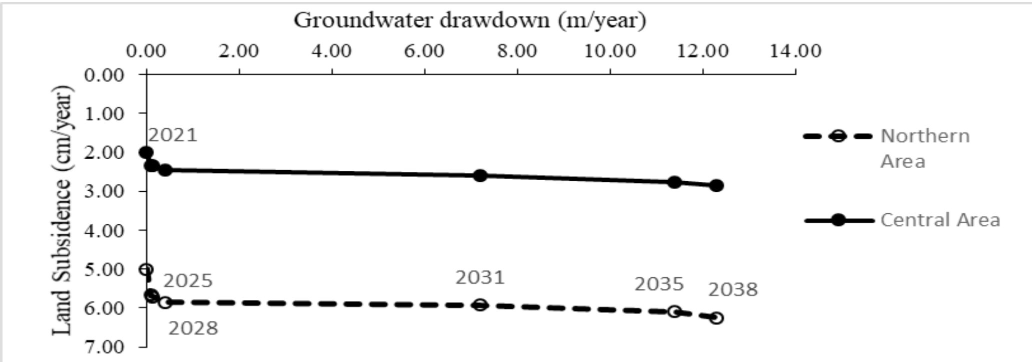

Figure 10. Graph of the relationship between groundwater drawdown rate (m/year) and land subsidence rate (cm/year)

Groundwater drawdown causes land subsidence in Jakarta area, even though it only contributes around 2-23% from measured land subsidence (Dirjen SDA dan PT Ganesha Piramida, 2014; Prasojo, 2018; Prayogi & Gunawan, 2018). Theoretically, the groundwater drawdown impacts the pressure drop of piezometer head of confined aquifers, so that it is transferred to an effective pressure of the pores which then results in (regional) consolidation or land subsidence. By taking into account the initial condition, the land subsidence is divided into two parts: the Northern and Central area. The simulation result of land subsidence conditions from 2018 to 2038 shows that the Northern region has a higher rate of subsidence than the Central Jakarta (Figure. 9, Figure. 10, and Figure. 11).

It could be seen from Figure 10 that the groundwater drawdown rate and land subsidence rate shows a positive correlation. The groundwater drawdown of 10 m/year will cause a land subsidence rate of 5.7 cm/year in Northern Jakarta and 2.5 cm/year in Central Jakarta. The declining pattern of land subsidence due to groundwater drawdown happened at the beginning of the year, 2021 and 2025, then the land subsidence pattern becomes flat. Since 2028, the rate becomes slower, and the pattern follows a general consolidation chart.

The land subsidence caused by the abstraction of groundwater not only happening in Jakarta but with many cities around the world also face the same problem, especially in the deltaic regions with dense populations. There are more than 150 cities affected by this phenomenon, with more than 45 cities in China are affected (Hu et al., 2004). Over-exploitation of groundwater caused by the emergence of industries and urbanization is the main cause of the subsidence (Hu et al., 2004), the same cause with Jakarta based on this research. Nowadays, many cities in China have implemented subsidence-controlling projects to control the subsidence, which makes the subsidence rate in the city of Tianjin only 14 mm/year from previously 66.67 mm/year (Hu et al., 2004), nearly the same rate as the expected drawdown in Jakarta based on this model. The success of this project could be an example for Jakarta to minimize its subsidence rate. In many other cities in China, however, the subsidence will still be happening at an uncontrolled rate due to industrialization and urbanization (Hu et al., 2004). Industrialization and urbanization also cause land subsidence in other big cities in Indonesia, e.g. Semarang (Sarah et al., 2018) and Bandung (Taufiq et al., 2018a) with nearly the same subsidence rate like Jakarta.

