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MODELING OF GROUNDWATER LEVEL CHANGES DUE TO DEEP WELL EXTRACTION USING MODFLOW IN THE NORTH OF BANDAR LAMPUNG

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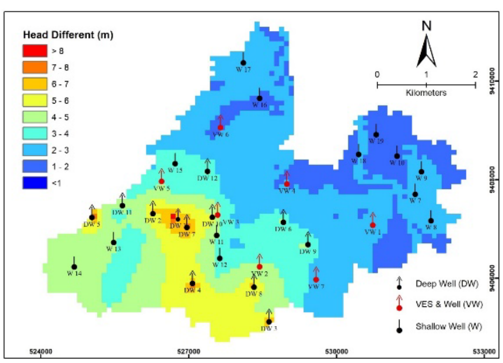
Graphical abstract



Abstract

The growth rate of urban areas in the north of Bandar Lampung has caused the extraction of groundwater resources through deep well pumping to increase. Therefore, it is necessary to study the impact of pumping to prevent groundwater depletion. This study performs numerical simulation modeling to identify the impact of deep well pumping on changes in groundwater levels in three sub-districts north of Bandar Lampung city. Modeling is done using MODFLOW-6 and ModelMuse as a graphical user interface (GUI). The simulation method uses steady-state and transient models with four stress periods in 2000, 2010, 2020, and 2030. A total of 30 data wells are used for model setup, and 15 of them as observation and validation points. The simulation results show that hydraulic head changes occur at depths of 10 m to more than 40 m. Drawdown and groundwater head changes are concentrated at deep well points with a radius of up to 1 km. The model also successfully identified a decrease in groundwater level to more than 8 m in the deepest well area DW1. Thus, it is necessary to take action that can overcome the impact of changes in groundwater level due to pumping from deep wells. Furthermore, groundwater storage engineering can be one solution by utilizing rainwater harvesting technology to recharge the groundwater aquifer system.

Keywords: Deep well extraction, drawdown, groundwater modeling, MODFLOW, ModelMuse

1.0 INTRODUCTION

Globally, the problem of groundwater subsidence is increasing rapidly due to population growth, especially in urban areas [1,2]. The need for groundwater in urban areas, especially those just developing, such as in the northern area of Bandar Lampung, is increasing every year [3]. This situation triggers a significant increase in groundwater extraction in areas that do not yet have a water piping system. The option of drawing water through shallow wells increases to deeper wells. With the increasing development of residential and industrial areas, groundwater extraction activities have increased [4]. One of the impacts of this increase in the extraction process is a decrease in the groundwater table. If these impacts are not handled properly, there is the potential for more significant impacts such as subsidence that can trigger flood points to a clean water crisis due to seawater intrusion in coastal areas [5,6]. The groundwater crisis will significantly impact the economy and people's lives [7,8].

Groundwater modeling is one method of monitoring and planning groundwater management [9]. In general, groundwater modeling can provide information about groundwater resource systems based on mathematical calculations or simulations by computer. This simulation is based on various information such as hydrogeology, geology, geography, and climatology [10]. The simulation results can predict conditions that may occur in groundwater in the future and evaluate the causes of current conditions. One software widely used for groundwater modeling is MODFLOW [2,11]. In addition to being open source, this software can also model groundwater systems in 2D and 3D using a finite-difference approach [12].

In the city of Bandar Lampung, deep wells are used to extract groundwater to fulfill basic water needs, including drinking water [13,14]. This massive activity has destructive impacts in several areas, especially on the coast [15]. Several densely populated sub-districts on the southern coast of Bandar Lampung have experienced a clean water crisis, especially those sourced from groundwater. This condition has been caused by seawater intrusion due to pumping groundwater for decades [3]. In addition, other impacts such as subsidence have also been identified in this area [16]. There is a fairly large groundwater basin in the northern part of the city [17]. However, there is also an increase in groundwater extraction in this area. Without good monitoring and handling activities, the groundwater crisis may continue to the northern part of Bandar Lampung City. Moreover, there is currently an increase in groundwater extraction from deep bore wells in the area.

This study focuses on modeling groundwater levels to identify the impact of groundwater extraction using MODFLOW-6 with a graphical user interface (GUI) using ModelMuse. The model parameters are built from secondary data in the form of groundwater level measurements in 30 data wells. Simulations are carried out based on groundwater level data from 2000 to 2020. Steady-state model simulations were used to approximate groundwater conditions in 2000. Meanwhile, transient simulations are carried out to identify groundwater level changes with a stress period every ten years until 2030. The selection of this stress period is based on deep well data obtained from observations in 2010 and 2020.

2.0 METHODOLOGY

Study Area

The research area is located in the northern part of the city of Bandar Lampung, precisely in three sub-districts, namely Rajabasa, Labuhanratu, and Tanjungsenang sub-districts (Figure 1). This educational area is proliferating, accompanied by the development of residential and tourist areas [18,19]. A total of 30 well-observation data were used in this study. Eighteen shallow wells were measured in 2000 (labeled with W1-W18) to obtain the groundwater level data, of which 7 of them have been carried out 1D geoelectric measurements using the Vertical Electrical Sounding (VES) method (labeled with VW1-VW7). Then obtained groundwater level data from deep drilled wells as many as 11 wells in 2010 (DW2-DW12). The well observation data is an archive of measurement data carried out with the Bandar Lampung City Public Works. Meanwhile, the latest data measured in 2020 is one deep well data complete with cutting log data (DW1).

