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Forward Problems Solving of Groundwater Flow using Stochastic Groundwater Vistas Method

Pemecahan Masalah Aliran Air Tanah Forward Problem dengan Pemodelan Metode Stokastik Groundwater Vistas

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ABSTRAK

Pada permasalahan *forward problem*, nilai head hidrolik dapat dihitung dengan mengetahui nilai parameter air tanah. Parameter air tanah, seperti konduktivitas hidrolik, bervariasi dalam ruang karena variasi dari karakteristik geologi akifernya. Konsekuensi dari hal ini adalah sulit bahkan tidak mungkin untuk memperlakukan variabilitas ini dengan pendekatan deterministik karena tidak ada nilai yang pasti untuk digunakan sebagai input dari satu parameter. Penelitian ini bertujuan untuk mendapatkan model matematik dan nilai head hidrolik estimasi dari aliran air tanah yang dibuat dengan Program *Groundwater Vistas* yang sesuai dengan model fisik. Pemodelan matematik aliran air tanah menggunakan Program *Groundwater Vistas* dengan pendekatan stokastik dan metode simulasi Monte Carlo dimana data input (konduktivitas hidrolik, head hidrolik) diperoleh dari model fisik. Hasil penelitian menunjukan *nilai sum of squares* dari diagram scater plot seluruh titik realisasi mempunyai nilai yang sangat kecil (mendekati atau bahkan nol). Nilai *error* dari diagram *residual mean for all realizations* seluruh realisasi memiliki nilai yang sangat rendah mendekati nol. Nilai head hasil perhitungan (computed) dengan hasil observasi mempunyai selisih nilai yang cukup kecil (berkisar antara 0,0006–0,009 m). Hasil ini dinilai cukup baik, karena dalam suatu pemodelan tidak mungkin bisa didapatkan hasil pemodelan yang betul-betul sama dengan yang dimodelkan. Hasil menunjukkan bahwa Program *Groundwater Vistas* dapat digunakan untuk pemodelan dengan *error* yang sangat kecil dan dapat mengestimasi nilai head hidrolik dengan cukup baik.

Kata kunci: akifer, head hidrolik, konduktivitas hidrolik

ABSTRACT

In the forward problems, the hydraulic head value can be found by knowing the value of the groundwater parameter. Parameters of groundwater such as hydraulic conductivity, vary over space due to the variation of aquifer properties. Consequently, it is difficult or almost impossible to treat these kinds of variability by a deterministic approach because there is no exact value to be used as input for a parameter. The objective of this research was to obtain a mathematical model of groundwater flow made with the Groundwater Vistas Program that is in accordance with the physical model. Mathematical modeling of groundwater flow using the Groundwater Vistas Program with a stochastic approach and Monte Carlo simulation method where the input data (hydraulic conductivity, hydraulic head) is obtained from the physical model. Results showed that the sum of squares value from the scatter plot diagram of all realization points had a very small value (close to or even zero). The residual mean diagram showed the error value of all realizations had a very low value close to zero. The calculated head value (computed) compared with the results of the observation had a fairly small difference value (ranging from 0.0006−0.009 m). These results were considered quite good because in modeling it is impossible to get modeling results that are exactly the same as those being modeled. The results show that Groundwater Vistas can be used for modeling with very small errors and it can estimate values of hydraulic heads quite well.

Keywords: aquifer, hydraulic conductivity, hydraulic head

INTRODUCTION

Groundwater is one of the important water resources to be protected. Groundwater is as important as river water and rainwater in maintaining the balance and availability of raw water for domestic and industrial use (Rejekiningrum, 2010). Groundwater is a limited resource in which when disturbed, it is difficult to recover (Hendrayana, 2014). Lack of groundwater can occur when human pumping exceeds natural recharge (Harjito, 2014). Besides, the decrease in groundwater level can be caused by seawater intrusion and land subsidence (Sudarto, 2012). Generally, groundwater flows in heterogeneous geological formations. Groundwater parameters, such as hydraulic conductivity, vary in space due to variations in the geological characteristics of the aquifer (Simaremare, 2015). In heterogeneous formations, the hydraulic conductivity of a soil layer varies between 10^{-2} meters to 10^{3} meters (Cahyadi et al., 2014). Consequently, it is difficult or even impossible to treat this variability with a deterministic approach because there is no definite value to be used as input for one parameter (Ye et al., 2010).

