Hydrograph monitoring and analysis for sustainable karst water management in Nyadeng Spring, East Borneo

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Abstract. Karst aquifer stores abundant water resources within its matrix, conduits, and intergranular pores. Karst aquifer plays an important role in providing water supply, especially in the areas nearby that commonly dry and lack of surface water resources. Karst spring hydrograph analysis is very fundamental step to assess and determines the condition of the catchment area in karst terrain. Recession curve is believed to be the most stable part in single flood hydrograph that represents the aquifer characteristics. Nyadeng is one of the most significant karst springs that located in Merabu Karst Area, East Borneo. Villagers in Merabu highly depend on Nyadeng Spring for fulfilled their freshwater need. Hydrograph monitoring has been initiated for one year in Nyadeng Spring as a preliminary action for karst water management in Merabu. Water level data series obtained using automatic water level data logger and then correlated with manual discharge measurement to generate stage-discharge rating curve. The stage-discharge rating curve formula for Nyadeng Spring calculated as \( y = 0.0102e^{5.8547x} \) with \( r^2 = 0.8759 \). From the combination of several single flood events, Master Recession Curve (MRC) was generated to determine flow regime as the main consideration for karstification degree calculation. From the MRC result, flow regimes formula determined as \( Qt= 3.2 - 0.001t + 1.2(1-0.012t)+1.6(1-0.035t) \) indicated that one sub-regime with laminar flow and two sub-regimes with turbulent flow existed. From the MRC formula, the degree of karstification in Nyadeng Spring classified at seventh scale (developed karstification of the aquifer) based on Malik’s karstification degree (2012). The degree of karstification in Nyadeng Spring indicates that the aquifer formed by large conduit channels, fissures, and macro fissures which are able to provide significant water sources that can be utilized for multi purposes. Therefore, it is concluded that spring hydrograph monitoring provide essential information in order to establish a careful water resources management actions.

1. Introduction

Environmental problems regarding the quality and quantity of water resources is one of the major issues all over the world. Groundwater and surface water are the most water reservoirs utilized by humans because of their accessibility. Groundwater resources are facing management problem including karst aquifers. Karst aquifers formed in a very complex hydrological system. Developed in fracture media and soluble rocks have led karst aquifers into various porosity types and aquifer properties. Karst terrain stores abundant water resources, despite lack of surface water [6] [16] [16] [17].

One of the most dependable surface water resources in karst area are karst springs [2] [8]. Karst springs are considered as one of the most enormous water resources compared to others springs from other aquifer types. Karst springs emerge as the most important surface water sources in karst area [4]. Nyadeng Spring is located in the middle of the traditional forest of Merabu Village Nyadeng is the biggest karst spring located in Merabu Karst, Berau Regency (figure 1). Nyadeng spring utilized by the villagers to meet their daily need of freshwater. Nyadeng play very important role as the main
water resources for the villagers. Nyadeng also initiated as a tourism spot that included in the Merabu Forest and Merabu Village tourism schemes.

![Figure 1. The location of Nyadeng Spring.](image)

Despite intensively utilized and being the most significant water source in Merabu, Nyadeng Spring has not been monitored before. Therefore, a quantitative research based on automatic water level monitoring has been conducted in Kakap Spring to provide hydrograph data. Karst spring hydrograph monitoring is necessary to obtain quantitative parameters of the aquifer. The forms of hydrograph reflect the output discharge and the networking systems of an aquifer. Therefore, karst spring hydrograph is important to determine and characterize the aquifer condition. The spring hydrograph features provide valuable information in order to establish a careful water resources management action [3] [7]. This research aimed to determine the hydrograph fluctuation of Nyadeng Spring. Furthermore, this research also aimed to determine the karstification degree as the main consideration for karst water resource management.

2. Result and discussion
The primary material for karstification degree determination is hydrograph series data that obtained from automatic water level logger installation. Onset HOBO Water level data loggers were installed for annual water level observation. The HOBO water level data logger sensor measures the water pressure and compensated with barometric pressure to generate water level data. Water level measurement accuracy up to 1.5 cm with very minimum error. Manual discharge measurements have been done with velocity area method. From the manual discharge measurements, discharge data and water level data combined to generate exponential regression.

Derived from hydrograph data, several single recession curves were selected and respectively a Master Recession Curve assembled. Master recession curve is a graph that shows the average recession curve shape that assembled from several recession periods in a particular site. Master
Recession Curve (MRC) commonly used to describe and analyze the average recession from a set of hydrograph recessions [12] [13].

The determination of karstification degree is based on the identification of karst discharge regime. The discharge regime defined as a pattern of changing conditions in the groundwater depletion graph. Later Study described that more than two flow components presence in karst spring hydrograph [3] [10] [14]. Other description of recession curve that describes each flow component is also necessary to be considered.