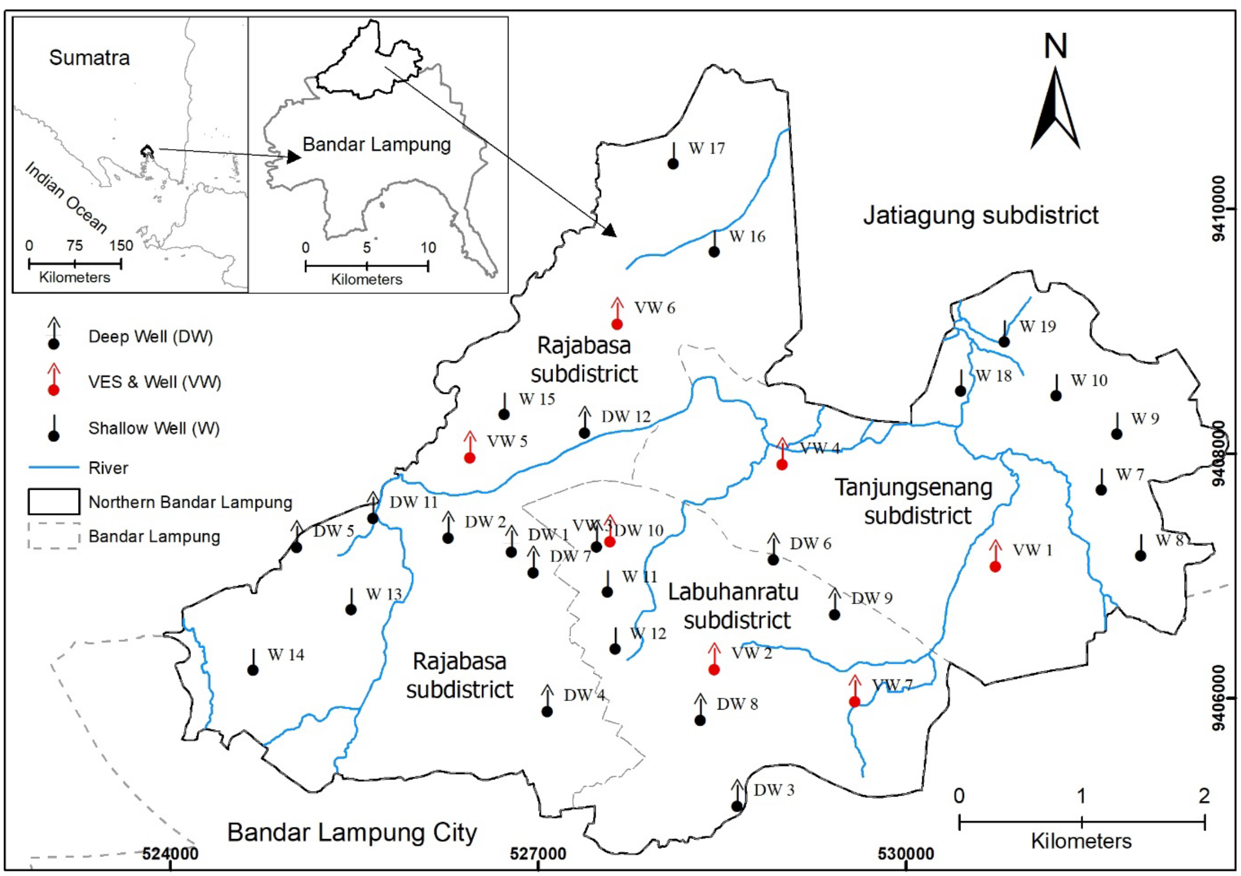


Figure 1 Location of the research area north of the city of Bandar Lampung

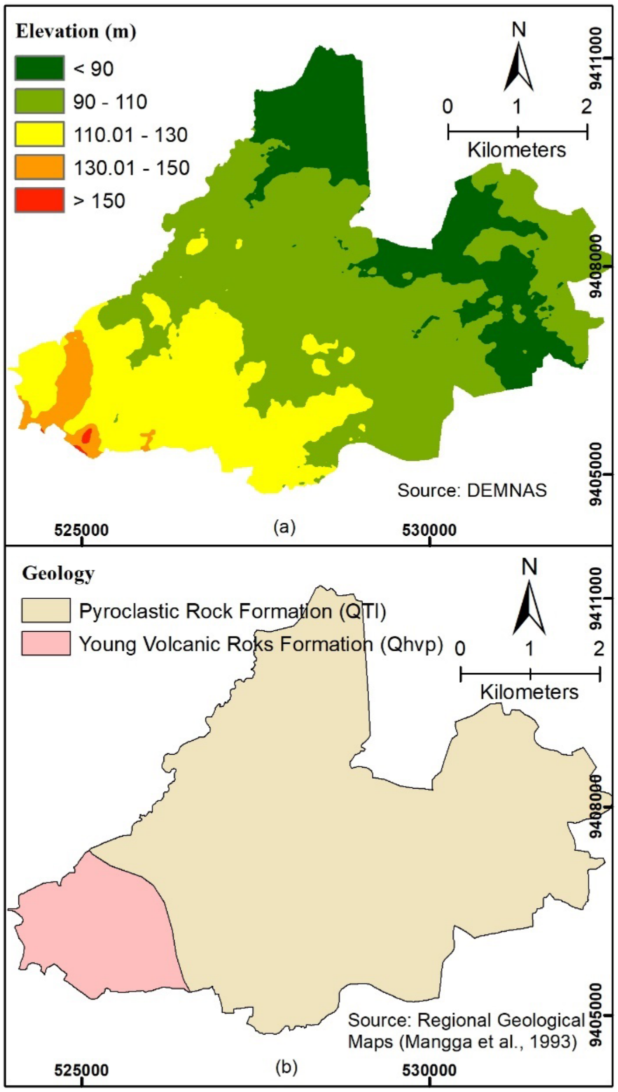


Figure 2 Elevation (a) and geology (b) of the study area

Regionally, the surface rock formations in the study area are dominated by pyroclastic rocks from the Lampung Formation (QTl) and volcanic rocks from the Young Volcano Rock Formation (Qhvp) [20], as shown in Figure 2. However, there are sandstone and claystone units in the Lampung Formation to become groundwater aquifers. In addition, there are andesite breccias in the Young Volcanic Rock Formation that can potentially become groundwater aquifer gaps. The potential for groundwater aquifers is also supported by the results of previous studies which identified the presence of groundwater basins in the north of Bandar Lampung [17].