Uncertainty in groundwater flow problems can be solved by modeling groundwater. Groundwater modeling is a method that is widely used in decision-making processes related to groundwater management (Goderniaux et al., 2011). There are various kinds of groundwater modeling with their respective advantages and limitations in their use (Kumar, 2012). One modeling approach that can be used is the Stochastic method (Xin He et al., 2015). The stochastic approach can provide a probabilistic prediction of aquifer conditions by considering that the parameter is a random variable (Garcia & Power, 2017). This approach can be done by making groundwater modeling using the Groundwater Vistas Program (Kiptum et al., 2017).

In this research, mathematical modeling of groundwater flows using the Groundwater Vistas Program was carried out. Input data (hydraulic conductivity, hydraulic head) were obtained from physical models using porous media. The Groundwater Vistas program is a groundwater flow and transportation modeling program that uses a stochastic analysis approach and Monte Carlo simulation (Rumbaugh & Rumbaugh, 2017).

This program performs forward problem calculations using hydraulic conductivity data and hydraulic head as random variables (Pasetto et al., 2013). The purpose of this study was to obtain an estimated hydraulic conductivity value and a mathematical model of groundwater flow that was in accordance with/following the physical model.

MATERIALS AND METHODS

This research was conducted at the ITS Environmental Engineering Department Workshop Room. This research phase began with a literature study of various modeling methods for groundwater. Then the measurement of the porous media material was followed by making a physical model. The results obtained from this physical model simulation were tested using the Groundwater Vistas Program. The analysis results from the Groundwater Vistas Program were compared with the results obtained in the physical model. After that, conclusions and suggestions were made regarding the suitability of the Groundwater Vistas Program in groundwater physical modeling.

Materials Preparation

In this research, sand was used as a porous medium. The sand used consisted of 8 types and came from different sources. Before being used, the sand was performed with the hydraulic conductivity test. The test used the constant head method (Chegenizadeh & Nikraz, 2011). Testing using a permeameter was done at the ITS Civil Engineering Soil Mechanics Laboratory. The K value of the test results varied from 3.2 m/day to 28.2 m/ day. This variation in K value occurred due to the different types (origin) of sand and density of sand formations (Table 1).

Tools Preparation

The main equipment used in this study was a reactor/ physical model made of glass in the shape of a box with a size of 250 cm x 250 cm x 100 cm. The physical model consisted of 2 parts, namely the water column and the media box. The water column was located on the left and right sides of the physical model as the inlet and outlet, each measuring 25 cm x 200 cm x 100 cm, equipped with a water head/ height control pipe on the inside. A 200 cm x 200 cm x 50 cm media box was located in the center of the physical model. The media box was divided into 64 rooms with a screen made of wire, each cell measuring 25 cm x 25 cm. The physical model was equipped with a water reservoir (tank) with a capacity of 2200 liters and a pump that functioned as a source of water supply (Figure 1).

Assembling Tools and Materials

The sand was put into a model box with a random arrangement of spaces, with a thickness of 50 cm as a porous medium. On the porous media, 3 transparent pipes that function as piezometers were installed, 2 as monitoring wells and 1 as a pump well. Monitoring well 1 (r1) was 109 cm from the pump well and monitoring well 2 (r2) was 52 cm from the pump well. The pipe was installed measuring 50 cm in length according to the thickness of the media, given holes with a diameter of 0.5 cm, and given a screen of cloth to prevent sand from entering. The pump well pipe was connected to a pump to suck water in the porous medium (Figure 2).

Operating the Physical Model

Before the operation, the top of the physical model was closed first so that it was waterproofed. Operation started with filling water from the reservoir using a pump. Water was flowed from the AD (Head I) side to the BC (Head II) side. The water level was set at Head I in 66 cm and Head II in 64 cm. When the water level on both sides was reached, a pumping test was performed. Pumping was done through a pump well with a water flow of 105.3 ml/second for 23 minutes.

