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# GROUNDWATER FLOW MODELING IN THE WATES COASTAL AQUIFER, KULON PROGO DISTRICT, YOGYAKARTA SPECIAL PROVINCE, INDONESIA

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**ABSTRACT:** Due to overcapacity, the current airport of Yogyakarta is going to be replaced with a new one, which is located in Wates coastal area, Kulon Progo District, Yogyakarta Special Province, Indonesia. One of the consequences of the development of the new airport is groundwater abstraction due to the airport's needs and related supporting activities. An excessive withdrawal of groundwater in the new airport will potentially change the system and the pattern of groundwater flow. Therefore, groundwater modeling should be done to predict the impact of groundwater abstraction in this area. MODFLOW code is used to simulate the groundwater flow and the impact of groundwater pumping in the Wates coastal aquifer. The model is calibrated using water level data from 40 wells in the research area. The results show that the calculated values are fit to the measured data, which indicates that the model is reliable. The effects of groundwater pumping on water table and seawater intrusion are investigated using a calibrated model. The results show that the pumping scenario from the airport area causes the groundwater level to drop 0.75 m and seawater intrusion inland to increase around 100 m.

*Keywords: Groundwater flow modeling, coastal aquifer, seawater intrusion*

## 1. INTRODUCTION

Fresh water is a limited resource because only a little amount of fresh water is found on Earth. Only 2.4 % of the total global water is located on the main land, of which only a small portion can be utilized as fresh water. The utilization of fresh water has been rising due to the growing population along with the improved standard of living and economic. Groundwater is a precious and valuable natural resource found under the earth's surface. It has several advantages over surface water sources such as better quality and quantity for domestic, agriculture, and industrial purposes. However, due to the rapid economic development and population growth, the pressure imposed on groundwater increases. Over exploitation of groundwater has been causing many problems such as the decline of groundwater level, seawater intrusion, and ground water pollution [1]. Therefore, to reduce the negative impact of groundwater utilization, groundwater modeling is necessary to be conducted. Groundwater flow models are beneficial for the management of groundwater resources due to the involvement of various hydro-geological parameters [2]. The development of computation technology and the wide availability of groundwater software have made the groundwater modeling a standard tool for professional hydrogeologists to perform most tasks effectively. One of groundwater flow model functions is as an analytical tool for predicting future conditions or impacts of human activities [3]. Groundwater flow modeling has become an invaluable tool to assess the impact of existing and future activities on groundwater resources [4]. This flow modeling can also be used to better manage groundwater resources in the aquifer [5].

Coastal aquifers are unique by virtue of their proximity to seawater bodies where a dynamic interaction between seawater and freshwater constantly exists. Seawater intrusion constitutes the main environmental problem facing coastal aquifers worldwide [6][7]. It is shown that excessive groundwater exploitation in coastal area leads to seawater intrusion and influences the quality of the groundwater in aquifers [8][9]. Hence, when the hydrogeological characteristics of a coastal aquifer are being assessed, they are usually done with seawater intrusion in mind [10]. In order to achieve the sustainable exploitation of groundwater resources and to quantify the impact of climate change on water resources, a proper understanding of the behavior of the groundwater system and assessment of the groundwater resources are important prerequisites [11].

The development of the new airport will give a potential impact in the decrease of groundwater quality and quantity. It is reported that over exploitation of groundwater caused the groundwater level to drop up to 46 m at the El

Paso Airport wellfield and also chloride salinization of wells resulting from waters upconing from a deeper aquifer [12][13]. Therefore, in the present study, an impact of groundwater exploitation from the new airport is assessed with groundwater modeling before the establishment of the airport. The study area is located in Wates coastal area, Kulon Progo District, Yogyakarta Special Province as shown in Fig. 1.

