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# Application of head-guided zonation method to delineate groundwater vulnerability zones in a data-scarce catchment

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**Abstract:** Developing a reliable groundwater model which often requires an extensive and costly subsurface profiling is a real challenge in data-scarce. In this study the Head-Guided Zonation (HGZ) methodology was applied on the recharge area of Oemau Spring in Rote Island, Indonesia, which is under potential risk of contamination from land use changes. The methodology involves calibrating a groundwater model using the HGZ method in parameterisation step. Using distribution of hydraulic gradient, HGZ method aims to represent distribution of subsurface parameters, such as hydraulic conductivity and specific yield, in areas where geologic data is scarce. This study shows that the HGZ method can be effectively used to calibrate a physically-based groundwater model. The results from reverse particle-tracking simulation were used to develop vulnerability zones.

**Key words:** vulnerability zones, groundwater contamination, model calibration, particle tracking, karst aquifer

## 1. INTRODUCTION

Estimation of contaminant migration can be used as a predictive tool to draw vulnerability zones which delineate influence areas categorised by simulated travel distance and time of particles moving through the model domain. However, developing a reliable groundwater model which often requires an extensive and costly subsurface profiling is a real challenge in data-scarce areas such as those in developing countries (e.g. Li et al., 2009; Candela et al., 2014). Consequently, choosing the most appropriate and adaptable method in parameterising a groundwater model is important to overcome data limitation and realistically represent a complex subsurface system. The aims of this study were to develop, calibrate and validate a physically-based groundwater model using the Head-Guided Zonation (HGZ) method; and to develop groundwater vulnerability zones based on the result of particle-tracking simulation.

## 2. METHODOLOGY

### *2.1 Study area*

Rote Island (Figure 1) with a total area of 1,223 km$^2$ is situated in the southernmost part of Indonesia (located between latitudes 10º25′00′′S ~ 11º00′00′′S and longitudes 121°49′00′′E ~ 123°26′00′′E). The community relies entirely on karst springs for their domestic and agricultural purposes. Nevertheless, provision of freshwater from karst springs in Rote Island is presently under threat from human activities due to rapid population increase and land use change, particularly in the recharge area of Oemau Spring (ORA). The rapid change in land use in ORA could potentially result in substantial and immediate effects on the water quality of the spring. Geologically, the subsurface of ORA is dominated by carbonate formations featured as karst landscape with Holocene coralline limestones (63.93%), Bobonaro formations (27.83%) – mainly consist of a mixture of carbonate rocks and scaly clay, and alluvium deposits (8.25%). Governed by a monsoonal climate, ORA has mean annual precipitation of 1000 - 2300 mm and humidity between 75 and 92%.

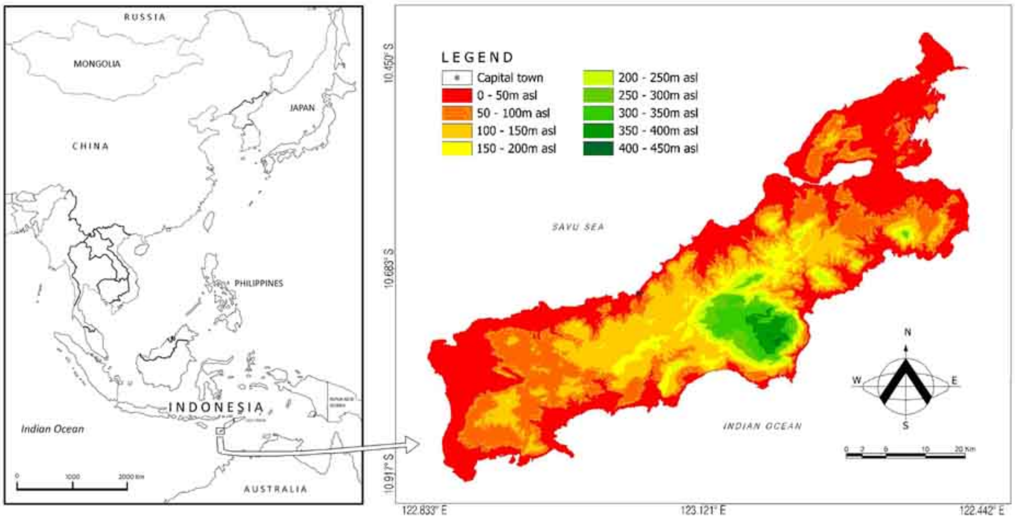


*Figure 1. Study area: Indonesia, Rote Island.*

### *2.2 Model development and analysis*

This study employed MODFLOW (McDonald and Harbaugh, 1988) to perform groundwater flow simulations under both steady-state and transient conditions. Using Groundwater Modeling System (GMS) suite (BYU, 2014), the conceptual model was set up as one horizontal layer and discretised into 50 x 50 m grid cells (Figure 2). Recharge package, RCH (Harbaugh et al., 2000) was employed to simulate recharge calculated using water balance method (Bras, 1990). Penman-Monteith (Allen et al., 1998) and SCS-CN (Viessman and Lewis, 1995) methods were used to calculate evapotranspiration and surface runoff respectively. Seven dug wells were selected as observation wells to provide the basis for groundwater simulations. Two model boundaries were assigned: (1) no-flow boundary assuming no flux flowing through the surface-water divides, and (2) specified head boundary (Dirichlet) at downstream using Time-Variant Specified-Head.

