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Development of Model for Simulation Study of Groundwater under Affection of Various Surface Condition in Cidanau Watershed

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Abstract

The groundwater model was developed adopting USGS Modflow model, a three dimensional ground water flow modular model that could be readily modified. The simulation was conducted for the caldera of Cidanau watershed, the flat area where the natural reserve of Rawa Danau swamp lays. The area was assumed to have only one soil layer with uniform properties of soil hydraulic conductivity, specific storage, specific yield and porosity of 0.0001 m/s, 0.0001/m, 0.2 and 0.2. Digital Elevation Data (DEM) was fed to the software to generate the thickness and the elevation of the ground layer. Only 6 rivers were used for boundary condition, and as well as the swamp their water level were assumed constant along the simulation for simplification. There are 6 land uses taken into account which area paddy field, bare field, plantation, residential, swamp forest and upland field. The simulation was conducted in daily time step for 90 days with initial groundwater level at 2 meter depth below the surface. Since precipitation has not yet been taken into account, alteration of the groundwater was only happen by mean of evaporation, percolation and leakages from river and swamp. The simulation shows the largest decreased of groundwater level occurs in bare field, and in paddy field the level seems to be preserved.

Keywords: Groundwater, Modflow, Landuse

Introduction

Cidanau is an important watershed in Banten Province Indonesia. Cidanau River takes the role as the drain of Rawa Danau Natural Reserve. The Rawa Danau swamp is located in the caldera of the Danau volcanic complex at an elevation of around 100 m above sea level. According the UNEP-IETC report (Weir and Sukimin, 1999), this swamp area is concluded to experienced major physical and hydrological alteration. Two hundred years ago, a much larger area of land was permanently covered by water in the caldera than is covered at present. The water in the lake would have largely prevented the soil in the area of the swamp forest from drying out. In the present day, the caldera is utilized for various human activities. Beside of its natural surfaces, alterations made by human activities also occure and the changes of surface contitions, which affects surface processes, are also happening.

Water existence in this watershed is very important, and affects the natural reserve that is known to be effectively ceased to exist. Groundwater quality and quantity are affected by the surface conditions and also human activities on it. In this study, a numerical model of groundwater of Cidanau watershed using Modflow model is proposed. The model takes into account the effects of various surface conditions to the ground water by means of evaporation and recharge.

Groundwater flow model (MODFLOW)

The ground water simulation in this study was performed using USGS Modflow model, a three dimensional groundwater flow modular model that could be readily modified, simple to use and maintain, could be executed on a variety of computers with minimal changes, and was relatively efficient with respect to computer memory and execution time. The complete theory of ground water flow models, its solutions

and the design of the Modflow model is described in detail in McDonald and Hauges (1988).

The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial-differential equation

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

where K_{xx} , K_{yy} and K_{zz} are values of hydraulic conductivity along the x , y , and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (m s^{-1}); h is the potentiometric head (m); W is a volumetric flux per unit volume and represents sources and/or sinks of water (s^{-1}); S_s is the specific storage of the porous material (m^{-1}); and t is time (s).

In general, S_s , K_{xx} , K_{yy} , and K_{zz} may be functions of space ($S_s = S_s(x, y, z)$, $K_{xx} = K_{xx}(x, y, z)$, etc.) and W may be a function of space and time ($W = W(x, y, z, t)$); equation (1) describes ground-water flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

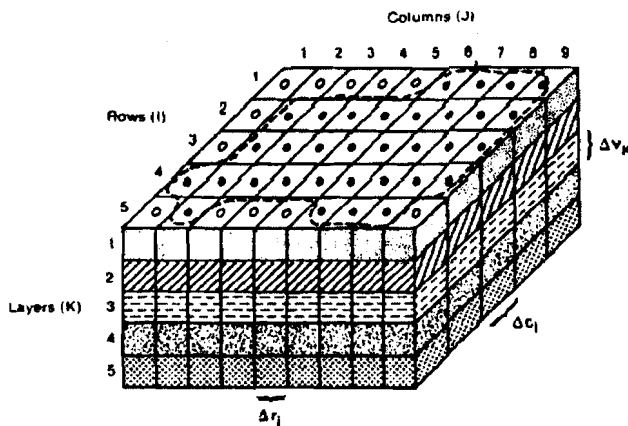
Equation 1 is the basic equation of Modflow model. This equation is approached by the finite-difference method, wherein the continuous system described by equation 1 is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. Fig.1 shows a spatial discretization of an aquifer system with a mesh of blocks called cells, the locations of which are described in terms of rows, columns, and layers, with an i, j, k indexing system.