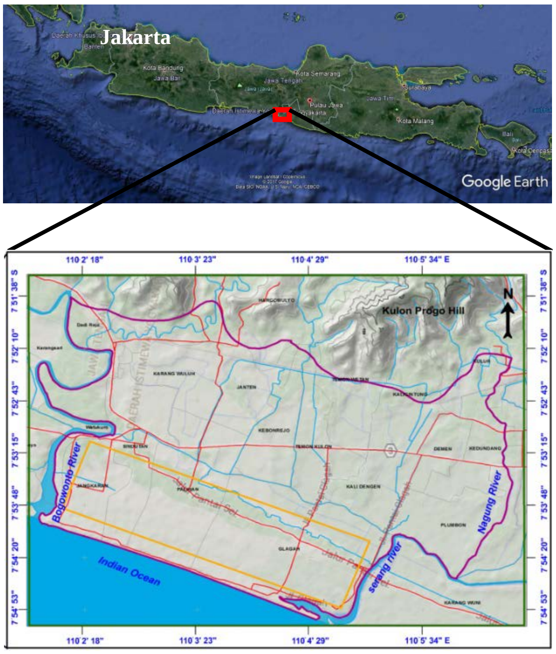


Fig. 1. Location of study area

## 2. GEOLOGICAL CONDITION

The geological condition of the study area can be divided into Tertiary and Quaternary rock. Tertiary rock consists of andesitic breccia and limestone which are located in the north of the study area. These rocks are very compact and impermeable. Quaternary rock is dominated by coastal alluvial deposit and sand dunes [14]. The distribution of lithologies in the study area is shown in Fig. 2.

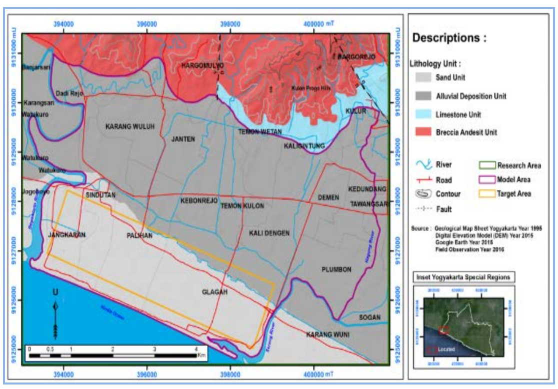


Fig. 2. Geological map of the study area

## 3. METHOD

The hydrogeological data were collected from the Meteorological Agency of Kulon Progo District. The fieldwork consists of both geological and geomorphological observation, the measurement of the hydrological data (river) such as the measurement of river width, water elevation, water depth, thickness of sediment, and the testing of river sediment permeability. The observation and the measurement of the hydrogeological data include the measurement of the depth of the water table in 40 wells and 3 pumping tests to determine the hydraulic conductivity (K) value. 12 geo-electrical measurements were conducted to understand the vertical and spatial distribution of lithologies. The analysis of groundwater modeling engages both primary and secondary data. Numerous data from various sources and different types are collected, homogenized, and integrated in the GIS spatial database [4]. Water Hydrogeological Software (WHS) solver package of MODFLOW 3.1 is used for groundwater flow computation [15]. MODFLOW is a software, which is US Geological Survey modular finite-difference based, used to solve the groundwater flow equation. The program is used to simulate the flow of groundwater through aquifers. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)\pm Q = S_s\frac{\partial h}{\partial t} \quad (1)$$

Where Kx, Ky, and Kz = hydraulic conductivity along the x, y, and z axis which are assumed (m/s); h = piezometric head (m); Q = volumetric flux per unit volume representing source/sink terms; Ss = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material. The different input layers, i.e., recharge, boundary conditions, well locations, and hydraulic conductivity, have been input to create a model using Visual MODFLOW [16]. This deterministic numerical model is based on Darcy's law and mass conservation concept. It is well documented and extensively used all over the world, based on the horizontal and vertical discretization of the modeling domain which solves the groundwater flow equation for each cell [4].

The model calibration consists of a modification of the value of model input parameters to match field conditions within some acceptable criteria. The calibration is carried out by trial and error adjustment of parameters. The calibration process is conducted in the steady-state conditions. In steady-state simulations, there is no changes of hydraulic head with time for the field conditions being modeled. In the present study, during calibration, recharge and hydraulic conductivity values are modified in sequential model to match the simulated heads and measured heads. The calibration of groundwater flow model makes use of data from water level of 40 observation wells. If hydraulic heads of measured data and calculated data show a reasonably good correlation and same model, it indicates that the model is good and can be used for the prediction of ground water levels in the future and the estimation of groundwater for further developmental activities in the model area [1].

