Numerical Groundwater Modeling of an Eogenetic Karst Catchment Using Analytical Head-Guided Zonation Method: A New Analytical Approach

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Numerical Groundwater Modeling of an Eogenetic Karst Catchment Using Analytical Head-Guided Zonation Method: A New Analytical Approach

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Abstract. In parameterisation step, implementing suitable calibration methods that accurately represents the actual system is crucial in developing a dependable groundwater model in data-scarce areas. In this study, the Head-Guided Zonation (HGZ) method was applied to accommodate the limitation of subsurface data, such as the lack of comprehensive spatial distribution of hydraulic conductivity and specific yield values. This study demonstrated that the spatial distribution of groundwater heads can be used to assume the spatial distribution of sub-surface parameters, hence, hydraulic conductivity zones in the model domain can be established using the distribution of hydraulic gradient. We conclude that the HGZ method is practical and applicable for development of a physically-based groundwater model.

1. Introduction
Employing appropriate calibration methods that achieves the modelling objective (good fit between simulated and observed values) and properly represents the corresponding system is an important task in developing a robust groundwater model in data-limited areas [1]. In this study, the Head-Guided Zonation (HGZ) method was chosen to accommodate the limitation of subsurface data, e.g. the absence of spatial distribution of hydraulic conductivity and specific yield values. Therefore, the main objectives of this paper are:

1. to develop a physically-based groundwater model for the recharge-bounded area of Oemau Spring in Rote Island, Indonesia using the Head-Guided Zonation (HGZ) method.
2. to calibrate and validate the model using statistical measures.

2. Materials and methodology

2.1 Study area
The experimental area is Oemau recharge area (ORA) enclosing an area of 20.11 km². Geographically located between latitudes 10°46’42.17"S ~ 10°43’36.91"S and longitudes 123°3’14.84”E ~ 123°9’17.64”E, ORA’s terrain is characterised by highly undulated topography with surface elevation ranges from around 98 m to 340 m above sea level. Areas of low and medium slopes (< 10 degree) are mainly found in the middle and lower end of the catchment where rice paddies and settlements are located, whereas steeper slopes largely dominate the upper areas of the catchment [2]. Geologically, the subsurface is distinctively dominated by two main carbonate formations, i.e. permeable Holocene coralline limestones, Bobonaro formations, featured as karst landscape [3-10]. Governed by a
monsoonal climate with two distinct seasons: dry (May-November) and wet (December-April), ORA has mean annual precipitation of 1000 - 2300 mm and humidity between 75 and 92% [8]. The long-term daily precipitation records are available from Lekunik station located around 3 km upstream of the spring (Figure 1).

**Figure 1.** Time series of rainfall at Lekunik Station and groundwater level at Oemau Spring

### 2.2 HGZ method and zone delineation

HGZ method assumes that each zone has the same hydogeologic characteristics represented by similar hydraulic gradient of groundwater flow. In regions with parallel hydraulic conductivity, the hydraulic gradients are equally similar. A low hydraulic gradient is expected in areas with high conductivity while a high gradient suggests a slow groundwater flow in a low conductivity area. Therefore, hydraulic conductivity zones in the model domain can be established using hydraulic gradient distribution. In this study head slope calculation was incorporated to delineate the zones. Using dimensionless hydraulic gradient \(i\) between two groundwater heads, the locations of zones are decided empirically by:

\[
\frac{dh}{dL} = i
\]

where, \(dh\) is the difference between two groundwater heads (m), and \(dL\) is the length of flow line between the two heads (m). The flow line is drawn perpendicular to groundwater contour.

### 2.3 Groundwater model

To perform groundwater flow simulations under both steady-state and transient conditions, this study employed MODFLOW [11] which solves by means of the following groundwater flow equation:

\[
\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) + W = S_y \frac{\partial h}{\partial t}
\]

where, \(K_{x,y,z}\) is the hydraulic conductivity along the \(x, y,\) and \(z\) coordinates in “m/day”, \(W\) is the volumetric flux that represents sources or sinks of water (1/s), \(h\) is the hydraulic head (m), \(S_y\) is the specific yield, and \(x, y,\) and \(z\) are coordinate directions, and \(t\) is time (day).

The conceptual model was set up as one horizontal layer and discretised into 50 x 50 m grid cells using Layer Property Flow, LPF package [12]. Assuming a continuum representation of unconfined eogenetic carbonate aquifer in the study area, the model is comprised of 210 columns and 106 rows resulting in 8,061 active cells. Using Drain package, DRN [13] the distribution of surface drainage
(Figure 4) was input into model. Drain conductance values ranging from 2,700 to 8,125 m/d represents drain dimension and hydraulic conductivity values derived from local pumping test analysis. A constant porosity value of 0.3 was assigned into the model to embody dominating carbonate formation of the study area [14]. Two model boundaries (Figure 2), were assigned: (1) no-flow boundary; and (2) specified head boundary (Dirichlet) using Time-Variant Specified-Head, CHD.

Figure 2. Model discretisation and boundary conditions.

3. Results and discussion

3.1 Zone delineation
The groundwater level contours were interpolated and drawn [15-16] using available groundwater level data inside and outside ORA (Figure 3a). The result is distribution of groundwater contour (Figure 3b). Hydraulic gradients between groundwater heads were then calculated to delineate the zones. The next step is to divide the model domain into three zones based on the hydraulic gradient values. The zone division resulted in six parameters to be calibrated and validated (each zone represents two parameters; hydraulic conductivity and specific yield).

Figure 3. (a) Groundwater contour distribution; and (b) Zones obtained from hydraulic gradient calculation.

3.2 Model calibration and validation
In steady-state calibration, the maximal rainfall of 86.5 mm/day on 19 April 2011 and its corresponding groundwater levels at seven observation wells were initially used to represent the response of the highest groundwater heads to the maximal daily recharge. Head differences between the modelled and observed values are insignificant, characterised by small $ME_h$. The negative bias values of $ME_h$ of -0.57 and -0.09 m in both steady-state and transient calibrations respectively suggest relatively minor underestimations of simulated heads by the model. The total residuals between observed and simulated heads demonstrated consistent results represented with $RMSE_h$. The model performances in both transient calibration and validation were considered acceptable with $RMSE_h$ values of 0.36 and 0.48 respectively, indicating an overall well calibrated and validated model.
3.3 Sensitivity analysis
The analysis shows that, for $K_h$ and $S_y$ respectively, zone 1 has the highest $css$ values of 0.040 and 0.008. Parameters in zone 2 and 3 are considerably less sensitive than those in zone 1. This indicates that among all calibrated parameters $K_h$ and $S_y$ in zone 1 provide the greatest constraints to the model.

4. Conclusions
In this study, a new analytical approach of HGZ method was applied to accommodate the limitation of subsurface data, such as the lack of comprehensive spatial distribution of hydraulic conductivity and specific yield values. This study showed that hydraulic conductivity zones in the model domain can be established using the distribution of hydraulic gradient. The calibrated and validated model shows a well fit between simulated and observed values. Therefore, it is concluded that the HGZ method is practical and applicable for development of a physically-based groundwater model.

References


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