Morphologically, the research area is dominated by plains with elevation about 90 – 150 m above sea level. Only the area west of the research location is a hilly morphological area part of Mount Betung. Rainfall in this area reaches 2000 mm/year [21]. This high rainfall causes the water supply to the aquifer to be quite good, especially in unconfined aquifers. However, in the last ten years, heavy rainfall has also resulted in runoff which causes inundation points to floods. This condition is in line with the increase in land-use change into built-up land and the increase in groundwater extraction. Geological and hydrogeological condition data integrated with VES results and cutting logs are used to build a conceptual model that will be used before building a simulation model.

Groundwater Modeling

A numerical model simulation approach is carried out to identify groundwater systems in the research area. The activity was carried out as an initial step in identifying the impacts of groundwater extraction using limited data. Modeling is done using MODFLOW-6, which is integrated with a graphical user interface (GUI) using ModelMuse [22,23]. These two software have been widely used for groundwater modeling [2,9,24,25]. Apart from being open source, MODFLOW modeling has a high-efficiency level and extensive use in groundwater research [10,24].

MODFLOW can simulate flow in three dimensions using the finite difference method [22]. The model building combines Darcy's equation with the principle of conservation of mass. In 3D, groundwater flow through the axis media on MODFLOW generally uses Equation 1 below [2,10].

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s\frac{\partial h}{\partial t} \quad (1)$$

With values K_{xx}, K_{yy} and K_{zz} are hydraulic conductivity (L/T) along the x, y and z coordinate axes, respectively. While W is the rate of inflow (recharge) and outflow (discharge) per unit volume (T^{-1}). The head or pressure head (L) and specific storage (L^{-1}) are symbolized by h and S_s. Simulations in MODFLOW maintain a balance of flow within each cell. Therefore, the flow continuity at constant density is given by Equation 2 [2].

$$\Sigma Q_i = S_s\frac{\Delta h}{\Delta t}\Delta V \quad (2)$$

Where Q_i is the flow rate per cell (L^3/T), S_s specific storage (L^{-1}), Δh is the change in head concerning time Δt, and ΔV is the change in volume in cells (L^3).

Model Parameters And Boundary Conditions

The initial parameters used in this study were obtained from secondary data obtained in previous studies and Bandar Lampung City Public Works Service. The groundwater level data used results from measurements in 2000 for shallow wells and 2010 for deep wells, and one deep well in 2020. The value of hydraulic conductivity ranges from 1×10^{-5} m/s to 2×10^{-4} m/s and the specific yield are obtained from the correlation of cutting log data between 8% – 15% for sandstone [26]. Meanwhile, the rainfall ranges from 2000 – 2500 mm/year [21]. The elevation data used is DEMNAS with 0.27-arcsecond resolution obtained from the portal of https://tanahair.indonesia.go.id/.

The groundwater model arrangement was carried out using ModelMuse in approximately 56.55 Ha with a grid of 100 m in each cell. In total, there are 5655 cells, consisting of 2969 active cells and 2686 inactive cells, which are divided into 87 columns and 65 rows. The model domain is divided into five layers, namely three aquifer layers and two aquiclude layers parallel to the topography and geological conditions of the study area. The top aquifer layer is defined as an unconfined aquifer, and the other two are confined aquifers. These five layers were obtained from the deep bore well-cutting log data (DW1 in Figure 1) carried out in 2020. In summary, the model parameters used in the simulation are shown in Table 1.

Table 1 MODFLOW model parameters in the study area

Parameter	Detail
Cell size (x, y)	100 m , 100 m
Number of layers	5 (3 aquifer, 2 aquiclude)
Hydraulic conductivity	1×10^{-5} m/s to 2×10^{-4} m/s
Specific yield	0.08 – 0.15
Simulation type & length	Steady-state & Transient, 2000-2030 i.e. 30 years
Stress period	4 (steady-state at 2000, transient at 2010, 2020 and 2030)
Flow package	LPF: Layer Property Flow
Boundary package	CHD, RCH, WEL, DRN, EVT
Observation	Head observation

The boundary conditions used in this simulation consist of Time-Variant Specified-Head (CHD), Recharge (RCH), Well (WEL), Drain (DRN), and Evapotranspiration (EVT). These boundary conditions were chosen based on the approach to the hydrogeological conditions of the study area and available data. This simulation uses large rivers in the north and east of the study area for the CHD package, as shown in Figure 3. This selection is based on existing rivers whose water is stable during the dry season. Meanwhile, other rivers are used as drainage (DRN) due to fluctuations in their discharge and water level. The same area applies to all active areas for the Recharge (RCH) and Evapotranspiration (EVT). For recharge, the data used is 10% of the average rainfall, which is 6.34×10^{-9} L/s, while the EVT value is 4.62×10^{-8} L/s [21][27]. For discharge data from wells (WEL) obtained from the measurements on 30 wells consisting of 18 shallow wells, 11 deep wells, and one deepest well. Shallow wells have an average discharge of 1.2×10^{-2} L/s, while deep wells are between 1.7×10^{-2} to 2.3×10^{-2} L/s. A total of 15 well points were then used as head observations (HOB), as shown in Figure 3.

Calibration and Validation of Groundwater Model

The calibration process is carried out to obtain the best groundwater model. This process is done by changing several parameter values to get a model close to the actual condition or reaching acceptable criteria. This study uses two conditions in the calibration process: steady-state and semi-transient conditions. The steady-state model calibration was carried out initially because the time series of groundwater flow was unknown until 2000. Therefore, a database of 18 shallow wells in 2000 was used to obtain the steady-state model. The results of the steady-state model approach are then used as a reference for transient modeling. The steady-state simulation process makes parameter adjustments to the hydraulic conductivity value to obtain a low error value or close to the 2000 head value. The result is a hydraulic conductivity value of 1.15×10^{-5} m/s in the aquifer.