## 4. RESULT AND DISCUSSION

### 4.1. Hydrogeology

Based on the data from the Meteorological Agency, the average annual precipitation in the study area is 1,876 mm/year and the surface temperature of study area ranges from 25.19 to 28.14 °C, according to data from 2005 to 2015 as shown in Table 1.

Table 1. Data of Annual Rainfall and Temperature

| No. | Year | Rainfall (mm/year) | Annual Average Temperature (°C) |
|---|---|---|---|
| 1 | 2005 | 2,301 | 27.8 |
| 2 | 2006 | 1,529 | 25.2 |
| 3 | 2007 | 2,201 | 27.7 |
| 4 | 2008 | 2,092 | 27.0 |
| 5 | 2009 | 1,263 | 27.0 |
| 6 | 2010 | 2,584 | 27.6 |
| 7 | 2011 | 1,135 | 28.1 |
| 8 | 2012 | 1,754 | 26.7 |
| 9 | 2013 | 2,035 | 27.3 |
| 10 | 2014 | 2,004 | 27.7 |
| 11 | 2015 | 1,743 | 27.3 |
| | Average | 1,876 | 27.2 |

The evapotranspiration was calculated by applying Turc Equation (1954) as shown in equation (2) with result of 1,402 mm/year [17].

$$ET_A = \frac{P}{\sqrt{0.9 + \frac{P^2}{(300 + 25.Tm + 0.05.Tm^3)^2}}} \quad (2)$$

where:
$ET_A$ = Actual Evapotranspiration (mm/year)
P = Rainfall (mm/year)
Tm = Temperature (◦C)
while runoff was calculated using the empirical equation from the Department of Agriculture of India (1990) which is proven to be suitable for predicting surface runoff in the rural area of Java Island [18].

$$Ro = \frac{1.511xP^{1.44}}{Tm^{1.34}xA^{0.0613}} \quad (3)$$

Where:
Ro = Runoff (cm/year)
P = Rainfall (cm/year)
Tm = Temperature (◦C)
A = Catchment Area ($Km^2$)

The result of runoff value using equation (3) is 274 mm/year. Thus, based on the calculation, the groundwater recharge is 200 mm/year.

The aquifer system is divided into two sub-systems of aquifer namely sand dune aquifer (aquifer 1) and coastal alluvial aquifer (aquifer 2) which is unconfined aquifer [19]. Data from 12 geoelectrical measurements (GE1-GE12) and 2 bore wells (E15-KP and E13-KP) show that the coastal alluvial aquifer consists of silty sand while the sand dune aquifer is dominated by sand. The coastal alluvial aquifer has a thickness of 10 to 65 meters, while the sand dune aquifer system has a thickness of 20 to 30 meters (Fig. 3). The basement of the research area is dominated by Tertiary massive limestone which has a very low permeability. According to the pumping test result, the hydraulic conductivity value in the sand dune aquifer is 5.06 m/day while the hydraulic conductivity value in the coastal alluvial aquifer is 0.86 to 1.74 m/day. The natural system of the study area is shown in Fig. 4 and 5.

