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Coping with climate change in a tropical karst island: Assessment of groundwater resources under HadCM3-GCM scenarios and proposed adaptive strategies

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Abstract. Embracing appropriate management strategies to ensure the sustainability of groundwater resource under climate is decisive for tropical karst islands. In this study, long term impacts of climate variability on groundwater recharge and discharge at the Oemau spring, Rote Island, Indonesia using HadCM3-GCM predictor variables for the H3A2a and H3B2a climate scenarios were investigated. The analysis suggests that the sustainability of groundwater resources generally varies over the period and will be adversely affected by climate change during dry years when the area is projected to experience supply shortage of around 29-67 L/s as a result of 5.24-23.63% decrease of rainfall, 2.48-24.57% reduction of recharge, and 2.53-22.80% decrease of spring discharge, under HadCM3 GCM scenarios. A subsequent comprehensive set of management strategies as palliative and adaptive efforts was proposed to be implemented by relevant stakeholders to assist the community dealing with water deficit during the dry years.

1. Introduction

Rote Island, geologically characterised by kast landforms of carbonate formations, is under high stress of increased population and land use modification as a result of power devolve policy in Indonesia [1-4], resulting in corresponding rapid land use change for settlement in the expense of about 4% of the total area of bush, grass, forest and plantation in the recharge area of the Oemau spring [5-6]. Data of over 31 years (1982-2015) recorded in Lekunik station indicates an increasing trend of temperature (0.06%) and rainfall (0.15%). Change on climatic condition can potentially modify the hydrological system related to recharge regieme of the Oemau spring, which may result in a change of the amount of spring discharge in the future. Therefore, examining the current situation and taking into account the aforementioned remarks, the aim of this study was to generate a dataset of climate variables (rainfall and temperature) using downscaling technique (SDSM) of projected period of 2010-2020 as an input data for simulating groundwater model for the projected period of 2020-2090.

2. Materials and methodology

2.1. Study area

The study area is the recharge area of Oemau spring (RAOS), 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. With a recharge area of 20.11 km², the topography is typified by highly rippled terrain with surface elevation ranges from around 98 m to 340 m above sea level [7-8]. The area is geologically characterised by under-developed conduits system and low karstification degree [9-10] based on the analysis of discharge timeseries data at Oemau Spring using modified Boussinesq approach of recession curve [11]. Governed by a monsoonal climate with two distinct seasons: dry (May-November) and wet (December-April), the area experiences mean annual precipitation of 1000-2300 mm and humidity of 75-92% [12].
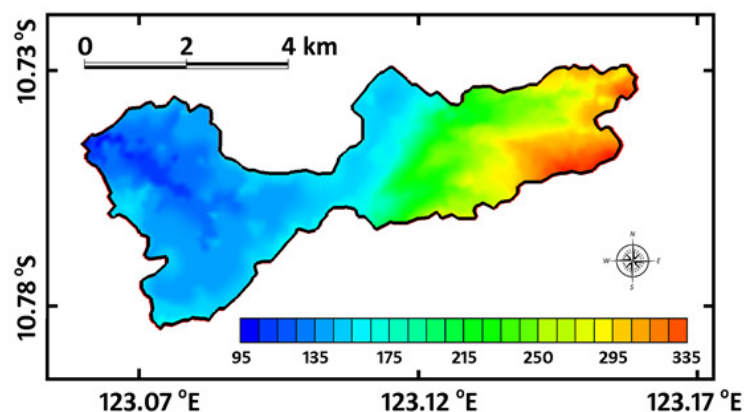
Figure 1. Study area: Oemau Spring Recharge area (OSRA)