Malik and Vojtkova introduced a quantitative method for karstification degree classification. The development of karstic area classified using a 10-degree scale, from the 1st degree for the lowest karstification, and 10th degree for most developed (Table 1) [10]. Typical recessional equations used to describe recessional types that characterized by the existence of different flow sub-regimes. There are more than two flow components presence in karst spring hydrograph. Exponential function represents diffuse aquifer type with laminar flow characteristics (Eq 1.) [9], while linear function represents conduit channels with turbulent flow characteristics [5].

\[ Q_r = \sum_{i=1}^{n} Q_0 e^{-\alpha rt} \]  

\[ Q_t = \sum_{i=1}^{n} Q_0 e^{-\alpha rt} + \sum_{j=1}^{m} \left( \frac{1}{2} + \frac{|1-\beta jt|}{2(1-\beta)} \right) Q_{\alpha j} = Q_0 (1- \beta j t) \]  

Water level data monitoring in Nyadeng Spring have been conducting from April 2016-presents. However, the water level data series that available and ready to be analyzed was only until March 2017. A stage-discharge rating curve then constructed based on six manual discharge measurement (figure 2). The stage-discharge rating curve equation in Nyadeng Spring expressed in the Eq. 3:

\[ y = 0.0102e^{5.8547x} \]  

![Figure 2. Stage discharge rating curve of Nyadeng Spring.](image)
Karstification degree in recharge areas of springs according to recession curves parameters.

| Karstification degree | Groundwater flow sub-regimes type | Characteristic recession curve equation | Characteristics of recession-curve parameters |
|-----------------------|-----------------------------------|----------------------------------------|-----------------------------------------------|
| 0.5                   | Single laminar sub-regime, lower values of α1 | \( Q_t = Q_{01}e^{-\alpha_1t} \) | \( \alpha_1 < 0.001 \) |
| 1.0                   | Single laminar sub-regime, higher values of α1 | \( Q_t = Q_{01}e^{-\alpha_1t} \) | \( \alpha_1 = 0.001-0.0025 \) |
| 2.0                   | Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α1 and α2 | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} \) | \( \alpha_1 < 0.0024 \) and \( \alpha_2 > 0.033 \) |
| 2.3                   | Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α1 and α2 | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} \) | \( \alpha_1 < 0.0024 \) or \( \alpha_2 < 0.033 \) |
| 3.0                   | Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α1 and α2 | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} \) | \( \alpha_1 > 0.0043 \) and \( \alpha_2 < 0.060 \) |
| 3.5                   | Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α1 and α2 | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} \) | \( \alpha_1 = 0.0024-0.0045 \) or \( \alpha_2 = 0.053-0.067 \) |
| 4.0                   | Combination of two or more sub-regimes with merely laminar flow characterized by different discharge coefficients, lower values of α1 and α2 | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} \) | \( \alpha_1 = 0.0041-0.018 \) and \( \alpha_2 = 0.055-0.16 \) |
| 4.3                   | Discharge hydrogram is composed of a sub-regime with turbulent flow and a sub-regime with laminar flow. | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{04}(1-\beta_1t) \) | \( \alpha_1 < 0.016 \) or \( \alpha_2 > 0.16 \) |
| 4.7                   | Complex discharge regime, a combination of one sub-regime with turbulent flow and two sub-regimes with laminar groundwater flow. | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} + Q_{04}(1-\beta_1t) \) | \( \beta_1, \beta_2, \alpha_1, \alpha_2 \) high values |
| 5.0                   | Very complex discharge regime, a combination of two sub-regimes with turbulent flow and two sub-regimes with laminar groundwater flow. | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} + Q_{04}(1-\beta_1t) + Q_{05}(1-\beta_2t) \) | \( \beta_1, \beta_2, \alpha_1, \alpha_2 \) high values |
| 5.5                   | Discharge regime is a combination of one sub-regime with laminar flow with two to three sub-regimes with turbulent flow. Substantial role in groundwater discharge plays by the sub regime with laminar flow | \( Q_t = Q_{01}e^{-\alpha_1t} + Q_{02}e^{-\alpha_2t} + Q_{04}(1-\beta_1t) + Q_{05}(1-\beta_2t) \) + \( Q_{06}(1-\beta_3t) \) | \( \beta_1, \beta_2, \beta_3, \alpha_1 \) high values |
| 8.0                   | Discharge regime is a combination of a sub-regime with laminar flow with two to three sub-regimes with turbulent flow. | \( Q_t = Q_{01}(1-\beta_1t) \) | \( \beta_1, \beta_2, \beta_3, \alpha_1 \) high values |
| 8.5                   | Groundwater flow regime is represented merely by turbulent flow, with only one turbulent flow sub-regime present, which represents turbulent circulation in channel systems (conduits) without hydraulic connection to the groundwater in adjacent rock blocks. Groundwater circulation is mostly connected to vadose zone | \( Q_t = Q_{04}(1-\beta_1t) \) | \( \alpha_1; \alpha_2 = 0 \) and \( \beta_1 > 0 \) |
| 9.0                   | Groundwater flow regime is represented merely by turbulent flow, consisting of two turbulent flow sub-regimes. These represent turbulent circulation in channel systems (conduits) without hydraulic connection to the groundwater in adjacent rock blocks Groundwater circulation is mostly connected to vadose zone | \( Q_t = Q_{04}(1-\beta_1t) + Q_{05}(1-\beta_2t) \) | \( \beta_1 \) dan \( \beta_2 \) low values |
| 10.0                  | Complex turbulent flow regime of groundwater discharge, consisting of three different turbulent flow sub-regimes. Probability of a very complex groundwater circulation by occasional flows in the vadose zone. Documented only in perennial flows. | \( Q_t = Q_{04}(1-\beta_1t) + Q_{05}(1-\beta_2t) + Q_{06}(1-\beta_3t) \) | \( \beta_1, \beta_2 \) dan \( \beta_3 \) high values |
Nyadeng Spring catchment area has not been defined yet, due to the minimum information and data in Merabu Karst Area. The flow characteristic of Nyadeng Spring is dominated with significant diffuse flow input, indicated with slow discharge response to the precipitation events. However, Nyadeng also dominated by strong turbulent flow regime, indicated by extreme flood pulses. The lowest discharge in Nyadeng Spring recorded at 1.47 m³/second, and the maximum discharge recorded was 6.2 m³/second (figure 3).