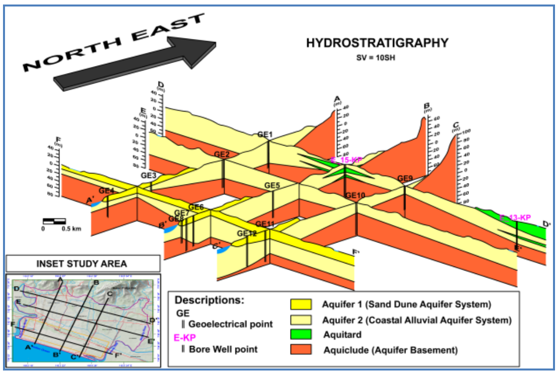


Fig. 3. Hydrostratigraphical fence diagram

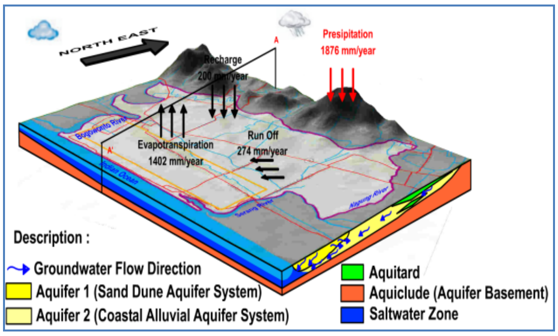


Fig. 4. An illustration of the natural system in a three-dimensional

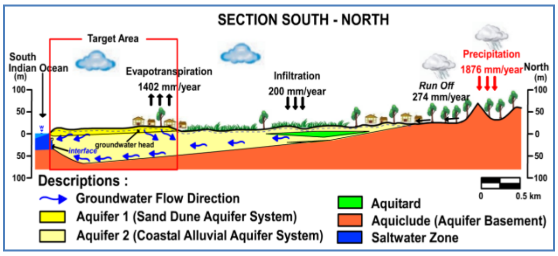


Fig. 5. An illustration of the natural system in a two-dimensional south-north section

### 4.2. Conceptual Model

The study area of Wates coastal alluvial aquifer comprises an area of 32.6 km$^2$ with an average width of 6.8 km east to west and an average length of 4.8 km north to south. The study area consists of 4 types of boundary condition namely no flow boundary, constant head boundary, river boundary, and drain boundary. The boundary conditions in the east and west are Nagung – Serang river and Bogowonto river, respectively as river boundary. The boundary condition in the southern area is Indian Ocean, which is then determined as a constant head boundary (sea level head 0.0 m-SWL). The boundary condition in the north area is a contact between the coastal alluvial aquifer and Tertiary rock (limestone and andesitic breccia), and therefore is set as a no flow boundary (Fig. 6). There are some drains flowing from the north to the south in the study area which are then applied as a drain boundary in the model. The model has a grid of 236 column and 129 rows, each grid has a dimension of 64 x 64 meter while in the target area (the new airport area), it has smaller grid size of 32 x 32 meter (Fig.s 7). The layer of rock is divided into 4 layers; aquifer 1 (sand dune aquifer), aquifer 2 (coastal aquifer), aquiclude (basement aquifer), and aquitard. The locations of the calibrated wells are randomly distributed in the model area shown in Fig. 7.

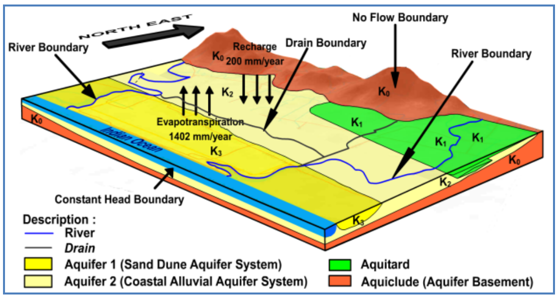


Fig. 6. 3D conceptual model in research area

The sand dune aquifer has a hydraulic conductivity value of 5.06 m/day (K4). The coastal aquifer system has two different hydraulic conductivity values of 0.86 m/day (K3) and 1.74 m/day (K2), therefore in the model, the average of the above values was applied. Aquitard hydraulic conductivity value is determined based on the existing references of value of 1x10$^{-5}$ m/sec or 0.08 m/day (K1) [20]. The aquifers are assumed as homogen anisotropic which vertical permeability is determined to be 0.1 from horizonal permeability [21]. The distribution of hydraulic conductivity (K) in 3D view is shown in Fig. 8.

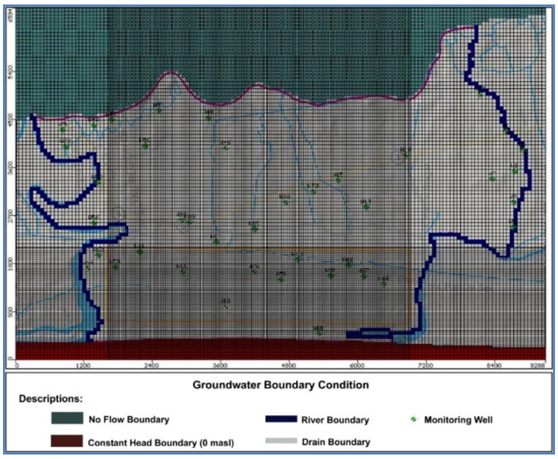


Fig. 7. Groundwater model boundary.