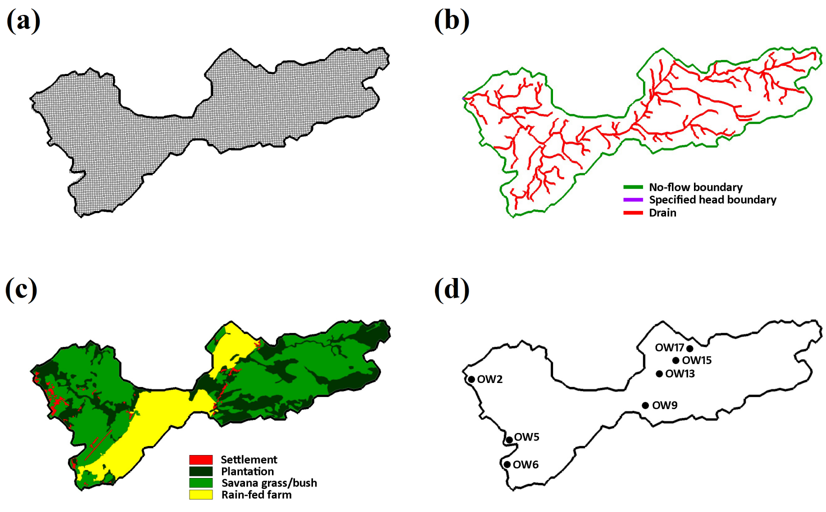


*Figure 2. Conceptual model and boundary conditions of the groundwater models showing (a) Model grid; (b) Source and sinks; (c) Recharge; and (d) Observation wells*

# 3. FINDINGS

### 3.1 Zone delineation using HGZ method

The HGZ principally employs available groundwater level data to divide the area of interest into several zones of piecewise constant. It assumes that each zone has the same hydogeologic characteristics represented by similar hydraulic gradient of groundwater flow. Hydraulic gradients between groundwater heads were calculated to delineate the zones after drawing groundwater contours from the interpolation of groundwater level data recorded from the seven dug wells in ORA (Fetter, 2001; Hudak, 2005). Based on the hydraulic gradient calculation the model domain was divided into three zones. The selected zones resulted in six parameters to be calibrated (each zone represents two parameters; hydraulics conductivity and specific yield).

### 3.2 Model calibration and validation

The negative bias values of $ME_h$ of -0.57 and -0.09 m in both steady-state and transient calibrations respectively suggest a relatively minor underestimations of simulated heads by the model. In transient validation the head is slightly overestimated by 0.19 m. In both transient calibration and validation, the model performances were considered acceptable with $RMSE_h$ values of 0.46 and 0.48 respectively, indicating an overall well calibrated and validated model.

### 3.3 Delineation of vulnerability zones

The delineation of vulnerability zones are based on the time and pathlines taken by hypothetical particles travelling through the simulated model to arrive at the spring. The reverse particle-tracking method in MODPATH (version 5) computed the particles travelling through the simulated subsurface pathlines trajectories. In the simulation, pathlines were tracked backwards through times by computing values of velocity vector based on the flow rates at every grid cell. Figure 3a illustrates the zones of influence and their corresponding travel time produced by reverse particle-tracking simulation. It shows the maximum distance particles can travel in 3 years which is around 6.5 km from the Oemau spring. Figure 3b shows the developed vulnerability zones, in which the zonation is categorised into three different zones.

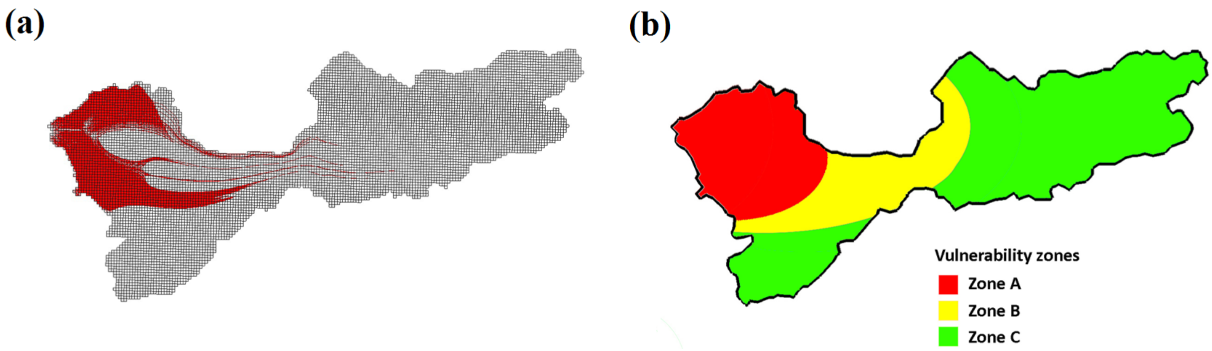


*Figure 3. Development of vulnerability zones showing (a) zone of influence using reverse particle-tracking simulation, and (b) proposed vulnerability zones based on the result of particle-tracking simulation.*

# 4. CONCLUSIONS

This study shows that the HGZ method can be successfully used to calibrate a physically-based groundwater model. Using the result of particle-tracking simulation (travel time and pathline trajectory) and the potential risk of current human activities to water quality at Oemau Spring, three zones of vulnerability were developed. The proposed vulnerability zones can be used by the regional decision makers to protect the spring from contamination and to ensure provision of safe and good quality water from Oemau Spring. It is worth noting that the HGZ method is considered valid for a homogenous and anisotropic groundwater system, such as karst aquifer. Therefore, this method can be recommended to be applied in other areas characterised by similar hydrogeological settings.

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