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Runoff Characteristics in a Tropical Rain Forest Catchment

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Abstract

Knowledge of runoff characteristics plays an important role in managing the function of water conservation in the forests. Hydrological observation was conducted at Bukit Tarek Experimental Watershed (BTEW) of a tropical rain forest in Peninsular Malaysia. Stormflow, groundwater recession and stream regimen characteristics were analyzed based on 3-y (1992–1994) of record. Small storm events (< 30 mm) produced less than 10% of rainfall as stormflow, which may have been determined in the stream channel and riparian areas. The stormflow depended strongly on the antecedent wetness as represented by the antecedent flow rate during large storm events (≥ 30 mm). The depth and physical properties of soils could be important factors to determine production of stormflow. The discharge-duration curves were different among 1992, 1993 and 1994 because of the differences of variation in rainfall (e.g. monthly distribution) and annual rainfall. The relationship between ratio of plentiful runoff to scanty runoff and recession coefficient at BTEW was similar to the results from watershed underlain by the same geology in Japan. These results imply that soil, variation in rainfall, as well as annual rainfall and geology are important factors to understand runoff characteristics.

Discipline: Watershed and regional resources management
Additional key words: Bukit Tarek Experimental Watershed, groundwater recession, Peninsular Malaysia , stormflow, stream regimen characteristics

Introduction

Forests play significant roles in hydrological cycles. Tsukamoto[16] classified the function of water conservation in forests as (1) function for production of subsurface flow or recharge, (2) function for evaporation as pump, (3) function for natural dam, and (4) function for water quality formation. Recently, the high rate of deforestation in tropical regions has become a cause of concern[2]. The decline in the function of water conservation in tropical rain forests has become the causes of frequency of flood, sediment disaster, and degeneration of water quality in the region. It is necessary to clarify the runoff characteristics of tropical rain forests based on hydrological observations in order to solve such problems.

Forest Research Institute Malaysia and Forest Department have established the Bukit Tarek Experimental Watershed (BTEW) in Peninsular Malaysia to quantify the effects of forest plantation establishment on hydrological parameters since 1989. Detailed hydrological observations have been conducted at BTEW. Noguchi et al.[6] pointed out that saturation overland flow may not be dominant but subsurface flow must play important roles in streamflow generation. During dry conditions, rainwater was mostly retained in the soil and did not produce substantial stormflow[7,8].

South-East Asia is composed of small island, peninsular, and continental areas. There are different rainfall characteristics and geology among small island, peninsular and continental areas in South-East Asia. Thus, Kuraji et al.[4] suggested that we should conduct hydrological observations at each area in order to clarify the runoff characteristics of tropical rain forests in South-East Asia.

A useful approach for understanding hydrological characteristics is to compare hydrological characteristics

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among several sites, which are located in areas with different geology, soils, and climate etc[4,9]. In this paper, we address stormflow, groundwater recession and stream regimen characteristics at BTEW using hydrograph analysis. Additionally, the runoff characteristics of BTEW are compared with those of temperate forested watersheds in Japan.

Materials and methods

1. Site description

This study was conducted at catchment C1 (32.8 ha) in Bukit Tarek Experimental Watershed (3º31′30″N, 101º35′E, 48–213 m), Peninsular Malaysia. The forest in C1 was logged in 1963 and it was a regenerated secondary forest. The forest can be classified as a lowland forest, which is dominated by *Koompassia malaccencis*, *Eugenia* spp., and *Canarium* spp. Surficial geology is metamorphic sedimentary rocks consisting of quartzite, quartz mica schist, graphitic schist, and phyllite from the Arenaceous Series[12]. Soil depth ranged from 1.2 to 6.4 m with a mean of 1.5 m. The soil profile was characterized by thin dark colored A_h horizon and light colored underlying horizons. Saturated hydraulic conductivities were ranged from 6.40×10^{-6} to 7.51×10^{-4} m s^{-1} [10]. The soil is classified as Acrisols. Rainfall characteristics are characterized by short duration and high intensity[5]. Average annual rainfall based on 3-y (1992–1994) is 2,655 mm. The monthly rainfall had a two-peak distribution (Fig. 1). The average yearly maximum and minimum temperature are 33.0 and 21.9ºC, respectively.

2. Hydrological observation

Runoff discharge is measured by the 120-degree V-notch at the stream outlet of catchment C1. Steven's F-recorder with a float and counterweight mechanism was used to record water level on 7-day charts. The water level records were digitized and discharge was calculated using rating table for discharge-stage relationships. Rainfall is measured by a weighing-type recording rain gauge and a tipping bucket rain gauge near the weir. Hydrological data for three years (1992–1994) was used in this study.

3. Hydrograph analysis

Hourly discharge was plotted continuously on semi-logarithmic paper. A point of inflection was obtained on the falling limb of the hydrograph between 12 and 72 h after a storm. Stormflow was defined as the area above the separation line; the line on the hydrograph which connects the point of rise to the point of inflection.