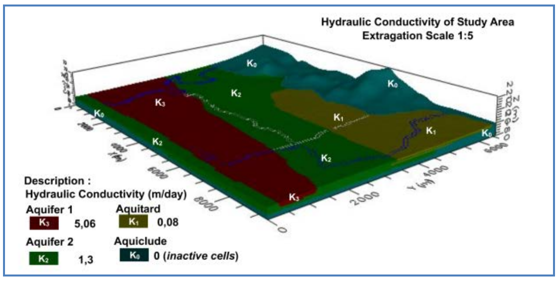


Fig. 8. Distribution of hydraulic conductivity

### 4.3. Groundwater Flow Modeling

Two types of flow simulation in the groundwater modeling are steady state and transient model. The steady state model occurs when a magnitude and direction of flow is constant with time throughout the entire domain. On the contrary, the transient flow occurs when a magnitude and direction of the flow changes with time. The limitation to use a steady state simulation to evaluate groundwater resources potential is that transient response within the aquifers is not represented when changes in stress are applied to the flow system. However, steady state simulation provides conservative estimates of the long term effect of additional groundwater development in the system. In this model, the flow simulation was run only under steady state condition. The transient simulation could not be run due to the unavailability of regular monitoring data of groundwater level in the research area used for the simulation calibration. The accuracy of the computed groundwater levels is determined by mean error, mean absolute error, root mean square error (RMS), and normalized root mean square error (NRMS) of computed values for points on the graph [22]. The groundwater flow model from the initial data shows that model calculation and water table measurement have NRMS of 20.94 %. The model is accepted if the difference between calculated and measured conditions (residual) is less than 10% of the variability in the field data across the model area [1]. Generally, the flow model is calibrated by modifying the value of several parameters (permeability and recharge, river stage and aquifer thickness) within a narrow range until the best fit is obtained between the measured heads and calculated heads [23]. In this model, the modification is conducted by changing recharge rate value and hydraulic conductivity value as shown in Table 2. The recharge rate is adjusted based on the calculation from secondary data. There is also a different value of hydraulic conductivity in the coastal aquifer. The simulation using different values of recharge rate gives a significant impact in reducing the error. However, the scenario using the best recharge value and modified hydraulic conductivity value does not reduce the error. The best simulation scenario is achieved when the recharge rate is 85 mm/year and hydraulic conductivity value is the same with the initial model value which normalized RMS is 9.09% (Fig. 9). The result of the model shows that the computed values are fit to measured data, which indicates that the model is reliable to use for future prediction.

Table 2 Scenario Groundwater Flow Modeling

| Scenario | Parameter | | Normalized RMS (%) |
|---|---|---|---|
| | Recharge (U) (mm/year) | Hydraulic Conductivity (k) (m/day) | |
| Initial Model | 200 | K1=0.08, K2=1.3, K3=5.06 | 20.94 |
| Scenario 1 | 250 | K1=0.08, K2=1.3, K3=5.06 | 28.7 |
| Scenario 2 | 150 | K1=0.08, K2=1.3, K3=5.06 | 14.02 |
| Scenario 3 | 100 | K1=0.08, K2=1.3, K3=5.06 | 9.43 |
| Scenario 4 | 90 | K1=0.08, K2=1.3, K3=5.06 | 9.135 |
| Scenario 5 | 85 | K1=0.08, K2=1.3, K3=5.06 | 9.09 |
| Scenario 6 | 80 | K1=0.08, K2=1.3, K3=5.06 | 9.137 |
| Scenario 7 | 75 | K1=0.08, K2=1.3, K3=5.06 | 9.25 |
| Scenario 8 | 50 | K1=0.08, K2=1.3, K3=5.06 | 10.91 |
| Scenario 9 | 85 | K1=0.016, 2=0.26, K3=1.012 | 51.21 |
| Scenario 10 | 85 | K1=0.04, K2=0.65, K3=2.53 | 15.68 |
| Scenario 11 | 85 | K1=0.16, K2=2.6, K3=10.12 | 11.6 |
| Scenario 12 | 85 | K1=0.4, K2=6.5, K3=25.3 | 15.022 |

The result of the groundwater flow modeling can be seen in Fig. 10. It shows that the groundwater flow pattern in the coastal alluvial aquifer dominantly flows from north to south towards the Indian Ocean. However, in the eastern part of model area, the groundwater flows direction is centered. This condition is controlled by the topography condition as shown in Fig. 11. Shallow groundwater flow (local groundwater flow) commonly conforms to the topographic contour, however, the deep groundwater flow is controlled by dipping lithology and/or structural geology [24].