During the pumping, measurement and recording of the head initial value, the head reduction value (drawdown, s) on the piezometer for each well were monitored every 1 minute. The data obtained from the physical model simulation were used as input to the Groundwater Vistas Program.

Table 1. Range value for sand hydraulic conductivity

Sand	K (m/day)
1	4.8−8.1
2	20.6−27.8
3	4.9−21.8
4	14.3−24.2
5	17.6−28.2
6	13.6−21.0
7	13.4−26.1
8	3.2−7.3

Figure 1. Physical model of groundwater flow

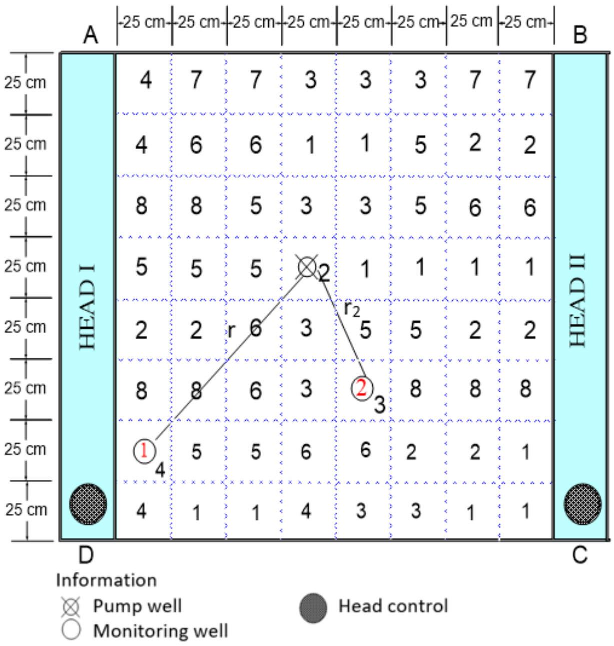


Figure 2. Series arrangement of sand media in the physical model

Making a Mathematical Model

After obtaining data from the physical model, the next step was making a mathematical model with the Groundwater Vistas program. At Groundwater Vistas, there were several steps in the modeling process, namely: grid design, boundary conditions, and aquifer properties.

Grid design was made following the physical model. In this model, 10 columns and 8 rows were made, columns 2 to 9 were made as aquifer layers, and columns 1 and 10 were used as boundary conditions. The results of the intersection of columns 2 to 9 with rows 1 to 8 obtained 64 cells for the aquifer layer with each cell of 0.25 m x 0.25 m (Figure 3a). The model was made of 2 layers, layer 1 (top) had a thickness of 0.1 m, functioned as an impermeable layer of water, and layer 2 (bottom) had a thickness of 0.5 m, functioned as a place for the aquifer layer (Figure 3b).

