Numerical groundwater flow model in Semarang/Indonesia

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ABSTRACT

Declining groundwater levels, land subsidence, and flooding are the most common problems related to groundwater usage in Indonesia's urban areas. In Semarang, which is a city on the north coast of the Java Island, the number of registered deep wells increased sharply in the 1980s. It went up, exceeding 1,000 registered wells with groundwater abstraction of around 37 MCM/yr in 1999. This study was aimed at simulating groundwater flow based on a new hydrogeological model. The study area covers urban (Semarang city) and suburban areas (Demak, Grobogan, and Semarang Regencies). It is approximately 1,070 km^2 wide. The finite element method was chosen as the numerical solution. The model domain consists of two aquifers (Aquifers 1 and 2) and three aquitards (Aquitards 1, 2, and 3) in 9 layers. A 6-node triangular prism for a three dimensional representation is selected as the spatial discretization into 294,020 nodes and 524,979 elements. Aquifers 1 and 2 represent unconfined and confined aquifers, respectively. Boundary conditions are a constant head following the coastline of the Java Sea, flux boundary in the south, water leakage from or into the river in the east and inside the model domain, and a zero-flux boundary in the west. The normalize RMS of the calibrated steady state model indicates an acceptable value (6.2%). The real groundwater recharge has a range between 30 and 176 mm/yr. Groundwater abstraction is around 60.7 MCM/yr based on the calibrated steady state model in 2010. Prognoses using the transient model indicate that reducing annual abstraction by 20 MCM/yr until 2031 is necessary to restore groundwater resources in Semarang urban area.

KEY WORDS - groundwater, finite element, steady state, transient, Semarang

INTRODUCTION

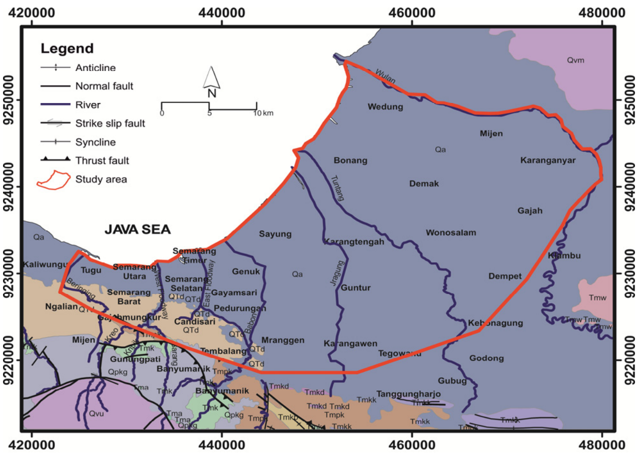
Indonesia's urban areas are facing various environmental problems (i.e. declining groundwater level, land subsidence, and flooding) related to groundwater usage. The groundwater demand as one of water resources increases continually in line with population growth. Abstraction via deep wells concentrates on a confined aquifer system. In Semarang, which is a city on the north coast of the Java Island, the number of registered deep wells increased sharply in the 1980s. It went up, exceeding 1,000 registered wells with groundwater abstraction of around 37 million cubic meter per year [MCM/yr] in 1999 (DGTL 2003). The study area covers urban (Semarang city) and suburban areas (Demak, Grobogan, and Semarang Regencies). It is approximately 1,070 km^2 wide with a population around 3 million inhabitants (BPS Prov. Jateng 2010). There is an urgent need to provide a quantitative assessment to the current situation as well as future change (climate) projections and its impact in groundwater levels and storages for the prognoses. Major improvements of the existing hydrogeological model are developed and then applied into a numerical groundwater flow model under both steady and transient conditions.

GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

Topographically, Semarang consists of two major morphologies: lowland and coastal areas in the north with a maximum elevation of 10 m mean sea level [msl] and the foothill of Mount Ungaran up to 210 m msl at the border of the study area in the south. The study area is located dominantly in the alluvial plains of the northern part of Java (**Fig. 1**), i.e. the Alluvium (Qa) and the Damar (QTd) formations (Thanden et al. 1996). Groundwater in plain and coastal areas flows primarily in an intergranular system, whereas fissures and interstices system occur in the south of Semarang (Said and Sukrisno 1988). A multiple layer aquifer system is found in the study area. It consists of an unconfined aquifer at the top and a confined aquifer below which is sub-classified into different units' (i.e. Quaternary marine, Garang and Damar). Groundwater flows from the mountain area in the south towards the coast in the north.

METHODOLOGY

The research was divided into three main sections: understanding the natural system, developing the hydrogeological model, and finally applying the numerical groundwater flow model. In order to improve the hydrogeological model, the following steps were done: constructing hydrogeological cross section and deriving hydrostratigraphical units (HSU), defining the water type using hydrogeochemistry analysis, calculating groundwater recharge based on long term climate from 1998 to 2007and land use allocation data, defining boundary conditions and initial parameters. The finite element method was chosen as the numerical solution using DHI-WASY FEFLOW 5.2. A steady state model was set up using data for 2010 due to a reasonably complete data base and complementary measurements of piezometric head from twelve monitoring wells in the model domain. The calibrated steady state model was applied for simulating a transient model. The transient model was created for the period from 1998 to 2010. Groundwater abstraction and recharge were implemented as time series with an annual resolution. Prognoses were simulated for the predictions related to the city development plan and future climate change. They were conducted as a reference for an early warning system related to the government policy. The growth of the community areas will perform to the increase of groundwater abstraction. The effect of climate change was adopted from the finding of regional climate change projection development and interpretation for Indonesia by the Centre for Australian Weather and Climate Research (CAWCR 2010). There were four prognoses, which were run until 2031, with respect to the spatial planning for Semarang city.



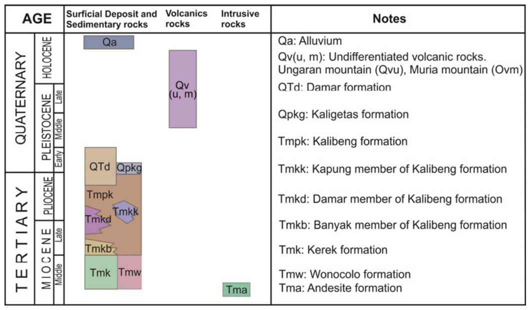


Figure 1. Geological map of the study area (left) and the regional stratigraphy (right) (Thanden et al. 1996)

RESULTS AND DISCUSSION

It was extremely difficult to correlate stratigraphical details over any significant extent due to the heterogeneous lithology in the study area. The concept of HSU was applied to generalize the hydrogeological system in the study area (**Fig. 2**). The HSU in the study area consists of two aquifers (Aquifers 1 and 2), three aquitards (Aquitards 1, 2, and 3). Aquifer 2a represents the Garang aquifer (Gr) as the main aquifer in the study area showing a predominantly bicarbonate alkaline water. It extends from the centres of Semarang to the north east. Aquifer 2b consists of Quaternary marine sediments (Qm) and has a predominantly chloride alkaline water, locally alkaline earth water type. It is prominent in plain and coastal areas. The Damar formation (Dm) is classified as Aquifer 2c. It contains fresh water in volcanic rocks of predominantly bicarbonate alkaline earth water type. A higher alkaline content is common. The Dm aquifer spreads out from the low to the intermediate slopes.