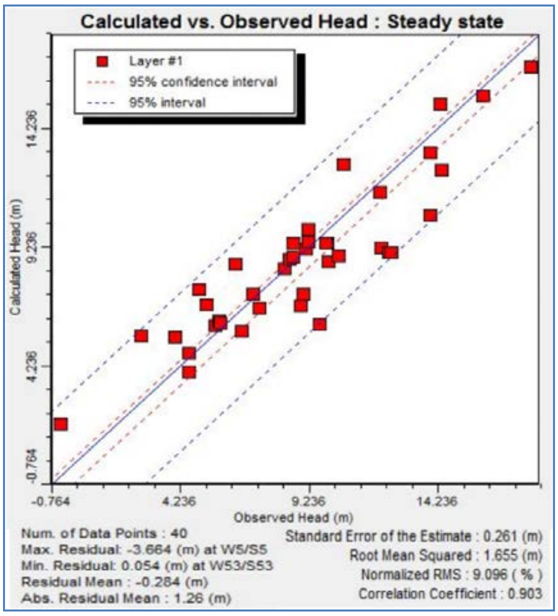


Fig. 9. Graphic of calculated head versus measured head

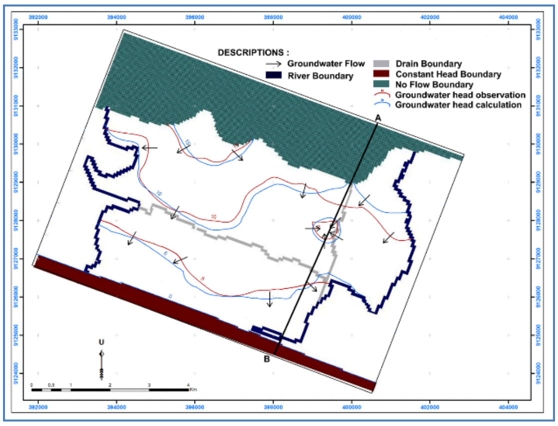


Fig. 10. The calibrated groundwater flow model

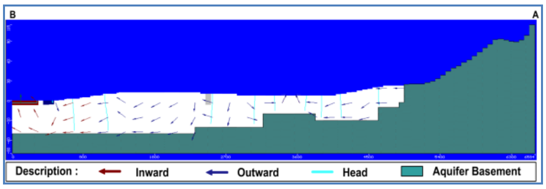


Fig. 11. A cross section of the groundwater flow model A –B section

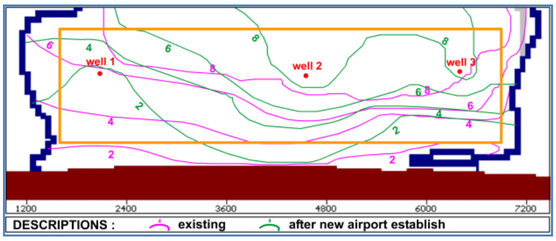


Fig. 12. The water table changes before and after new airport operated.

### 4.4. Prediction of Water Table and Seawater Intrusion

The decline of water table is predicted by simulating groundwater abstraction with pump discharge. The amount of pump discharge is calculated based on the estimation of the groundwater utilization according to the population and the airport projections after the new airport is fully operated. The groundwater abstraction for domestic used is calculated 2,122 $m^3$/day (8 wells with discharge for each well of 265 $m^3$/day) and the new airport 2,275 $m^3$/day (3 wells with each well discharge of 758 $m^3$/day). The depths of wells in the airport area are set up as follows: well 1 is 27.5 m, well 2 is 62.5 m, and well 3 is 52.5 m. The depth of each well was adjusted to the aquifer thickness. The result of groundwater flow simulation using final model under steady state simulation in the study area is shown in Fig. 12. The groundwater flow pattern also relatively changes especially in the western part of the study area due to the thinner aquifer. The greatest elevation decline of the water table reaches 1.5 m.