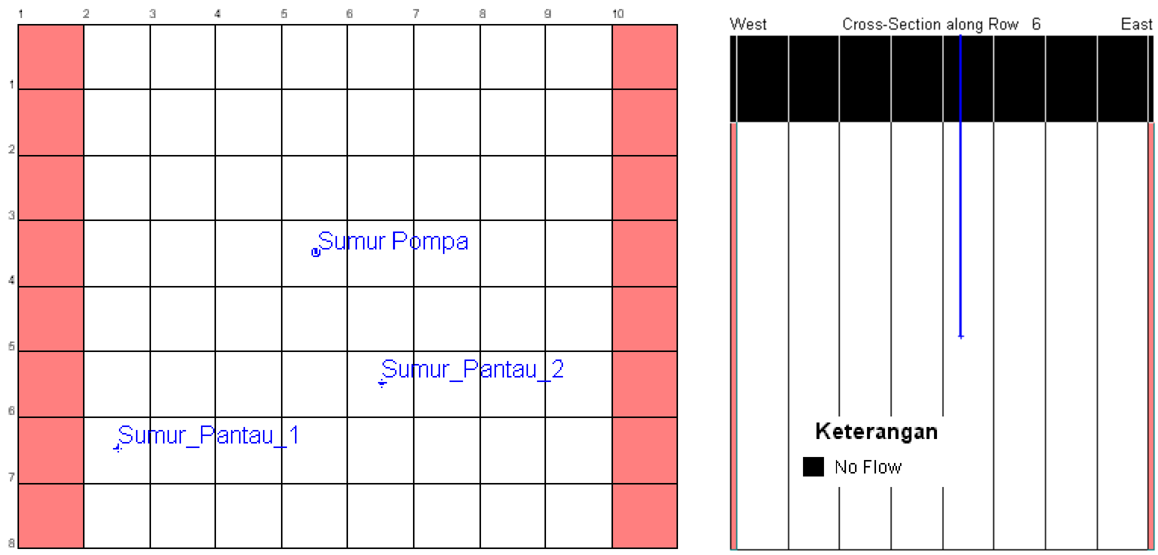
Making Boundary Conditions

The boundary conditions made were constant head and no-flow. The constant head was made in column 1 and 10 layer 2. Constant head in column 1 was 0.66 m and in column 10 was 0.64 m. In layer 1, no-flow was made so that in layer 1 there was no water flow or water-tightness. Making aquifer properties. Aquifer properties used were hydraulic conductivity and storage coefficient. The hydraulic conductivity model consisted of 8 types. The value used for the hydraulic conductivity input was any (random) value that was within the range value of the sand material test results (Table 2). The placement of the hydraulic conductivity was adjusted to the placement on the physical model (Figure 4).

After the model was formed, then the pump wells and monitoring wells (target) were placed. The well position was adjusted to the physical model. In the pump well, a constant flow rate input was entered similar to the pumping test discharge of −9.097 m^3/day (a negative sign indicates discharge). In the monitoring well (target), the head reduction value was entered from the results of the physical model pumping test (Table 3).

The last stage is running the modeling on the Groundwater Vistas program. In this modeling, the hydraulic conductivity (K) value and the hydraulic head of the physical model inputted/ entered were treated as random variables. Random variable values were generated repeatedly by Monte Carlo Simulation (Pasetto et al., 2013). Monte Carlo simulations produce several realizations containing different estimated hydraulic conductivity values (Fogg & Zhang, 2016).

After running the Groundwater Vistas program, it was obtained data of the hydraulic head, storage coefficient, discharge, pump time, display of modeling realization in the form of a sum of squares diagram, mean residual (error) diagram, and estimated hydraulic head values (Kiptum et al., 2017). Then, data interpretation was performed on the comparison graph between the hydraulic head of the observed monitoring wells on the physical model with the estimation results from the Mathematical Program (Singh, 2014).



(a) (b)

Figure 3. Mathematical model design: a). Top view b). Side view

Table 2. The value of the hydraulic conductivity input on the model

Sand	Range Value K (m/day)	K Input (m/day)
1	4.8−8.1	6.4
2	20.6−27.8	24.2
3	4.9−21.8	13.4
4	14.3−24.2	19.3
5	17.6−28.2	22.9
6	13.6−21.0	17.3
7	13.4−26.1	19.8
8	3.2−7.3	5.2