In formulating the equations of the model, an assumption was made that layers would generally correspond to horizontal geohydrologic units or intervals. In terms of Cartesian coordinates, the k , i and j index denote changes along the vertical z , columns y and rows x .

The sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. Flow into cell i, j, k in the row direction from cell $i, j-1, k$ (Fig.2), is given by Darcy's law as

$$q_{i, j-1/2, k} = KR_{i, j-1/2, k} \Delta c_i \Delta v_k \frac{h_{i, j-1, k} - h_{i, j, k}}{\Delta r_{j-1/2}} \quad (2)$$

where $h_{i, j, k}$ is the head at node i, j, k , and $h_{i, j-1, k}$ that at node $i, j-1, k$; $q_{i, j-1/2, k}$ is the volumetric fluid discharge through the face between cells i, j, k and $i, j-1, k$ ($\text{m}^3 \text{s}^{-1}$);



Explanation

- Aquifer boundary
- Active cell
- Inactive cell
- Δr_j Dimension of cell along the row direction. Subscript (j) indicates the number of the column
- Δc_i Dimension of cell along the column direction. Subscript (i) indicates the number of the row
- Δv_k Dimension of the cell along the vertical direction. Subscript (k) indicates the number of the layer

Figure 1. Discretized hypothetical aquifer system (McDonald and Hauges, 1988).

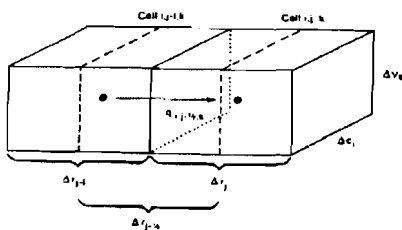


Figure 2. Flow into cell i,j,k from cell i,j-1,k. (McDonald and Hauges, 1988)

$KR_{i,j-1/2,k}$ is the hydraulic conductivity along the row between nodes i,j,k and $i,j-1,k$ (m/s); $\Delta c_i \Delta v_k$ is the area of the cell faces normal to the row direction; and $r_{j-1/2}$ is the distance between nodes i,j,k and $i,j-1,k$ (m). The term $KR_{i,j-1/2,k}$ of equation (3) is the effective hydraulic conductivity for the entire region between the nodes. The flows through others cells and cell faces are analogous.

As a modular model, Modflow model had been widely used, modified; and further developed and integrated with user friendly interface for working with graphical computer operating system (OS) and graphical user interface (GUI). One of the distributed software is Visual Modflow. The software intergrates visual tools for designing the model such as defining cell types, boundary, properties etc.; and also makes it easier to input maps, digital elevation data and presenting clear graphical outputs of the simulation.

Modflow model for Cidanau watershed

Figure 3 shows the topographic image of Cidanau watershed. The flat area inside the dash-lined box is the caldera. The simulation only covers this area due for convenience to start the model development of the model, due to the complexity of topography, geology and hydrology of the watershed. In the future, the whole watershed and its river system is recommended to be included, either partially or thoroughly modeled.

The existence of swamp forest and many rivers and creeks had made the development of the model become complicated. Moreover, the data available for each are very limited and unavailable and assumptions had to be made to simplify and complete the model. In this study, the swamp was assumed to have constant water level along the simulation which is equal to altitude of 87 m. Consequently evaporation does not affect the groundwater and was given the value of 0 in the swamp.