The simulation of seawater-freshwater interface (SFI) using cloride consentration in seawater is set to 10,000 mg/l as the constant concentration. The dispersivity value applied in the mass transport modeling based on the lithology type with vertical and horizontal value is the same [20]. The determination of the initial position of the interface uses the principle Ghyben – Herzberg [25]. As the result, SFI is located approximately 300 m landward from the shoreline. After the pumping wells are taken into account, the SFI moves to the landward up to 100 m from initial condition (Fig. 13).

## 5. CONCLUSION

The groundwater flow modeling in the coastal alluvial aquifer in Wates is conducted to predict the impact of the new airport development to the groundwater condition. The groundwater modeling using MODFLOW code is calibrated using 40 wells data which are located randomly in the model area. A good match is obtained between the measured and calculated levels for both the calibration and verification in the steady state simulation with error less than 10 %. In order to achieve higher reliability of prediction, it is necessary to develop a model in the transient simulation in the future. The calibrated groundwater model under steady state condition is used to predict the impact of groundwater abstraction from the new airport. The groundwater abstraction with estimated total discharge of 4,397 $m^3$/day from the new airport and its surrounding area has been applied in the final model and resulted in a significant contribution to the decline of groundwater level in the coastal area of 1.5 meter. In addition, the groundwater abstraction with estimated total discharge of 4,397 $m^3$/day may cause seawater-freshwater interface to move to inland around 100 m from the current location. However, in order to minimize the negative impact of the groundwater abstraction in the Wates coastal aquifer, the location of the well should be located far to the north from the new airport and the withdrawal discharge is reduced.

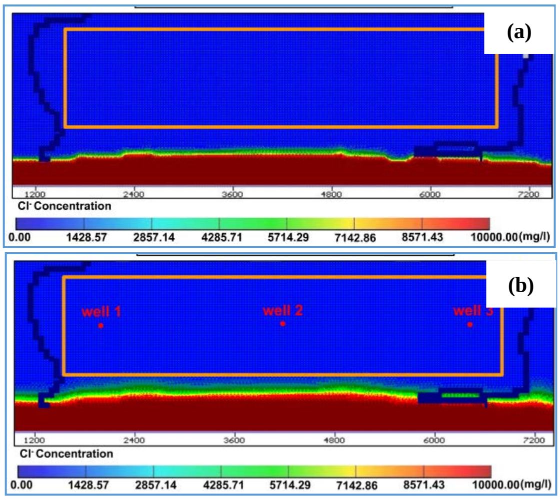


Fig. 13. The SFI patterns impacted by well abstraction. (a) before; (b) after new airport

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

[1] Khadri, S. F. R., and Pande, C., 2016. Groundwater flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India. Model. Earth Syst. Environ.2:39.

[2] Woodward, S.J.R, Wöhling, T., Stenger, R., 2016, Uncertainty in the modelling of spatial and temporal patterns of shallow groundwater flow paths: The role of geological and hydrological site information, Journal of