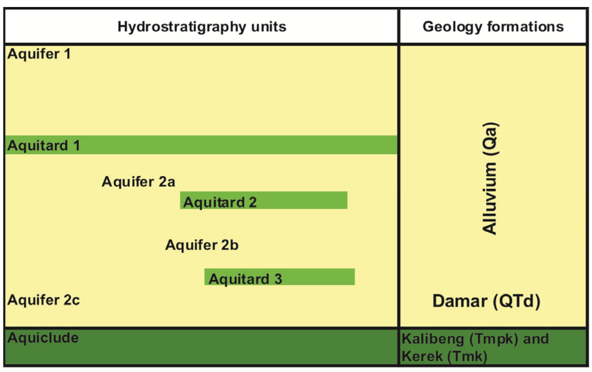


Figure 2. The concept of hydrostratigraphy units (HSU) in the study area (Putranto 2013)

To determine the potential natural and urban groundwater recharge, the meteoric water balance calculation was applied. Based on the long term climate data, the average annual precipitation rate and temperature were 2,092 mm/yr and 27.6°C respectively. Potential evapotranspiration (ET_p) and surface runoff (R_o) were calculated by empirical equations, Turc and surface runoff curve number. ETp was 1.082-1,1324 mm/yr while the range of R_o depth was around 772-1,039 mm/yr. Urban recharge was estimated as an impact of urbanization. Urbanization leads anthropogenic sources of recharge such as potential domestic waste water and leakage from water mains and sewers.

Totally the average of net urban recharge was estimated around 133 mm/yr. Thus, the potential groundwater recharge in the study area was calculated from 70 to 410 mm/yr.

It is an essential step to develop a conceptual model after defining the horizontal and vertical distribution of all HSU including its recharge calculation. **Fig. 3** shows the schematic diagram of the conceptual model in the study area. The model domain is divided into 9 layers and 10 slices. The aquifers and aquitards thicknesses are varying from 0.1 to 151 m.

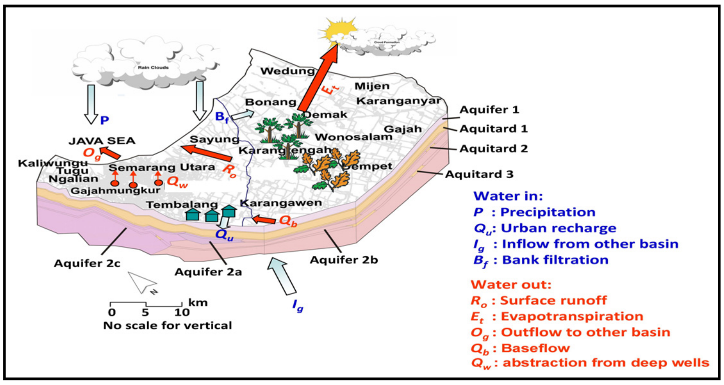


Figure 3. Conceptual model (Putranto 2013)

The Java Sea, in the north, forms a natural boundary condition with a constant head value of 0 m at sea level. The surface watershed is applied to enhance the distribution of flux boundary in the south while no-flow boundary represents in the west. A semipermeable boundary is assigned to accommodate the transfer rate values from rivers into an aquifer or vice versa in the east and inside of the model domain.

The horizontal hydraulic conductivity values (K_h) can be obtained from various sources (Said 1974; Spitz 1989; Haryadi et al. 1991; Marsudi 2000; Arifin and Wahyudin 2000; DGTL 2003; P.T. Gea Sakti 2006). Aquifers have K_h values from 0.13 to 3.01 10^{-4} m/s while K_h is 0.23-0.68 10^{-7} m/s for aquitards.

The discretization of the model domain is using a 6-node triangular prisms into 294,020 nodes and 524,979 elements as a three dimensional representation. A steady state model is set up to simulate hydraulic heads in 2010. Initial parameter values are assigned by selecting values based on the hydrogeological model. They needed to be evaluated in the numerical solution. During the calibration process, the goodness of fit parameter estimations compares the result of calculated and observed heads (residual heads). Calibration resulted in a high absolute error calculated as root mean square (RMS) of around 2.9 m, but normalized RMS indicates an acceptable value (6.2%). The normalized RMS value is a more representative measure of the fit than the RMS itself as it accounts for the scale of the potential range of data values (observed heads have a range from -39 to 8 m msl). The calibrated steady state model gives a reasonable value of abstraction around 60 MCM/yr with a real groundwater recharge of about 43% of the potential groundwater recharge (30-176 mm/yr). This amount is around 1-8% of the average precipitation in the model domain. The value coming from modelling is much higher than the officially documented groundwater extractions (35 MCM/yr).