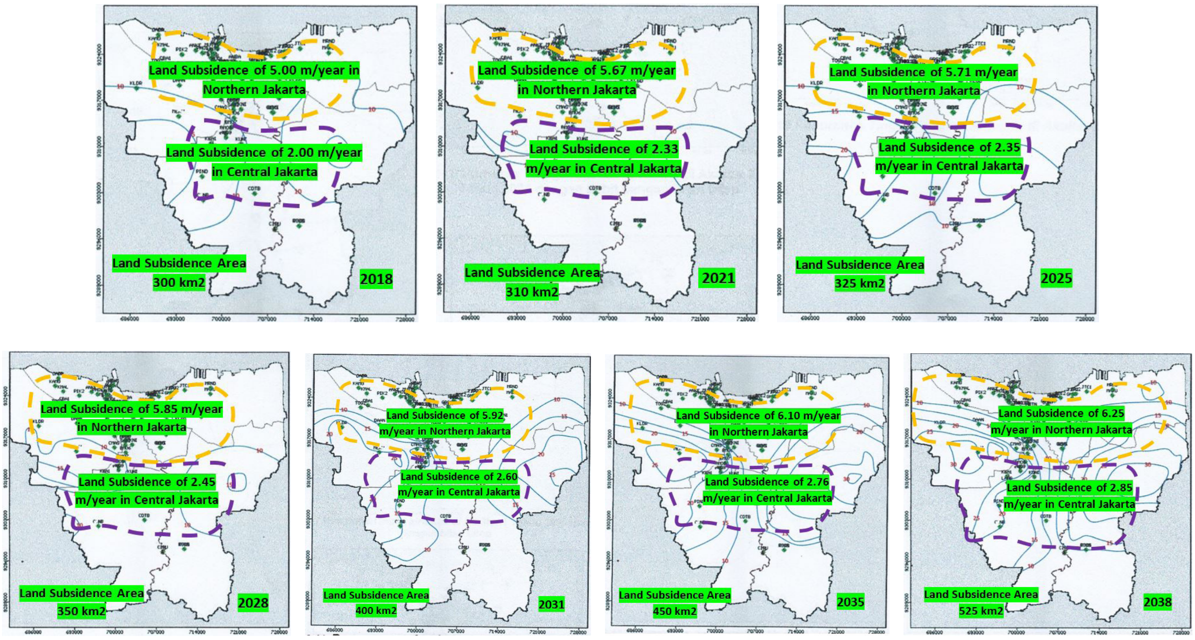

Figure 11. Prediction land subsidence map result from modeling a) 2018, b) 2021, c) 2025, d) 2028, e) 2031, f) 2035, and g) 2038

Remarkably, the groundwater drawdown in Jakarta area for the next 20 years resulted in two impacts simultaneously: seawater intrusion and land subsidence. A linear line relationship indicates that the groundwater drawdown impacts the land subsidence rate and the intrusion distance, which becomes farther landward (Figure. 12). Affected areas of two impacts increase every year until 85% of the total Jakarta area in 2038 but will impact the Northern Jakarta first (Figure. 13).

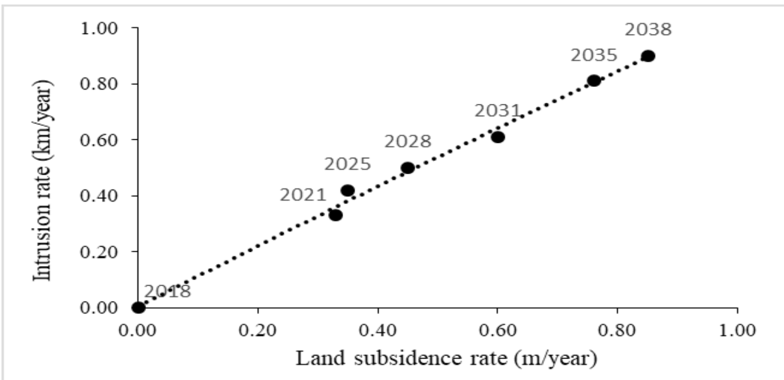

Figure 12. The relation between land subsidence rate and intrusion rate.

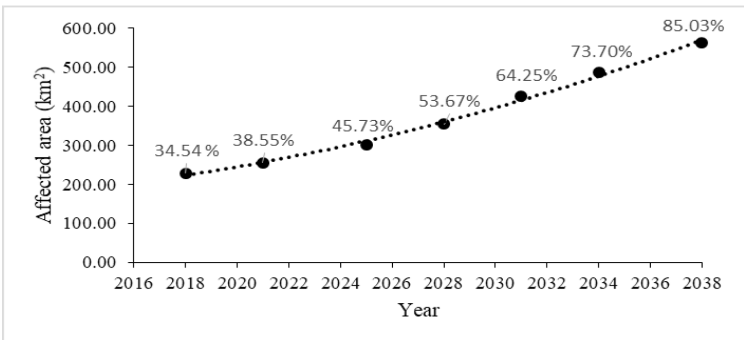

Figure 13. The relation between the total affected area with the period year of modeling

4. Conclusion

This study carries out groundwater survey and hydrogeochemical conditions for 2018, and numerical simulation for the next 20 years in Jakarta area. In 2018, as the existing and initial condition, seawater intrusion (SWI) occurs clearly, according to several SWI indicators, in the Western and Central coastal areas only, but has not been occurred on the Eastern coast. Meanwhile, the land subsidence from the latest data analysis shows that the highest rate is in the Northern part of Jakarta (> 5 cm/year); in the Central part is 1-5 cm/year that is caused by groundwater drawdown, as one of the contributing factors.

Numerical simulation results show that groundwater drawdown impacts the seawater intrusion. For every 10 m/year drop in groundwater level, the seawater will intrude 0.7 km/year landward in the Western and Central coastal Jakarta, and 1.1 km/year in Eastern coastal Jakarta, after 2028. Since 2028, the intrusion interface contours connects from Western to Eastern coastal Jakarta in one line. Groundwater drawdowns also have an impact on land subsidence rate. Every 10 m/year drop in groundwater level will cause land subsidence of 5.7 cm/year in Northern Jakarta and 2.5 cm/year in Central Jakarta with a land subsidence pattern following a general consolidation graph. The relationship between the effects of seawater intrusion and land subsidence is a directly proportional linear line which shows that groundwater drawdown rate has a great influence on land subsidence rate and it is getting wider and the distance of intrusion is getting farther ashore. Affected areas are growing every year until 85% of the total Jakarta area will be affected in 2038 with the Northern Jakarta will be affected first. This result is a new supporting conclusion as the critical period. This result is a very useful input for groundwater management policies and also for preventing the negative environmental impacts at large coastal cities in Indonesia.

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