Hydrology, Volume 534, March 2016, pp. 680-694
[3] Zhou, Y. and Li W., 2011, A review of regional groundwater flow modelling, GEOSCIENCE FRONTIERS 2(2) (2011) 205e214
[4] Lachaal, F. and Gana, S. 2016. Groundwater flow modelling for impact assessment of port dredging works on coastal hydrogeology in the area of Al-Wakrah (Qatar). Model. Earth Syst. Environ. 2:201.
[5] Singh, A., 2013, Groundwater modeling for the assessment of water management alternatives, Journal of Hydrology 481 (2013) pp.220–229.
[6] Don, N.C., Hang, N.T.M., Araki, H., Yamanishi, H., Koga, K.. Groundwater resources management under environmental constraints. Environ. Geol, Vol. 49, 2006. pp. 601–609.
[7] Sherif, M., Kacimov, A., Javadi, A., & Ebraheem, A.Z., Modeling groundwater flow and seawater intrusion in the coastal aquifer of Wadi Ham UAE. Water Resour. Manag. Vol. 26, 2012. pp. 751–774.
[8] Supriyadi, Khumaedi and Putro, A.S.P., 2017, Geophysical and Hydro Chemical Approach for Seawater Intrusion in North Semarang, Central Java, Indonesia, International Journal of GEOMATE, March, 2017, Vol. 12, Issue 31, pp. 134-140
[9] Pousa, J., Tosi, L., Kruse, E., Guaraglia, D., Bonardi, M., Mazzoldi, A. & Schnack, E., 2007, Coastal processes and environmental hazards: the Buenos Aires (Argentina) and Venetian (Italy) littorals. Environmental geology, Vol. 51, No. 8, 2007. pp. 1307-1316
[10] Idowu, T.E., Nyadawa, M., and K'Orowe, M.O., 2017. Hydrogeochemical assessment of a coastal aquifer using statistical and geospatial techniques: Case Study of Mombasa North Coast Kenya. Environ Earth Sci 76:422.
[11] Wu, Y., Wang, W., Toll, M., Alkhoury, W., Sauter, M., and Kolditz, O. 2011. Development of a 3D groundwater model based on scarce data: The Wadi Kafrein catchment/Jordan. Environ Earth Sci 64:771-785.
[12] Sheng, Z. and J. Devere. 2005. Systematic managementfor a stressed transboundary aquifer: the Hueco Bolson in the Paso del Norte region. Journal of Hydrogeology 13(5–6):813–825.
[13] Druhan, J. L., Hogan, J. F., Eastoe, C. J., Hibbs, B. J., and Hutchison, W. R., 2008. Hydrogeologic controls on groundwater recharge and salinization: a geochemical analysis of the Northern Hueco Bolson Aquifer, El Paso, Texas, USA. Hydrogeology Journal 16(2):281–296.
[14] Rahardjo, W., Sukandarrumidi, and Rosidi H.M.D. 1995. Geological Map of Yogyakarta, Scale 1: 100.000. Center for Geological Research and Development, Bandung.
[15] Waterloo Hydrogeological, 2001. Visual MODFLOW Pro, 3D Groundwater Flow and Contaminant Transport Modeling, V.3.1.
[16] Nayak, P.C., Kumar, S.V.V., Rao, P.R.S., Vijay, T., 2016. Recharge source identification using isotope analysis and groundwater flow modeling for Puri city in India, Applied Water Science.
[17] Singh, V.P., 1989, Hydrologic Systems Volume 2: Watershed Modeling, Prentice-Hall Inc, New Jersey, 320 p.
[18] Putra, D.P.E, 2007, The Impact of Urbanization on Groundwater Quality A Case Study in Yogyakarta City-Indonesia, Mitterilungen zur Ingenieurgeologie und Hydrogeologie, 147p.
[19] Sir M. Mac Donald and Partners., Binnie & Partners Hunting Technical Service Ltd, 1984, Greater Yogyakarta Groundwater Resources Study, Volume 3 Groundwater. Groundwater Development Project (P2AT). Ministry of Public Works, Government of Republic Indonesia.
[20] Spitz, K. & Moreno, J. 1996. A Practical Guide to Groundwater and Solute Transport Modelling. John Wiley & Sons, Inc. New York.
[21] Hemker, K., Bakker, M., 2006, Analytical solutions for whirling groundwater flow in two-dimensional heterogeneous anisotropic aquifers. Water Resour. Res. 42(W12419), 1–12.
[22] Anderson TW, 1992, Electrical-analog analysis of the hydrologic system, Tucson basin, South-eastern Arizona. U.S. Geological Survey Water-Supply Paper 1939-C, p 34
[23] Mayer A, May W, Lukkarila C, Diehl J., 2007, Estimation of fault zone conductance by calibration of a regional groundwater flow model: desert Hot Springs, California. Hydrology Journal 15(6) pp.1093–1106
[24] Brown, J., Wyers, A., Aldous, A., Bach, L., 2007, Groundwater and Biodiversity Conservation, The Nature Conservancy, 176p.
[25] Vacher, H.L, 1988, Dupuit-Ghyben-Herzberg Analysis Of Strip-Island Lenses, Gsa Bulletin (1988) 100 (4) pp. 580-591.