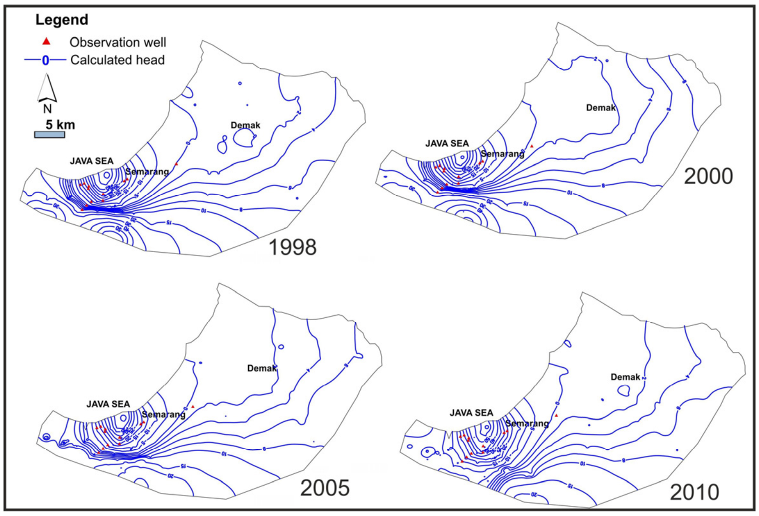


Figure 4. Calculated heads under transient simulation from 1998 to 2010

The transient model simulates groundwater flow from 1998 until 2010. The quantitative result of calibration shows that around 40% of the residual heads lie outside of the 95% confidence interval. RMS shows a high value of around 7.55 m, but normalized RMS indicates an acceptable value (around 12%). This is due to the high range of observed heads between -47.5 and 13.6 m msl. The model results show a decrease of piezometric heads in the north of Semarang year by year due to an intensive abstraction (**Fig. 4**). The parameters for calculating imbalance in the numerical calculation consist of three: fluxes in or out of boundaries, recharge on top of the layer and the total of groundwater abstraction. The imbalance under transient condition represents the change in storage. It is the sum of total groundwater inflow and outflow of the model domain. A positive imbalance implies a gain of water in the aquifer system. In the last year of the transient simulation (2010), groundwater fluxes exiting through boundaries are slightly higher (90 m^3/yr) than entering the model domain. Total groundwater recharge is around 72.8 MCM/yr, and abstraction from deep wells reaches 60.7 MCM/yr. Finally, the imbalance/storage decreases more than 50% of initial storage (1998) and becomes about 12 MCM/yr in 2010. Furthermore, hydraulic conductivity, groundwater abstraction, groundwater recharge, and flux boundary are parameters to be evaluated in the sensitivity analysis. Hydraulic conductivity and groundwater abstraction are the most sensitive parameters. A variation of these parameters leads to significant changes in both conclusion and residual statistics.

For the model application, there are four prognoses in order to predict groundwater levels and storages based on the future city development and climate change:

a. Prognosis 1: continues the calibrated transient model with total abstraction of a constant value (60.7 MCM/yr) starts from 2011 until 2031.
b. Prognosis 2: continues the calibrated transient model with total abstraction increased gradually to be 104 MCM/yr in 2031. The final total abstraction shows around 85% of the projection for the total water demand.
c. Prognosis 3: continues the calibrated transient model with total abstraction decreased gradually up to 20 MCM/yr in 2031.
d. Prognosis 4: illustrates the projection of climate change (decreases precipitation in Java Island up to 0.1 mm/d or around 37 mm/yr) and abstraction increases gradually to be 104 MCM/yr in 2031.