The steady-state modeling results are continued with semi-transient modeling in the second to fourth stress periods. The drawdown value in the steady-state model is used as a reference for the stress period of the transient modeling. The hydraulic conductivity values were maintained, and discharges from 11 deep wells were applied in the second stress period. Meanwhile,

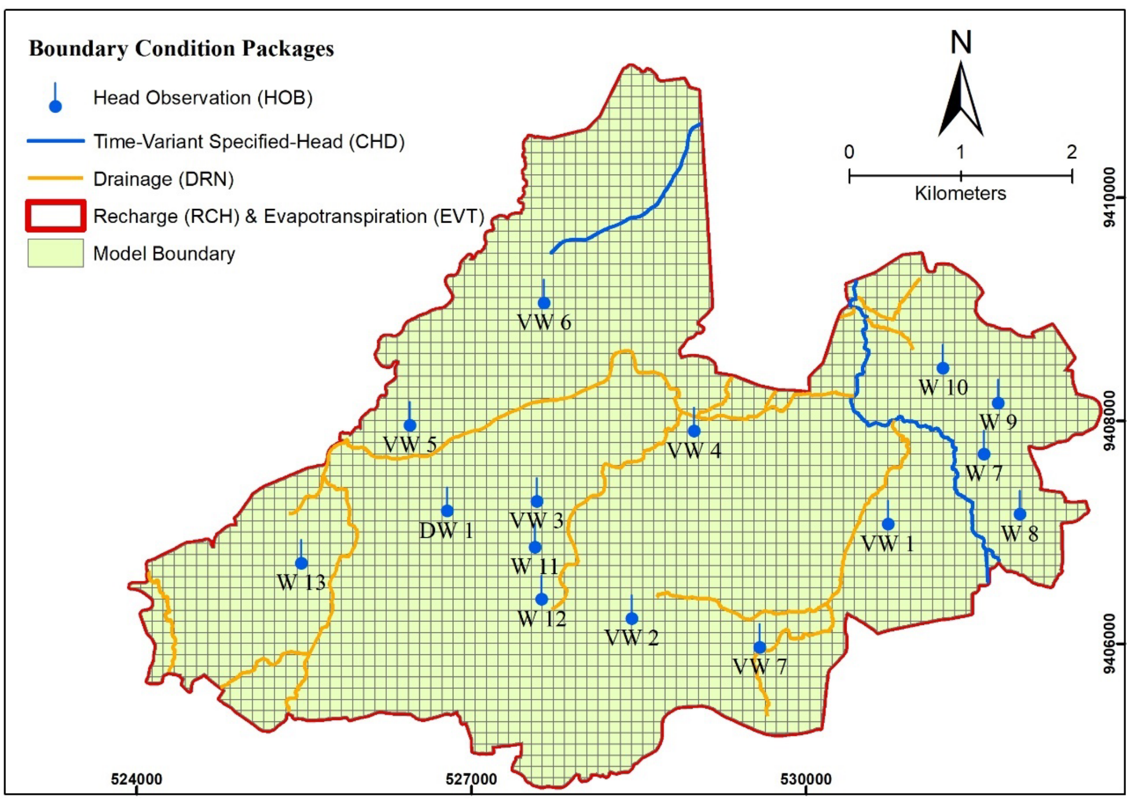


Figure 3 Boundary condition of the study area in ModelMuse

the discharge from the deepest well data begins to be applied to the third stress period. It is because following the operation of the well start in 2020. Parameter adjustments are only made to the specific storage or specific yield (S_s) value until the calculated head value is close to the observed head value. The results obtained a value of 0.08 from the range of 0.08 – 0.15.

Calculation of the value of the root means square error (RMSE) and percent error (PE) is used to evaluate the calibration results. The equations used are shown in Equation 3 and Equation 4 below.

$$PE = \left|\frac{h_o - h_s}{h_s}\right| \times 100 \tag{3}$$

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n}(h_o - h_s)^2}{n}} \tag{4}$$

Where h_o and h_s are the head values resulting from observations and simulations, while n is the number of wells that are monitored or observed. The RMSE value used in the validation is the best model and can be accepted as the best model for the simulation results, which is ≤ 1 m.

3.0 RESULTS AND DISCUSSION

The best model is obtained from several simulation processes by adjusting several parameters. Based on model validation by observation, PE values ranged from 0.67 – 4.21, as shown in Table 2. The best RMSE value in the steady-state model was 0.9 and was considered acceptable for this study. At the same time, the validation results on the semi-transient model get RSME values of 0.84 and 0.96 for 2010 and 2020, respectively. These results indicate a good alignment between the resulting model and the observation data. Thus the simulation can be continued to predict the model beyond this period. In this study, the stress period was modeled until 2030 to see the impact of groundwater extraction from deep wells for the next ten years. The graph of the relationship between the observed heads and the simulation results is shown in Figure 4.

Table 2 Calculation of the percent error of simulation steady-state model

Point	Observed Head	Simulated Head	Percent error (PE)
VW 1	87	86.42	0.67
VW 2	100	100.72	0.71
VW 3	99	98.02	1.00
VW 4	88	87.62	0.43
VW 5	100	98.96	1.05
VW 6	89	87.92	1.23
W 7	87	86.65	0.40
W 8	88	86.50	1.73
W 9	86	87.18	1.35
W 10	85	85.07	0.08
W 11	100	99.89	0.11
W 12	101	102.28	1.25
W 13	112	113.22	1.08
VW 7	97	96.56	0.46