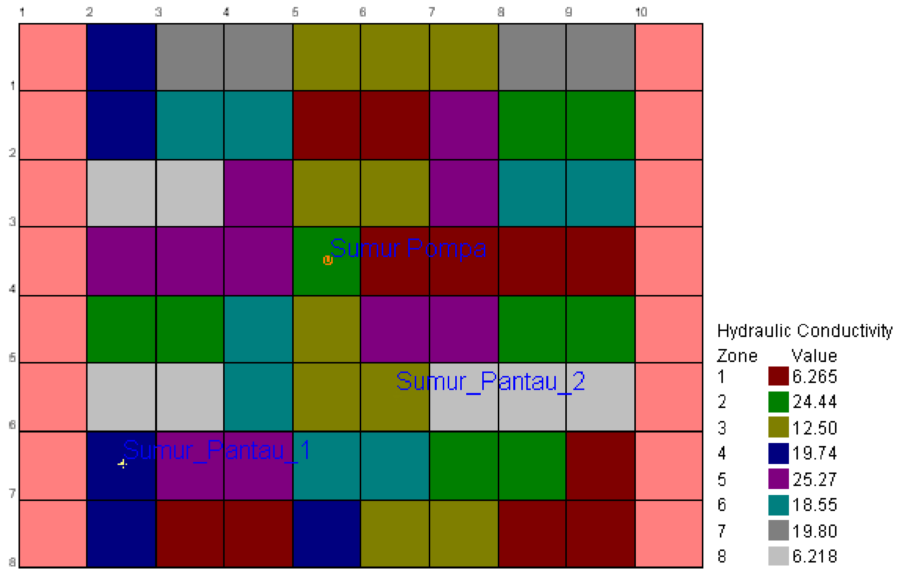


Figure 4. Grid design of *hydraulic conductivity* model placement

Table 3. Data input of target time & the head of monitoring well 1 & 2

Time (day)	*Head* (m)	
	Well 1	Well 2
0	0.659	0.649
0.0014	0.656	0.643
0.0063	0.6555	0.643
0.0077	0.6555	0.642
0.0105	0.6555	0.642
0.0136	0.655	0.64
0.0154	0.654	0.64

RESULTS

The Simulation Results of the Physical Model Pumping Test

From the pumping, it was obtained data of the head reduction on the piezometer of monitoring wells 1 and 2 (Table 4).

Storage Coefficient (S) Calculation

The data from the pumping test results were used to calculate the storage coefficient (S) from the physical model by forward problem using the trial & error method. From the results of trial & error, the obtained data on the S value was 0.0046. The S value obtained was quite relevant to use because it was still within the S value range for the confined aquifer layer, namely 0.00005−0.05.

Results of the *Groundwater Vistas* Mathematics Program Running

The results of the program running were presented in the form of diagrams. These diagrams were in the form of a scatter plot consisting of 20 points which were the results of all the realizations generated from the random variable model. The analysis results were seen from the sum of squares for all realizations and the residual mean for all realizations. These diagrams show the value of the realization rate and the error of each modeling result realizations (Figure 5).

Each realization result has a conductivity (K) value which could produce a different hydraulic head value compared to other realization results. From the existing 20 realization points, the value from the 4th realization was selected and the head reduction value, as well as the comparison graph between the observed head and the calculated head in monitoring wells 1 and 2 (Table 5 and Figure 6), were obtained.

Table 4. The head reduction in monitoring wells 1 and 2

Time (minutes)	*Head* (cm)	
	Well 1	Well 2
0 (initial)	65.9	64.9
1	65.6	64.3
2	65.6	64.3
3	65.6	64.3
4	65.6	64.3
5	65.6	64.3
6	65.6	64.3
7	65.6	64.3
8	65.55	64.3
9	65.55	64.3
10	65.55	64.2
11	65.55	64.2
12	65.55	64.2
13	65.55	64.2
14	65.55	64.2
15	65.55	64.2
16	65.55	64.2
17	65.5	64.1
18	65.5	64.1
19	65.5	64
20	65.4	64
21	65.4	64
22	65.4	64
23	65.4	64