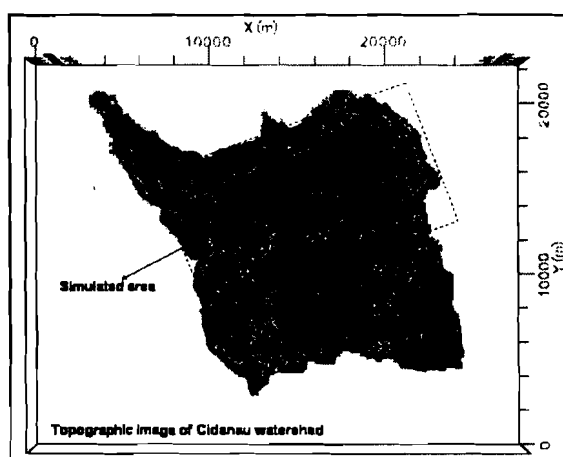


Figure 3. Topographic image of Cidanau watershed, and the simulated area.

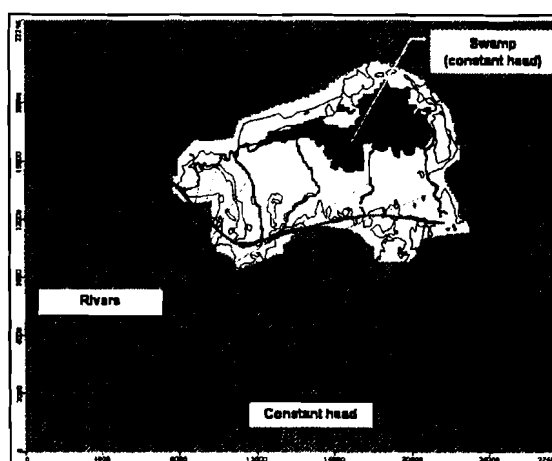


Figure 4. Boundary conditions of swamp, rivers and constant head.

Similar to swamp, rivers were also assumed to have constant head. The water level depends on the surface altitude. Only 6 rivers were taken into account. At the foot of the mountain in the southern area of the caldera a line of constant head was made connecting the upper of the rivers that were chosen for boundary condition. The boundary conditions of swamp, rivers and other constant head can be seen in Fig. 4.

Latent heat energy of various surface conditions in this area was estimated using surface energy balance methods. This analysis is based on the energy balance equation:

$$R_n = IE + H + G \quad (3)$$

With R_n is net radiation energy on the ground surface, IE latent heat energy flux, H sensible heat energy flux and G ground heat flux, all in the unit of Wm^{-2} . This basic equation is also used to analyse the heat balance on vegetated surface, which follow the multi layer resistance model of soil, plant and atmosphere energy fluxes transfer which was presented by Waggoner and Reifsnyder (1968). The method used in this study is a simplified method combined with numerical model of processes in atmospheric boundary layer, as described and used for limited cases in Saptomo *et al* (2003) and Saptomo *et al* (2004).

The evaporation was calculated by dividing the amount of latent heat energy with

amount of energy that is needed to evaporate water. Hourly evaporation and evapotranspiration rate b is presented in Fig.5.

The simulation was conducted with daily time step and the amount of evaporated water was only taken in daily rate, shown in Fig.6. The implementation of evaporation zone in our model is accommodated by evaporation package integrated in the software and attributed as a boundary. Fig.7.presents the evaporation zones implemented in the model using visual tools of the software. The evaporation will be in the maximum value (the value given to the model) when the water table is at the ground surface and will be extinguished as the water table decreases down to 20 m depth from the surface.

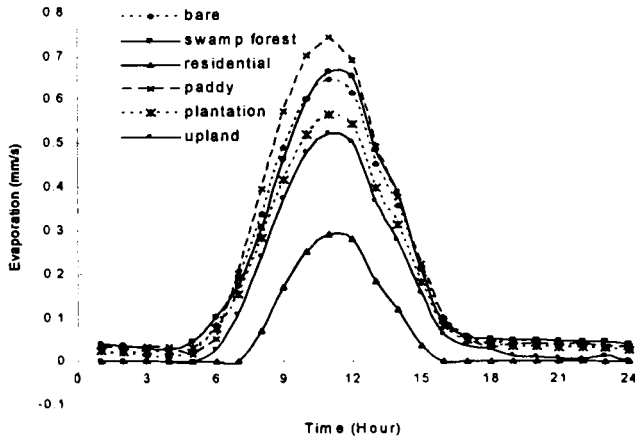


Figure 5. Hourly evaporation rate of various surface conditions in Cidanau watershed.