![Figure 3. Hydrograph data series of Nyadeng Spring.](image)

Based on automatic recession curves filters, more than thirty (30) flood events were identified. However, only four flood events were ideal for the analysis. The selection of ideal recession curve based on recession length and the inclination of the recession limb. Subsequently, each recession curve was calibrated with the appropriate flow model, based on the shape and inclination of the recession limb (figure 4).

![Figure 4. Calibration model of a single recession curve.](image)

The shape of each recession curve is distinctive, depends on several factor such as; the development of conduit, the catchment area size, the aquifer response to the precipitation intensity, etc. After each recession curve has calibrated, all the recession curves subsequently combined to
generate Master Recession Curve. The shape of calibrated MRC in Nyadeng Spring shows the combination of two turbulent flow regimes and one laminar flow regime as it presented in Fig. 5. The domination of turbulent flow regimes indicates the reduction of active fissures in the aquifer system (Malik & Vojtkova, 2012). This condition consolidates the hypothesis that open conduit channels dominate the systems. The flow types at Nyadeng Spring can be classified as turbulent fast flow.

Figure 5. Nyadeng Spring located in the middle of Merabu Forest.

However, the diffuse flow at Nyadeng Spring during also play important role during recession periods or the dry season. Diffuse flow provides steady discharge storages with abundant availability. From the hydrograph and MRC can be seen that the diffuse flow with laminar characteristics also exist in every single recession event. This condition indicates that the diffuse flows significantly contribute to the aquifer. The combination of linear and turbulent flow alternately dominate the aquifer, clarify that the aquifer in Nyadeng systems formed in mixed-aquifer type [1].

The determination of karstification degree at Nyadeng Spring derived from four individual recession events. Based on the sub regimes analysis, one laminar sub regime and two turbulent sub regimes were identified. Eq.4 express superimposed equation of flow regimes at Nyadeng Spring.

\[ Q_t = 3.2 - 0.001t + 1.2(1 - 0.012t) + 1.6(1 - 0.035t) \]  

Based on the MRC result, Nyadeng Spring dominated by turbulent flow regimes. According to [10] karstification degree classification, Nyadeng Spring classified at the scale of 7 to 8. Discharge regime in Nyadeng formed in a combination of sub-regime with laminar flow with two sub-regimes with turbulent flow. Excessive role in groundwater discharge is played by sub-regimes with turbulent flow. Sub-regime with laminar flow is less significant. This classification expresses a highly developed karstification of the aquifer, characterized by large karst channels/conduits. The role of phreatic zone is insignificant due to the domination of conduit channels with turbulent flow characteristics.
Hydrograph monitoring in Nyadeng Spring is a preliminary research that potentially provides many advantages in the future. This research was facing many technical and non-technical constraints. However, from this minimum result, it can be concluded that Nyadeng Spring play very important role as water resources in Merabu Karst area. This research is expected to provide more scientific data in the future. The determination of karstification degree in Nyadeng Spring shows that Nyadeng Spring formed in developed karstic aquifer with complex discharge regimes. These facts potentially provide a scientific document for karst river basin management.

3. Conclusion
Nyadeng Spring formed in a combination of sub-regime with laminar flow with two sub-regimes with turbulent flow. Excessive role in groundwater discharge is played by the combination of laminar and turbulent flow. The karstification degree in Nyadeng Spring classified at 7th-8th scale. The combination of linear and turbulent flow alternately dominate the aquifer, clarify that the aquifer in Nyadeng systems formed in mixed-aquifer type. These results indicate the development of Nyadeng Spring catchment area. This preliminary research expected to be continued in the future and provides comprehensive scientific considerations for karst water resources management.

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