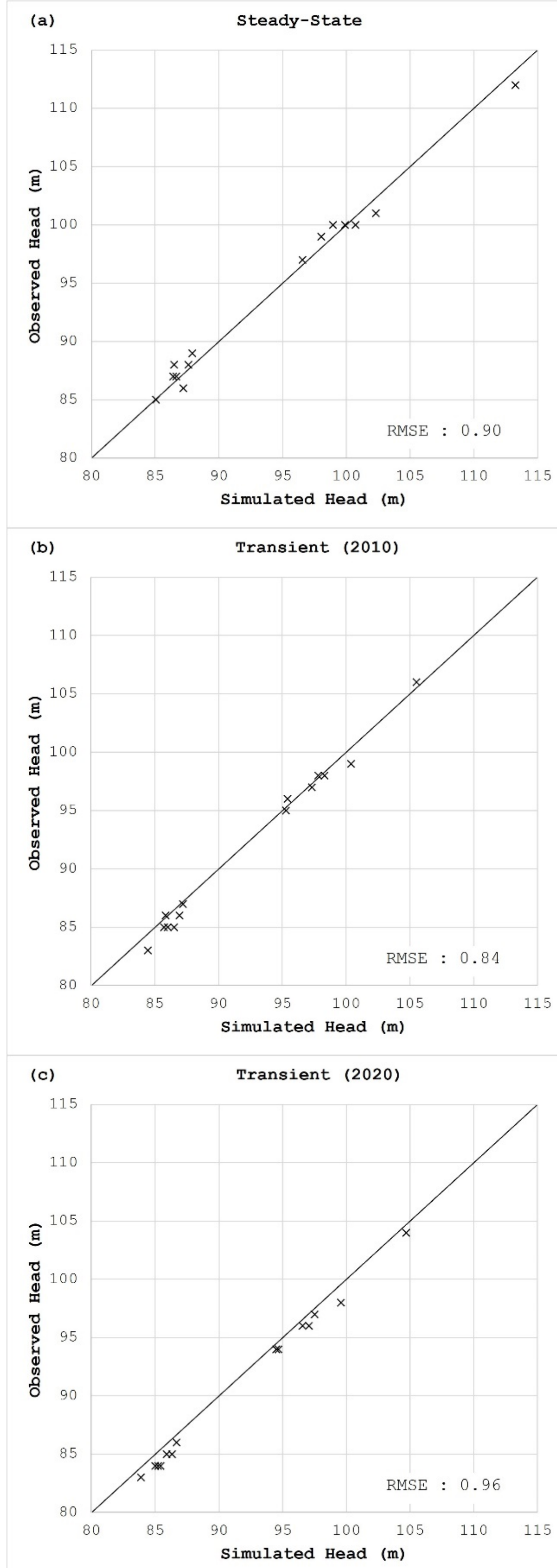


Figure 4 RMSE validation of the simulated model (a) steady-state, (b) transient 2010, and (c) transient 2020.

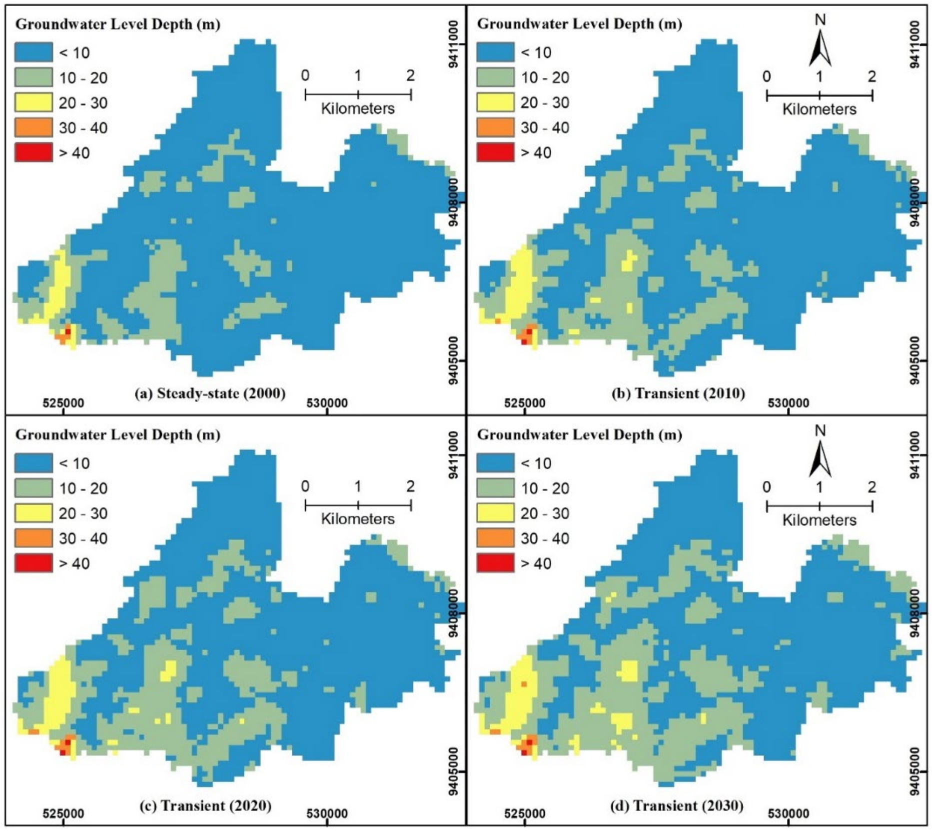


Figure 5 Hydraulic head (m) distribution of the model area in 2000 (a), 2010 (b), 2020 (c) and 2030 (d).