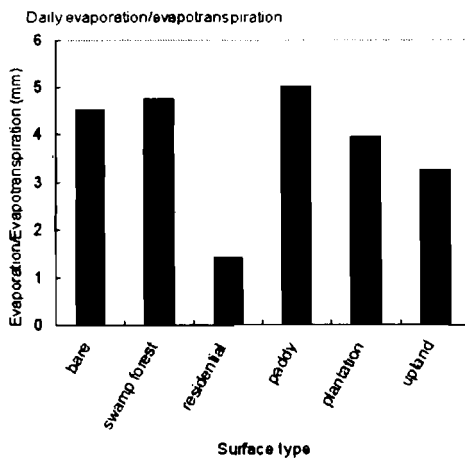


Figure 6. Daily evaporation of various surface condition in Cidanau watershed.

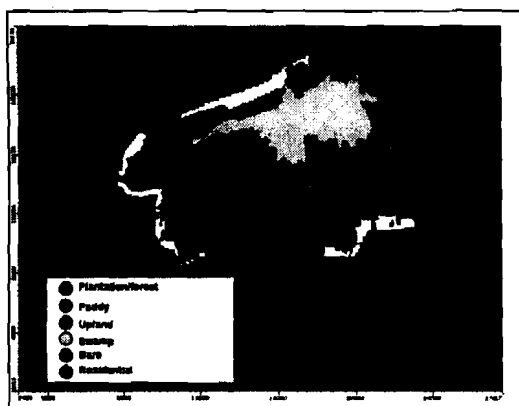


Figure 7. Evaporation zone (surface condition) of the area.

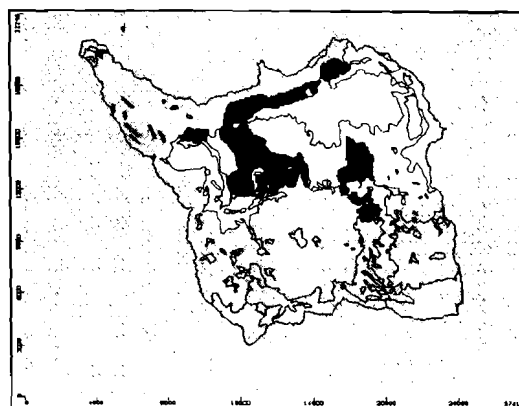


Figure 8. Recharge zone (paddy field percolation) of the model

Recharge to the ground water occurs only by mean off percolation in paddy fields. In this simulation, the water exists continuously during simulations and gives constant percolation. The amount of percolation was assumed 10 mm/day. Due to this assumption, the evapotranspiration of paddy field has no effect to the groundwater and given a rate 0 along the simulation.

The location of this recharge zone is presented in Fig.8. Another recharge such as infiltration by precipitation was neglected since the simulation was for dry season with assumption no precipitation or irrigation to the field, except paddy field. Simulation in the wet season should consider the infiltration caused by precipitation.

Results and discussion

Initial groundwater level was assumed as 2 meter below the surface in all area. This assumption was implemented in the model by creating an XYZ format of elevation data and imported to Visual Modflow. This initial condition is presented in Fig. 9. The groundwater level (described as elevation above sea level) is within the range 80-100 m. The soil were assumed to have uniform properties of soil hydraulic conductivity (K_{xx} , K_{yy} , K_{zz}), specific storage (S_s), specific yield and porosity of 0.0001 m/s, 0.0001/m, 0.2 and 0.2.