2.2. Groundwater model development and analysis

The groundwater flow under both steady-state and transient conditions was simulated using MODFLOW code and run within the Groundwater Modelling System, GMS ver. 9.2.9. The model domain was discretised in the Layer Property Flow package, LPF resulting in 201,139 active cells (530 rows and 1050 columns) in a homogenous horizontal model of 10 m × 10 m grid cells. A no-flow boundary along the catchment boundary was defined. A specified head boundary (Dirichlet) using Time-Variant Specified Head, CHD (Harbaugh et al., 2000) was assigned to the stream downstream of the Oemau spring. Water balance method (Bras, 1990) was employed to calculate the net recharge values assigned to each land-use zone. Surface runoff component was estimated using the SCS-CN and to calculate potential evapotranspiration modified Hargreaves method was applied. In the transient simulation, the model was calibrated and validated each for the period of eight months with each comprising of 10-time steps using observed data from January 2010 to April 2011 [12-13]. In the calibration and validation steps, the values of subsurface properties (K_h and Sy) were estimated using Pilot Point method. The pilot points were spatially distributed using 1000x1000 m grid across the model domain using a distance-area ratio of 0.05 as suggested by Klaas and Imteaz [13] to avoid model overfitting.

2.3. Climate variables downscaling

SDSM ver.4.2 [14] was employed to significantly reduce projection resolution of GCMs weather data for local or regional modelling purposes by extracting statistical parameters from observed data series. Several routines, i.e. input data examination, screening of predictors, generation of weather variables, calibration and validation and weather generation for future projections, were sequentially involved in the overall downscaling procedure. The selected atmospheric predictors were then paired with the predictands in the calibration step to establish statistical relationships and construct synthetic downscaled weather series for the period 1982-1991 using ordinary least square optimization method. Upon obtaining satisfactory results in the calibration step, the climate variables were then modelled for

the period of 1992-2001 in the validation step. Having obtained a statistically acceptable calibrated and validated result, the downscaled dataset of the climate variables modelled in the scenario generator using the HadCM3 GCM predictor variables [15] for the H3A2a and H3B2a climate scenarios. The generated meteorological timeseries were the inputs for the groundwater simulations to establish forecasted discharge for period 2020-2090.

2.4. Analysis of water demand
The sustainability of groundwater resources in the study area was evaluated by assessing the ability of the spring to supply estimated water demand during the projected period of 2020-2090. Total water demand is reflected by two main consumptions, i.e. domestic usage and regional gross irrigation demand. Water requirement for irrigation was estimated based on current agricultural practice in the study area, in where dry-field paddy is the main crop cultivated by local farmers employing traditional farming system. Agricultural water demand was calculated based on total irrigation water requirement for paddy irrigation, or Net Farm Requirement (NFR) per acreage recommended by Indonesian Public Work Ministry by considering irrigation system, type of crop, crop potential evapotranspiration, crop acreage, effective rainfall, and irrigation efficiency.

3. Results and discussion

3.1. Groundwater model calibration and validation
In the calibration period, RMSE value of 0.26 m and MAE value of 0.17 m were attained, while the values in the validation step are 0.27 m and 0.18 m correspondingly. The error statistics of the model are considered small confirming that the model is capable of reproducing hydraulic heads to a satisfactory level. In spite of model underperformance noticeably during low flow in the validation period, the groundwater model was reasonably well fit and considered very good ~ satisfactory model according to Moriasi criteria with NSE values of 0.93 and 0.63, in calibration and validation periods respectively.