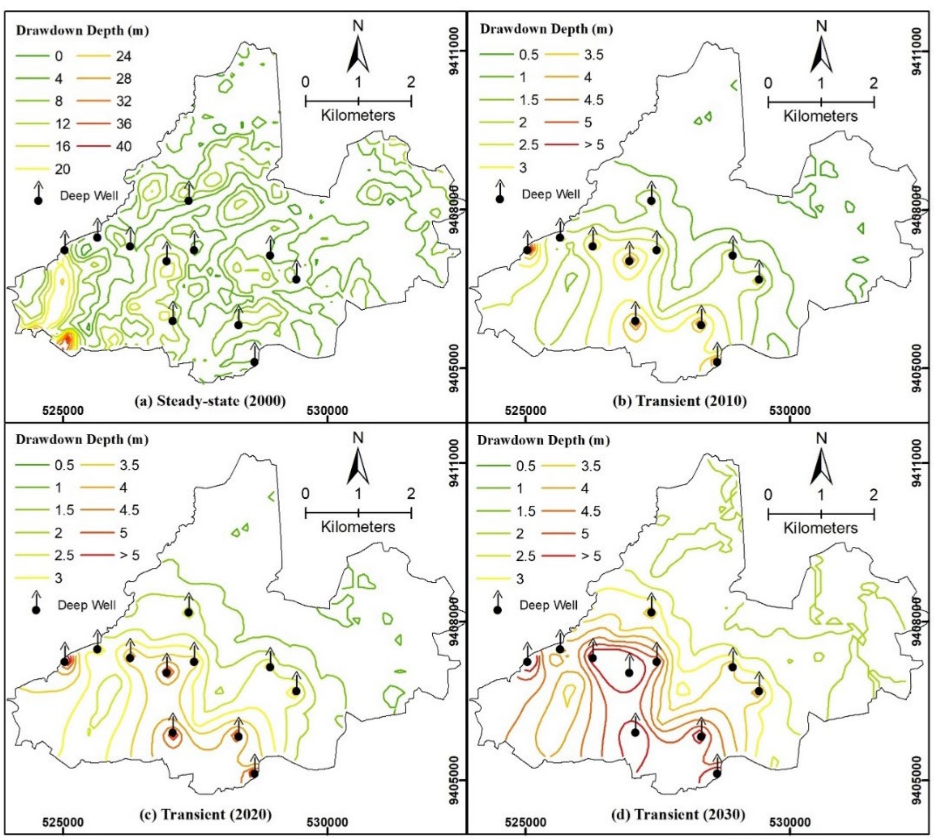


Figure 6 Simulated drawdown of groundwater level in the study area

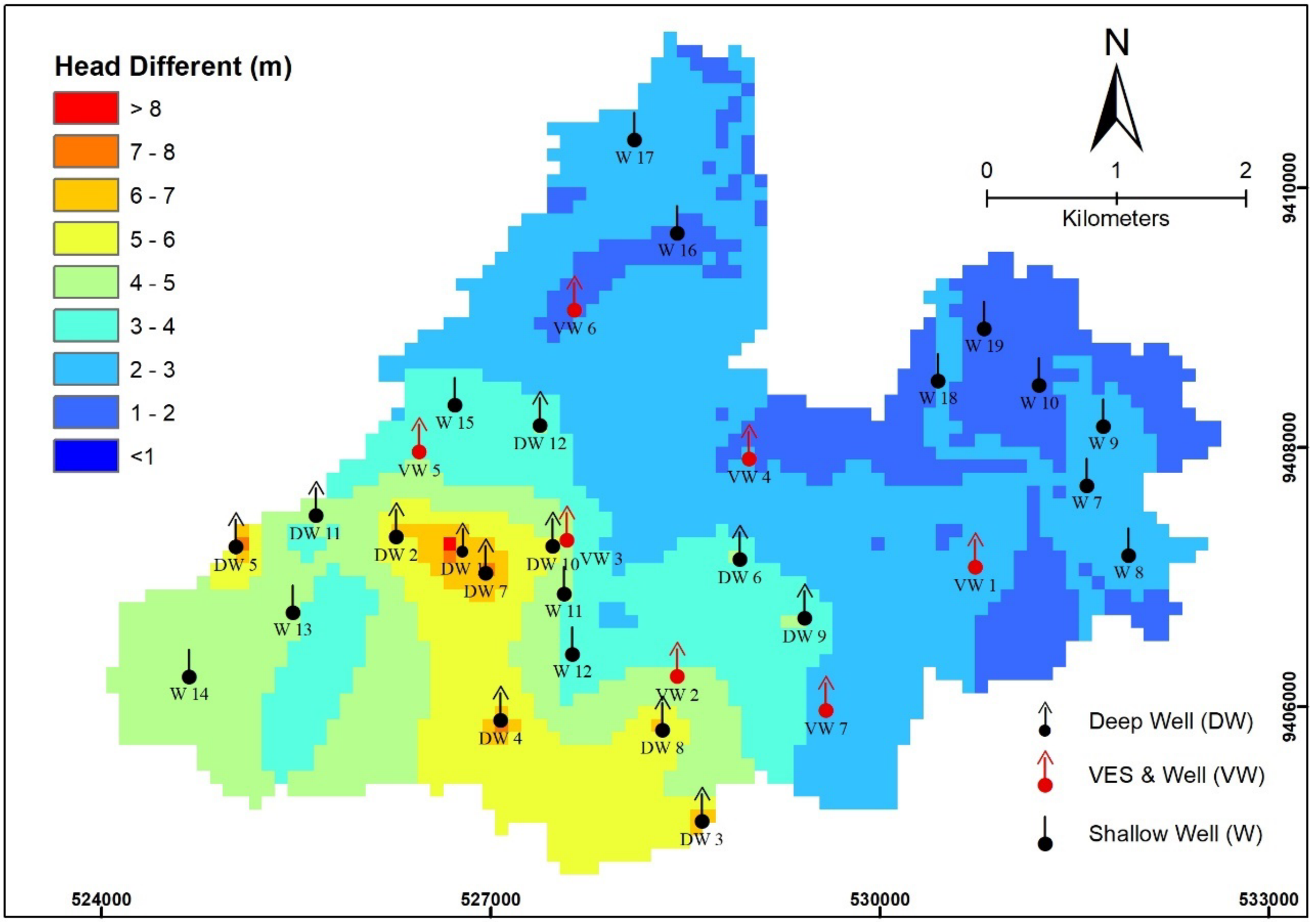


Figure 7 Groundwater level changes simulated in the Northern Bandar Lampung over 30 years.

The model simulation results show that the research area is experiencing an increasing trend of groundwater table decline. Observational data from 15 monitoring wells in the model clearly shows the impact of pumping on groundwater subsidence. The distribution of changes in the depth of the high groundwater table began to be detected in the western part of the study area. It spread widely towards the middle to the south of the study area, as shown in Figure 5. Based on this trend, the depth of the deep groundwater level increased from the west to the middle and south of research area. Groundwater depth varies from 10 to more than 40 m from the surface.