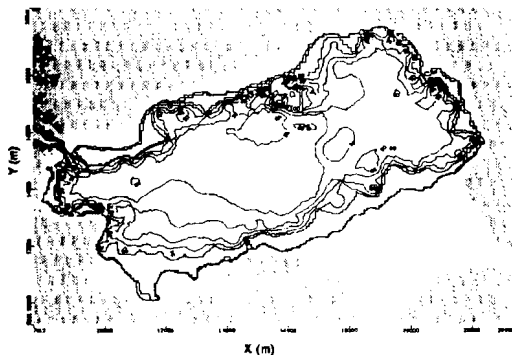


Figure 9. Initial ground water level conditions.

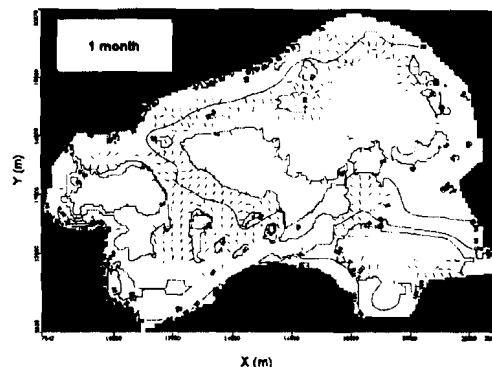


Figure 10. Groundwater distribution and flow direction after 1 month simulation.

After 1 month (30 days) of the simulation time, the groundwater level distribution was altered (Fig.10). The range level is within 80-100 m, but the contour shape was changed. Groundwater flow direction is marked by small arrows that are scattered in the figure.

From south-western part of the area, groundwater flows to the paddy field which has the lower altitude, and also roles as recharge through percolation. The flow continues and reaches the bare soil area. Flow to bare area also occurs from the swamp and the higher land in south-eastern of the area.

From the surrounding of the caldera, groundwater flow also occurs, directing to the flat area. It was said that the mountain that surrounds the caldera stores more water than the lower land of the caldera. The distribution of groundwater during simulation at 10 days, 1, 2 and 3 months are presented in Fig. 11, 12, 13 and 14.

It seems that the bare soil is the main discharge zone with its lowest groundwater level and became the direction of flows from many other zones. If the whole area is dominated by bare soil, it can be imagined that groundwater level will decrease more rapid than that was simulated here. This condition will surely affect the water level of the swamp, which is not constant in reality, and furthermore will contribute to the degradation of the natural reserve.

The utilization for paddy production contributes input to the groundwater by means of percolation. In a simple way, it can be concluded that paddy field will help the sustainability of the area. But in fact, the paddy field does not always have percolation, especially when it comes to harvesting season. Also, in the real condition, sedimentation and nitrification caused by human activities that includes paddy production is known as a problem that threatens the existence of the natural reserves.

Inflow and outflow rates by means of storage, constant head and evaporation vary in time, depends on the groundwater level distribution as shown in Table 1. Evaporation rate decreases in time, even though a constant daily value was used for the simulation as the groundwater level decreases. Similarly, the storage term of inflow and outflow rates decrease as the shape of the groundwater table was flattened. The recharge rate in the other hand is constant, since constant value was used and it is not affected by groundwater level.

In this study, surface conditions affect the groundwater by means of evaporation and percolation. The chart of total input and output of the groundwater, presented in Fig.15 shows the amount of contributions by each boundary condition: river leakage, evaporation, recharge and constant head. The term 'IN' and 'OUT' denote inflow to groundwater and outflow from the groundwater by means of each variables.

Evaporation seems to have the dominant outflow from the groundwater. In the other hand, recharge from percolation of paddy field does not balance this outflow. In the actual condition, infiltration also occurs. The amount of water infiltration depends on precipitation, surface run off and evaporation, and also the soil physical and hydrological properties. The first two variables have not yet been taken into account for this simulation, and should be considered for improvement of the model.

The contribution of river leakage is very small and not visible in this chart. This simulation in fact, had not yet included the actual numbers and conditions of rivers in the area. By

improving this, the more realistic flow rate contributed by river leakage can be estimated.