3.2. Assessment of groundwater resources under HadCM3-GCM scenarios
Overall, the changes of both recharge and spring discharge proportionally reflects the over-time variations of the downscaled weather variables (Figure 2). The result shows that a decrease of 5.24% precipitation results in 2.48% reduction of recharge for the period 2020-2059 under H3A2a scenario, while 17.81% rise in precipitation during 2060-2079 brings a 12.85% increase in recharge for the same period and scenario. Consequently, the reduced recharge into the karst aquifer results in decline of spring discharge of Oemau Spring by 2.53%. In the same period, a similar trend is shown for the groundwater simulation under the H3B2a scenario. In this scenario, spring discharge is projected to decrease by 5.19% as a result of 5.35% reduction of recharge due to 8.01% drop of rainfall over the period. Decreases of spring discharges of 22.80% and 20.70% are also anticipated under H3A2a and H3B2a scenarios respectively for the third period (2080-2090) in which recharge is simulated to decrease by 24.57% and 21.88% for the corresponding scenario. Meanwhile, the catchment is projected to experience a considerable recharge increase in the second period (2060-2079) under the two HadCM3-GCM scenarios, resulting in 14.41% and 15.04% increase of discharges at Oemau Spring.
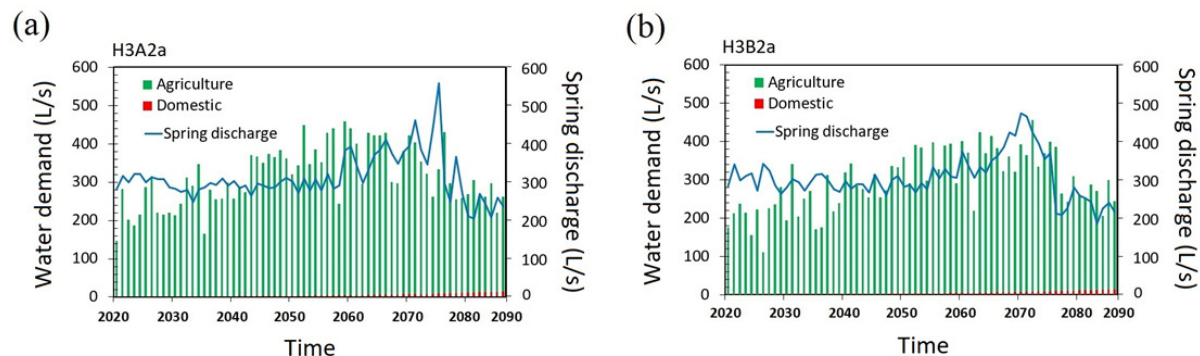
Figure 2. Results of the assessment of sustainability of groundwater resources, showing comparison of water demand and spring discharge projected under the H3A2a H3B2a scenarios, respectively.

3.3. Proposed management strategies
Given the assessment result on the groundwater resources sustainability for Oemau karst spring, it is concluded that under both H3A2a and H3B2a scenarios the total water demand in the study area is not met in the two projected periods. In the dry periods, mainly around 2050s-2060s and 2080s, anticipated water demand principally from irrigation requirement well surpasses modelled spring discharge by around 29-67 L/s or 10- 24% of the average discharge from January 2011-April 2012 observed at Oemau spring. In order to cope with the future alarming situation, several management strategies are proposed in this study. In this study three main tailored management strategies, namely socio-cultural, technical, and ecological measures, are recommended to be implemented by the local authorities and community. Scale of priority and time urgency were assigned on each measure to guide all stakeholders in the design and implementation steps. The strategies were selected mainly by incorporating local resources in terms of physical and social characteristics.

4. Conclusions
This study aimed at assessing the sustainability of groundwater resource of Oemau spring for the period from 2020-2090 using MODFLOW, in which groundwater flow was simulated using four downscaled weather model variables. The numerical groundwater model implemented within MODFLOW code was accurately able to reproduce the general groundwater flow observed. Calculation of water demand in the area shows that domestic consumption has much less effect—with a fraction (3.66%) of the irrigation water demand at 2090, on the sustainability of groundwater resources. The area is projected to variably experience around 29-67 L/s shortage in dry periods and 53-68 L/s over supply in wet periods. In order to assist the community to deal with water deficit during the expected dry periods, three main adaptive strategies, namely socio-cultural, technical, and ecological measures, were proposed. Considering the scale of priority and time urgency for each measure, all stakeholders, including decision makers, regional planner and community, could implement the management strategies to adapt with the expected climate change and to mitigate adverse impacts of climate change in term of water deficit during the dry periods.

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