Similar results are also shown by the calculation of groundwater drawdown in the 2010 and 2030 transient models, as shown in Figure 6. The groundwater drawdown contour pattern from the steady-state simulation in 2000 becomes the drawdown reference for the stress period of the transient simulation until 2030. The simulation results show an increase in the distribution of areas experiencing drawdown, which is in line with the depletion of groundwater level, namely from the west to the middle and south of the study area. The drawdown value ranges from 0.5 to more than 5 m. In the final transient simulation results, the drawdown at the W13 observation point reached 9.77 m and 8.27 m in the DW1 deep well.

The head difference calculation in the 2030 transient model is carried out against the initial transient model in the 2000 stress period to see the impact of the overall decrease in groundwater head from the model made. In general, the results of the model calculations show that the groundwater head has decreased by more than 8 m over 30 years (Figure 7). On average, this decrease was not significant compared to the downtown area of Bandar Lampung [16]. However, the impact of pumping groundwater on deep wells is quite significant, even though discharge data for deep wells has only been calculated since the stress period 2010 and 2020.

Based on the distribution of groundwater head differences shown in Figure 7, it can be seen that the center of groundwater level decline is dominated by the location of deep wells, especially in DW1 wells. As previously stated, the DW1 well is the deepest well, with an average simulated discharge of 2.3×10^{-2} L/s, although in reality, it has a pumping capacity of up to 3 L/s. In the 10-year forecasting modeling, since the DW1 well was operational, there has been a significant decrease in groundwater level in the surrounding area. This finding becomes essential information in managing groundwater resources in the area, including Northern Bandar Lampung. Several evaluations can be carried out by mapping the importance of using groundwater resources or engineering groundwater storage if groundwater needs are urgently needed from deep wells. In the future, evaluation of rainwater harvesting technology stored in reservoirs and then injected into aquifers can be considered to accelerate groundwater recharge in aquifers [28,29]. However, further studies and feasibility studies of surface water are needed to be injected into groundwater aquifers for this implementation.

4.0 CONCLUSION

Groundwater flow simulation using MODFLOW and ModelMuse successfully modeled the dynamics of the groundwater head in the study area. This study used 15 out of 30 data wells to evaluate and observe the resulting model. Assuming constant recharge and evapotranspiration rates, the model was run for 4 stress periods: steady-state until 2000, transient 2010, 2020, and 2030. However, some of the observed estimates are still far from observations due to a lack of detailed data for model settings. However, the validation of the simulation model with well observation data using RSME ranges from 0.84 to 0.96. These results follow the criteria of an acceptable model in this study.

The simulation model clearly identifies the groundwater head decrease due to extraction from deep well pumping. The hydraulic head change distribution is in the groundwater depths varying from 10 to more than 40 m from the surface. The spread of drawdown and changes in groundwater head is concentrated at deep well points. Even the radius of the area affected by the drawdown reaches 1 km. The resulting model also indicates a decrease in groundwater head up to more than 8 m and can continue if the extraction discharge is not appropriately managed. The impact of groundwater depletion can also cause the spread of subsidence on the southern coast of the city of Bandar Lampung. Therefore, it is necessary to take action that can overcome the impact of changes in groundwater level due to pumping from deep wells. Given the importance of groundwater needs in the research area, groundwater storage engineering can be a solution. Utilization of runoff water from high rainfall can be accommodated in ponds which are then used as recharge into the groundwater aquifer system.

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References

[1] Elshall, A. S., Castilla-Rho, J., El-Kadi, A. I., Holley, C., Mutongwizo, T., Sinclair, D. and Ye, M. 2021. Sustainability of Groundwater. In *Imperiled: The Encyclopedia of Conservation.* 3: 157166. DOI: https://doi.org/10.1016/b978-0-12-821139-7.00056-8

[2] Akter, A. and Ahmed, S. 2021. Modeling of groundwater level changes in an urban area. *Sustainable Water Resources Management*. 7(7): 1-20. DOI: https://doi.org/10.1007/s40899-020-00480-x

[3] Rustadi, Darmawan, I. G. B., Haerudin, N., Suharno and Setiawan, A. 2021. Geophysical approach for assessment of seawater intrusion in the coastal aquifer of Bandar Lampung, Indonesia. *IOP Conf. Series: Materials Science and Engineering*. 1173: 1–8.

[4] Foster, T., Brozović, N. and Speir, C. 2017. The buffer value of groundwater when well yield is limited. *Journal of Hydrology*. 547: 638-649. DOI: https://doi.org/10.1016/j.jhydrol.2017.02.034

[5] Alfarrah, N. and Walraevens, K. 2018. Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. *Water*. 10(2): 143. DOI: https://doi.org/10.3390/w10020143

[6] Das, S., Maity, P. K. and Das, R. 2018. Remedial Measures for Saline Water Ingression in Coastal Aquifers of South West Bengal in India. *MOJ Ecology & Environmental Sciences*. 3(1): 6–24. DOI: https://doi.org/10.15406/mojes.2018.03.00061

[7] Lan, Y., Jin, M., Yan, C. and Zou, Y. 2015. Schemes of groundwater exploitation for emergency water supply and their environmental impacts on Jiujiang City,China. *Environmental Earth Sciences*: 73(5): 2365-2376. DOI: https://doi.org/10.1007/s12665-014-3586-x

[8] Halder, S., Roy, M. B. and Roy, P. K. 2020. Analysis of groundwater level trend and groundwater drought using Standard Groundwater Level Index: a case study of an eastern river basin of West Bengal, India. *SN Applied Sciences*. 2(3). 507 DOI: https://doi.org/10.1007/s42452-020-2302-6

[9] Khadri, S. F. R. and Pande, C. 2016. Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin, India. *Modeling Earth Systems and Environment*. 2(1). 39. DOI: https://doi.org/10.1007/s40808-015-0049-7

[10] Aghlmand, R. and Abbasi, A. 2019. Application of MODFLOW with boundary conditions analyses based on limited available observations: A case study of Birjand plain in East Iran. *Water (Switzerland)*. 11(9). 1904. DOI: https://doi.org/10.3390/w11091904