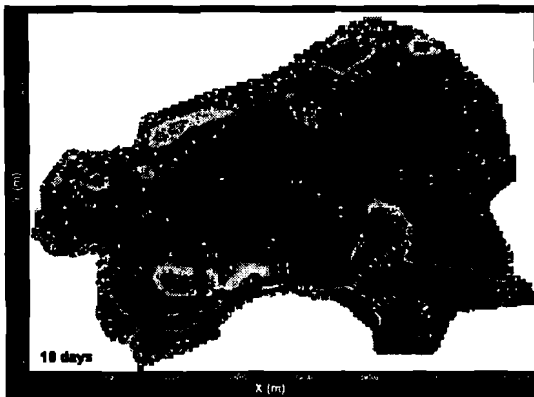


Figure 11. Groundwater distribution after 10 days simulation.



Figure 13. Groundwater distribution after 2 months simulation



Figure 12. Groundwater distribution after 1 month simulation.

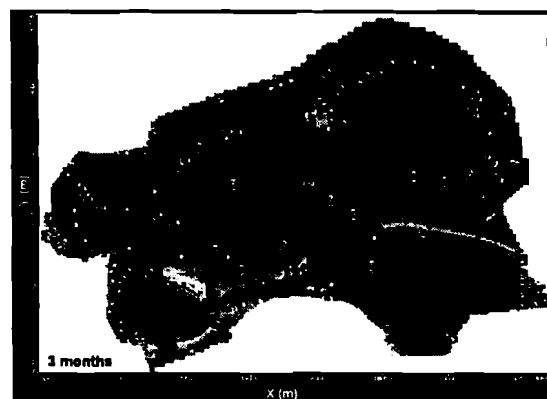


Figure 14. Groundwater distribution after 3 months simulation.

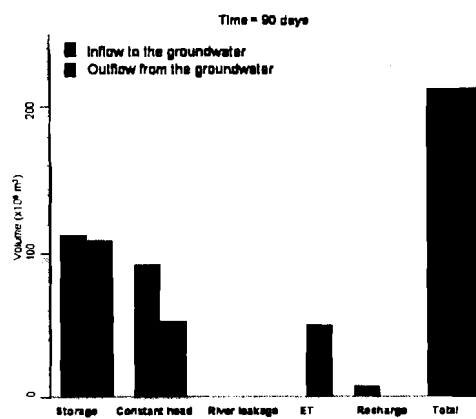


Figure 15. Groundwater inflow and outflow budget after 3 months simulation.

Table 1. Rates of groundwater inflow and outflow resulted from simulation

Inflow (In)/Outflow (Out)	Rate (m ³ /day)			
	10 days	1 month	2 months	3 months
Storage (In)	872145.81	244871.61	106829.97	62367.19
Constant head (In)	1367550.25	965249.44	825383.69	766125.56
Recharge (percolation) (In)	85390.33	85390.33	85390.33	85390.33
River leakage (In)	0.00	0.00	0.00	0.00
Total (In)	2325086.25	1295511.38	1017603.94	913883.06
Storage (Out)	1656424.50	745184.31	504850.34	408994.16
Constant head (Out)	626896.63	514469.25	485665.91	478027.59
Evaporation (Out)	41763.66	35851.14	27083.91	26854.02
River leakage (Out)	0.07	0.06	0.05	0.05
Total (Out)	2325084.75	1295504.63	1017600.25	913875.81
In - Out	1.50	6.75	3.69	7.25

Conclusions

The model of groundwater for the the caldera area in Cidanau watershed had been developed taking into account the effects of different surface conditions. Through the simulations, it is obvious that surface conditions highly affect groundwater level, and has possibility to affect the natural reserve sustainability.

Inflow to the groundwater by means of percolation is at a constant rate 85,390 m³/day, and reaches the total 7,685,375m³ in 3 months. The evaporation rate changes in time, depends on the groundwater level, the maximum rate occurs close to the initial time where groundwater is relatively near the soil surface. The total evaporation after 3 months simulation is 50,333,228m³.

The model is proposed for further simulation study of groundwater in the area. Many improvements still have to be made for the model, including the effects of surface conditions by means of infiltration. More observation data of soil properties and rivers conditions, as well as hydrological and geological properties of the area should be collected for further development of the model.

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