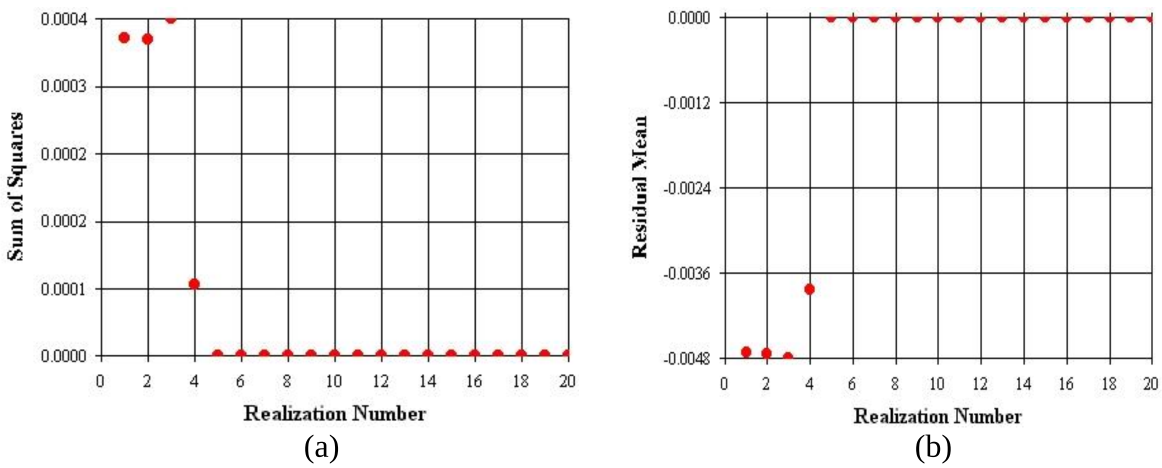
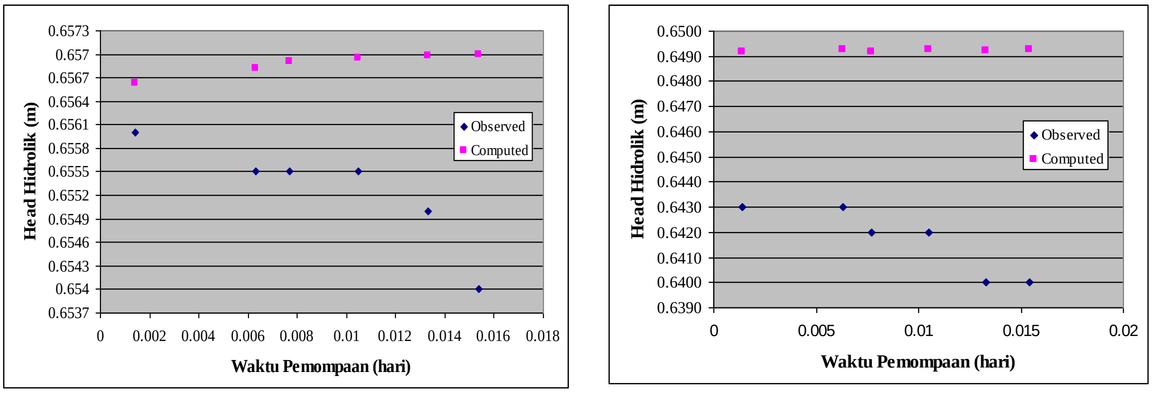


Figure 5. Diagrams of results analys was of program *running* a). *Sum of Squares for all Realizations* b). Residual Mean for all Realizations

Table 5. The hydraulic head of the estimation results and the 4th realization observation

Time (days)	Monitoring Well 1 (m)		Monitoring Well 2 (m)	
	Observed	Computed	Observed	Computed
0.0014	0.656	0.656635	0.643	0.649155
0.0063	0.6555	0.656822	0.643	0.649263
0.0077	0.6555	0.656909	0.642	0.649193
0.0105	0.6555	0.656956	0.642	0.649251
0.0133	0.655	0.65698	0.64	0.649236
0.0154	0.654	0.656997	0.64	0.649259



(a) (b)

Figure 6. Graphs comparison of the head from the observation and calculation results from the 4th realization a). monitoring wells 1 b). monitoring wells 2

DISCUSSION

The results of modeling with Groundwater Vistas show that the sum of squares diagram of all points of realization had a very small value (close to or even zero). The lower the sum of squares the better the result is (Yeh, 2015). Then for the value of the residual mean for all realizations, all realization points also had a value close to zero. This shows that the modeling error rate is very low (He et al., 2013). From all existing analysis results, it is shown that all have the same good value and are equally possible to be used in estimating the value of the head model. From the existing 20 realization points, one was selected by considering the value of the reduction in the hydraulic head which is in accordance with the value of the head (target) of the monitoring well. The realization result chosen was the 4th realization which was considered the best for estimating the head model value.

From the estimated value generated from the 4th realization, it was obtained that the computed head value with the results of the observation having a fairly small difference in value, ranging from 0.0006–0.009 m. These results were considered quite good because in modeling it is impossible to get modeling results that are exactly the same as those being modeled (Clement, 2011).

CONCLUSION

The Groundwater Vistas program can model and estimate the value of hydraulic head from a physical model of a confined aquifer. The error that occurs is very small (close to zero), as shown in the mean residual diagram. This shows that the estimation results are quite accurate. In this research, modeling of the aquifer layer with confined aquifer and isotropic conditions has been carried out, thus it is necessary to do other research with different aquifer conditions.

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