[11] Arumugam, K., Karthika, T., Elangovan, K., Sangeetha, R. K. and Vikashini, S. 2020. Groundwater modelling using visual modflow in Tirupur region, Tamilnadu, India. *Nature Environment and Pollution Technology*. 19(4): 1423-1433 DOI: https://doi.org/10.46488/NEPT.2020.v19i04.008

[12] Dawes, W., Ali, R., Varma, S., Emelyanova, I., Hodgson, G. and McFarlane, D. 2012. Modelling the effects of climate and land cover change on groundwater recharge in south-west Western Australia. *Hydrology and Earth System Sciences*. 16(8). 2709-2722. DOI: https://doi.org/10.5194/hess-16-2709-2012

[13] Susilo, G. E. and Prayogo, T. B. 2019. Rainwater Harvesting as An Alternative Source of Domestic Water in Lampung Province - Indonesia. *TATALOKA*. 21(2): 305-313 DOI: https://doi.org/10.14710/tataloka.21.2.305-313

[14] Yuwono, S. B., Sinukaban, N., Murtilaksono, K. and Sanim, B. 2013. Land Use Planning of Way Betung Watershed for Sustainable Water Resources Development of Bandar Lampung City. *Journal of Tropical Soils.* 16(1): 77-84. DOI: https://doi.org/10.5400/jts.2011.v16i1.77-84

[15] Wiyono, M. B. and Adji, T. N. 2021. Analysis of Groundwater Quality for Clean Water Supply in Pasaran Island, Bandar Lampung City, Indonesia. *Forum Geografi*. 35(1): 28-37 DOI: https://doi.org/10.23917/forgeo.v35i1.12270

[16] Zaenudin, A., Darmawan, I. G. B., Armijon, Minardi, S. and Haerudin, N. 2018. Land subsidence analysis in Bandar Lampung City based on InSAR. *Journal of Physics: Conference Series*. 1080(1): 1–7. DOI: https://doi.org/10.1088/1742-6596/1080/1/012043

[17] Zaenudin, A., Darmawan, I. G. B. and Laimeheriwa, G. 2020. 2D Gravity Qualitative Modeling to Identify Bedrock and Volcanic Rocks in South Lampung Region. *Jurnal Ilmiah Pendidikan Fisika Al-Biruni*. 9(1): 161–175. DOI: https://doi.org/10.24042/jipfalbiruni.v9i1.5859

[18] Ali, S., Maharani, L. and Untari, D. T. 2019. Development of religious tourism in Bandar Lampung, Indonesia. *African Journal of Hospitality, Tourism and Leisure*. 8(5): 1-8

[19] May, L. F., Abdurrahman, A., Hariri, H., Sowiyah, S. and Rahman, B. 2020. The Influence of Principal Managerial Competence on Teacher Performance at Schools in Bandar Lampung. *Tadris: Jurnal Keguruan Dan Ilmu Tarbiyah*. 5(1): 121-130 DOI: https://doi.org/10.24042/tadris.v5i1.5391

[20] Mangga, S. A., Amirudin, Suwarti, T., Gafoer, S. and Sidarto. 1993. *Geological Map of Tanjungkarang, Sumatra*. Bandung: Geological Research and Development Centre.

[21] Kusumastuty, N. A. E., Manik, T. K. and Timotiwu, P. B. 2021. Identification of temperature and rainfall pattern in Bandar Lampung and the 2020-2049 projection. *IOP Conference Series: Earth and Environmental Science*. 739: 012045 DOI: https://doi.org/10.1088/1755-1315/739/1/012045

[22] Langevin, C. D., Hughes, J. D., Banta, E. R., Provost, A. M., Niswonger, R. G. and Panday, S. 2021. *MODFLOW 6 Modular Hydrologic Model version 6.2.2*. U.S. Geological Survey Software Release. DOI: https://doi.org/https://doi.org/10.5066/F76Q1VQV

[23] Winston, R. B. 2020. *ModelMuse version 4.3*. U.S. Geological Survey Software Release. DOI: https://doi.org/https://doi.org/10.5066/P9XMX92F

[24] Bizhanimanzar, M., Leconte, R. and Nuth, M. 2020. Catchment-scale integrated surface water-groundwater hydrologic modelling using conceptual and physically based models: A model comparison study. *Water (Switzerland)*. 12(2): 363 DOI: https://doi.org/10.3390/w12020363

[25] Varalakshmi, V., Venkateswara Rao, B., SuriNaidu, L. and Tejaswini,

M. 2014. Groundwater Flow Modeling of a Hard Rock Aquifer: Case Study. *Journal of Hydrologic Engineering*. 19(5): 877–886. DOI: https://doi.org/10.1061/(asce)he.1943-5584.0000627

[26] Kuang, X., Jiao, J. J., Zheng, C., Cherry, J. A. and Li, H. 2020. A review of specific storage in aquifers. *Journal of Hydrology*. 581: 124383. DOI: https://doi.org/10.1016/J.JHYDROL.2019.124383

[27] Manik, T. K., Rosadi, R. B. and Karyanto, A. 2012. Evaluation of Penman-Monteith Method in Estimating Standard Evapotranspiration (ET0) in Lowland Area of Lampung Province, Indonesia. *Jurnal Keteknikan Pertanian*. 26(2): 121–128.

[28] Asnaning, A. R., Surya, S., Saputra, A. E. and Ahyuni, D. 2019. Water Conservation with Rainwater Harvesting System in Lampung Province (Case Study in State Polytechnic of Lampung Campus Area). *Journal of Science and Application Technology*. 2(1): 176 - 182 DOI: https://doi.org/10.35472/281453

[29] Sulistyiorini, R. 2020. Alternative Handling of Infrastructure Problems for Bandar Lampung City's Clean Water Needs Through Rainwater Harvesting. *Jurnal Sinergi*. 1(1): 18-24 DOI: https://doi.org/10.23960/jsi.v1i1.3