Mapping Groundwater Vulnerability Zones in Eogenetic Karst Catchment Using Particle-tracking Method

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Abstract. Accurate mapping of groundwater vulnerability zones based on robust groundwater model is crucial towards an appropriate development of management strategies. This study aimed at developing groundwater vulnerability zones in a tropical karst area in Rote Island, Indonesia. HGZ method was employed 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 map groundwater vulnerability zones using advective transport code (MODPATH), and
2. to develop corresponding management strategies based on 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.

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 [1-2]. In this study, the 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 map groundwater vulnerability zones using advective transport code (MODPATH), and
2. to develop corresponding management strategies based on 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.

2. Materials and methodology

2.1. Study area

The study area is the catchment area of Oemau spring (CAOS), 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 (Figure 1). Having a catchment area of 20.11 km², CAOS’s topography is characterised by highly rippled terrain with surface elevation ranges from around 98 m to 340 m above sea level [3-5]. Geologically, the area is typified by low karstification degree and under-developed conduits system [6] based on discharge timeseries data analysis at Oemau Spring using modified Boussinesq approach of recession curve [7]. The humidity in the area ranges from 75-92% and mean annual precipitation is 1000-2300
mm [8]. The area is governed by a monsoonal climate with two distinct seasons: dry (May-November) and wet (December-April), (Figure 1) [9-12].

![Figure 1](image_url)

**Figure 1.** Study area: Indonesia, Rote Island and the recharge area of Oemau Spring.

### 2.2. Particle-tracking simulation

Vulnerability zones were delineated based on the time and pathline taken by hypothetical particles travelling through the simulated model to arrive at the spring. In this study, the spring vulnerability is assumed to relate to the advection function represented by travel time of particle and pathline trajectory [13]. Reverse particle-tracking method in an advective transport code, MODPATH (version 5) incorporated in GMS suite were employed to compute the pathline of the particles travelling through the simulated subsurface pathlines trajectories. Particle-tracking has been widely applied due to its competence to trace various sources of contaminants in time and space, hence it can provide a foundation for mapping zone of influence of different pollutants. In the simulation pathlines are tracked backwards through times by computing values of velocity vector based on the flow rates at every grid cell. MODPATH [14] solves three-dimensional partial differential equation as follow:

\[
\frac{\partial}{\partial x} (n v_x) + \frac{\partial}{\partial y} (n v_y) + \frac{\partial}{\partial z} (n v_z) = W
\]

where, the \(v_x\), \(v_y\), \(v_z\) are the principal components of the average linear groundwater velocity vector (m/day), and \(n\) is dimensionless porosity.

### 3. Results and discussion

#### 3.1. Estimated flow paths and time

Using reverse particle-tracking analysis which principally calculates groundwater flow velocities, MODPATH predicted particles’ flow path and tracked the particle backwards toward their origins. The distance of influence over time associated to three plausible porosity values \((n = 0.15, 0.30\) and \(0.45\)) is presented in Figure 2. It shows that when the reduction of \(n\) values variably decreases the travel times to the spring. Given a distance of 4 km from the spring the travel time is reduced 30% from 24 months to around 17 months when \(n\) is reduced from 0.45 to 0.3. Reduction of \(n\) from 0.3 to 0.15 results in approximately 57% times travel reduction to about 7 months for the same distance. An intermediary value of 0.3 for \(n\) is selected in this study to draw zones of influence due to the absence of actual porosity value from sample measurement in the study area. Figure 2b illustrates simulated flow path from the source points to Oemau spring using \(n\) value of 0.3. It shows that in 6 months particles can travel for a maximum distance of around 2 km from the Oemau spring. As the travel time increases the trajectory of the pathlines extends towards the upstream area of the CAOS. Within one year the zone of influences reaches areas around Lekunik Airport; while in two years, it encompasses
beyond areas in the middle of CAOS. Hypothetically, the particles are traced back to the upper areas of CAOS in three years time.

3.2. Potential risk and development of vulnerability zones

The division of vulnerability zones is outlined by employing the influence distance using backward particle-tracking and travel time as presented in Figure 2. Incorporating appropriate preventive management measures, the vulnerability zones design considered the potential risk of human activities to the water quality at Oemau Spring by taking into account current practice in the community and land use type in CAOS. Figure 2 shows that in a period of two years, particles can be traced back to areas in the middle of CAOS. Dominated by rice farms, this area poses potential hazards to the quality of water at Oemau Spring. Chemical pollution from fertilizers and pesticides discharges, e.g. organochlorine, nitrate, residues, and various metals, such as lead, cadmium and arsenic, applied during cultivation period in wet season could infiltrate into the aquifer and travel to the spring.

![Figure 2. Results of particle-tracking simulation using MODPATH code](image)

**Table 1.** Vulnerability zones and corresponding management strategies.

| Zone | Level of vulnerability | Management strategies |
|------|------------------------|-----------------------|
| A    | High                   | 1. Health promotion on rural sanitation  
|      |                        | 2. Promoting lining septic tanks  
|      |                        | 3. Waste collection from households  
|      |                        | 4. Monitoring of water quality at spring and nearby dug wells |
| B    | Medium                 | 1. Management of pesticide and fertilizer application  
|      |                        | 2. Monitoring of water quality at dug wells |
| C    | Low                    | 1. Reforestation to increase recharge into aquifer |
Figure 3 shows the three proposed vulnerability zones and vulnerability level description of each zone is presented in Table 1. Zone A covers an area within 3 km from the spring. This area is categorised as highly vulnerable due to potential contamination from current and anticipated dispersion of settlement and government building. Therefore, it requires immediate management strategies. Having an intermediary level of vulnerability, zone B encompasses mostly areas of rice farm situated in the middle of CAOS. Area of zone C is designed as main reforestation area mainly to boost recharge to the spring.

4. Conclusions
Three vulnerability zones were proposed based on reverse particle-tracking simulation in this study. The corresponding management strategies were presented to ensure provision of safe and good quality water from Oemau Spring. Given the main purpose of zonation, comparatively small catchment size, groundwater flow characteristics, potential pollutants and their sources, the vulnerability zones are considered effectually representative to be used as a management instrument for the local decision makers. The measures were designed by accounting the simulation results (travel time and pathline trajectory) and potential groundwater contamination risk from human activities (land use type and current practice). The recommended measures can be used by the regional decision makers to safeguard the spring from contamination.

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