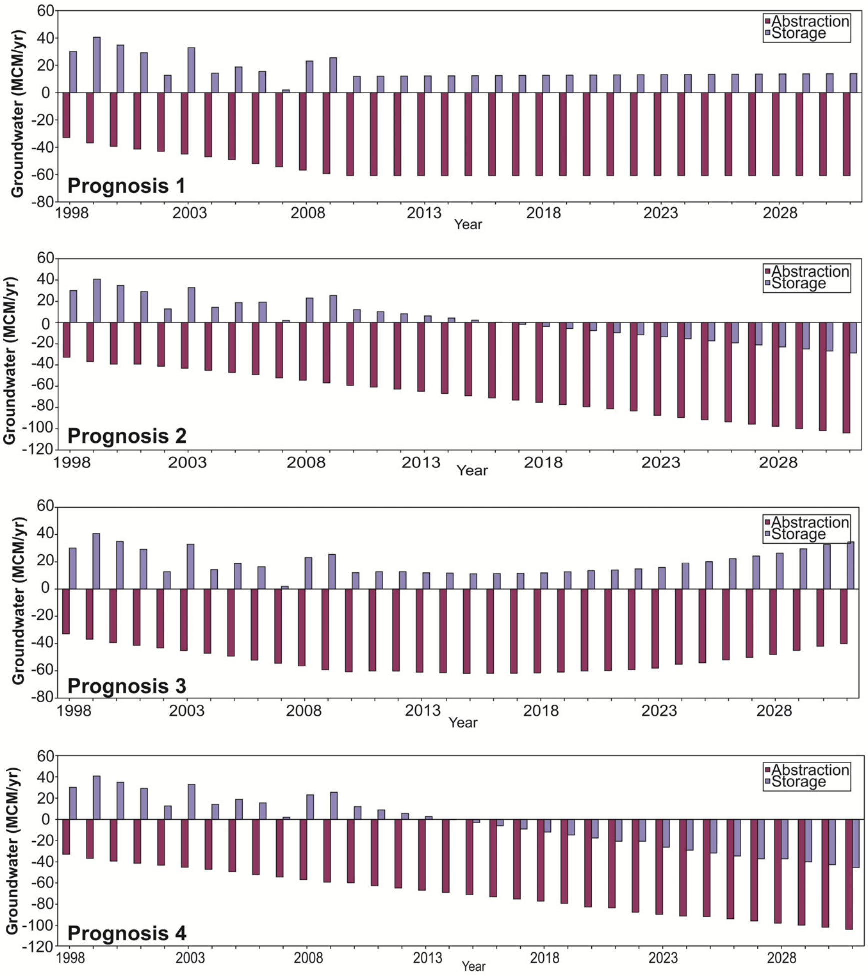


Figure 5. Result of the prognoses

All prognoses show the lowering of piezometric head in Semarang and cone of depression becomes wider to the south than other areas. The worst case (Prognosis 4) causes groundwater storage to decrease up to (-) 1.11 x 10^5 m^3/yr in 2014 (**Fig. 5**). Despite the widening of the cone of depression, prognoses using the transient model indicate that reducing annual abstraction by 20 MCM/yr until 2031 is necessary to restore groundwater resources in Semarang urban area.

SUMMARY

The hydrogeological model is developed successfully by integrating data of geology, hydrogeology and hydrology. To generalise the hydrogeological system in the study area, the concept of HSU is applied. There are two aquifers (Aquifer 1 and Aquifer 2), three aquitards (Aquitards 1, 2, and 3) and one aquiclude in the study area. A numerical model transforms the conceptual model as the response of the aquifer system. Groundwater abstraction of about 60.7 MCM/yr, 43% of the potential groundwater recharges, and the initial hydraulic conductivity value with the factor of 0.9 represent the best result during the calibration process. The process of abstraction and climate change will lead to high potential loss of groundwater resources in the future. The best solution is achieved by decreasing abstraction. It affects groundwater storage increase. Thus, it causes a low in potential loss of groundwater resources in the future. This should be a critical point for the decision makers at the local government (Semarang municipality) in order to control groundwater use in the future.

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