Since groundwater flow is determined by both long- and short-term groundwater storages, the groundwater portion of the recession limb is most likely a combination of groundwater flows resulting from the many previous rainfall events. Streamflow in mountain catchments during no rain days (date after there has been no rain for three days since rain has stopped) is considered as discharge from groundwater. Groundwater recession is analyzed using Takagi's method[14] in this section. In this method, the groundwater flow is composed of an exponential function (1) and a fractional function (2) derived for confined and unconfined groundwater flows:

$$Q = Q_0 e^{-\alpha t} \tag{1}$$

$$Q = \frac{Q_0}{(1 + \beta\sqrt{Q_0}t)} \tag{2}$$

where Q_0 (mm d^{-1}) is the flow at the beginning time of recession (initial flow), Q (mm d^{-1}) is the flow at time t, e is the base of the natural logarithm, α and β (d^{-1}) are recession coefficients of confined groundwater and unconfined groundwater, respectively. The calculation was done for dates with precipitation of less than 2.0 mm d^{-1} to provide sufficient sample numbers.

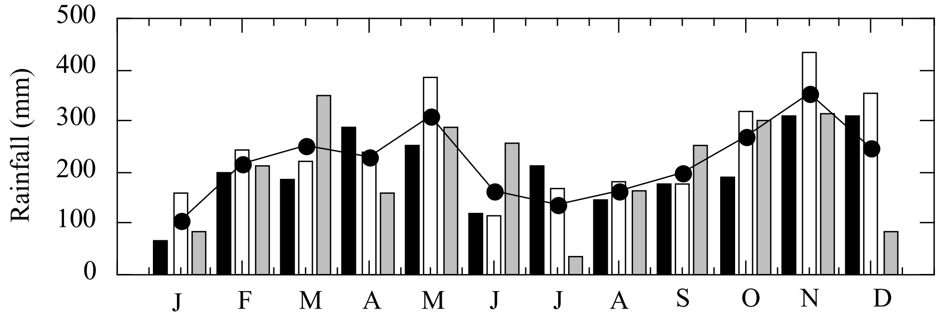

Fig. 1. Monthly distribution of rainfall based on a 3-y (1992–1994) record

■ : 1992, □ : 1993, ▨ : 1994, ● : Mean.

Results and discussion

1. Stormflow

The relationships between stormflow and rainfall are shown in Fig. 2. The three symbols denote differences in the antecedent conditions as represented by the antecedent flow rate, Q_i (mm h^{-1}). Q_i reflects soil moisture conditions such as pressure head[7]. Small storm events (< 30 mm) produced less than 10% of rainfall as stormflow, and the effects of the antecedent flow rate on stormflow were not clear. When the rainfall in a storm event was less than 30 mm, the stormflow may have been determined in the stream channel and riparian areas. When the antecedent flow rate was ≥ 0.1 mm h^{-1} (during wet conditions), large storm events (≥ 30 mm) produced stromflow as much as rainfall except for initial 30 mm. The tensiometric heads showed low suction and there was a downward soil water flux during the wet condition[7]. Subsurface flow from upper parts of the slope is likely to augment streamflow production during such conditions. This is because large stormflow occurred during the wet conditions. When the antecedent flow rate was ≤ 0.07 mm h^{-1} (during dry conditions), the loss (difference in amount between rainfall and stormflow) was more than 30 mm. This is because rainwater was mostly retained in the soil and did not produce substantial stormflow during dry conditions[7]. Thus, the stormflow depended strongly on the antecedent wetness as represented by the antecedent flow rate. Interestingly, the stormflow increased in proportion to rainfall during wet conditions after initial rainfall of 30 mm. The threshold of the initial rainfall could be higher during dry conditions than during wet conditions. The same relationship between stormflow and rainfall was also observed at the Tatsunokuchiyama-south valley watershed (TSVW) underlain by Palaeozoic formation in Japan[15]. Most of the soils at TSVW are thick (> 1 m) sandy clay loam with a thin (5–10 cm) A horizon. The geology is not but the depth and physical properties of soils could be main factors to determine production of stormflow.

2. Groundwater recession and stream regimen characteristics

The recession coefficient of confined groundwater was from 0.0290 d^{-1} to 0.0532 d^{-1} with a mean of 0.0417 d^{-1} (Fig. 3a). The recession coefficient is in proportion with the initial flow. However, the recession coefficient of unconfined groundwater recession was relatively constant to initial flow (Fig. 3b). The recession coefficient was from 0.0110 d^{-1} to 0.0196 d^{-1} with a mean of 0.0159 d^{-1}.

Ando and Takahashi[1] calculated the recession coef-

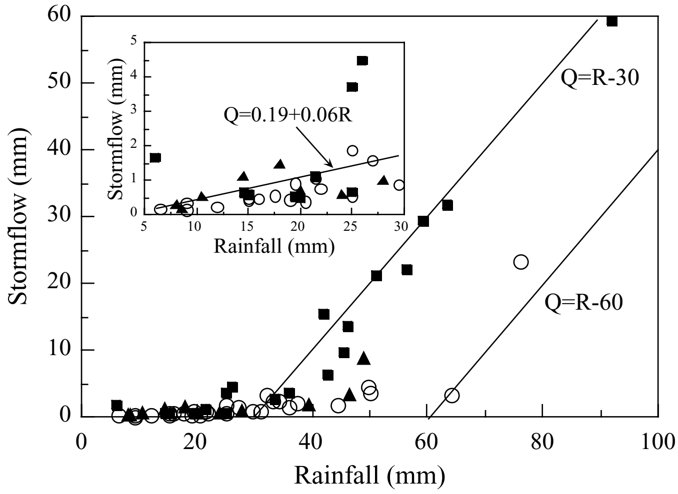

Fig. 2. Relationship between stormflow and rainfall
Q_i: Antecedent flow rate (mm h^{-1}), Q: Stormflow, R: Rainfall.
○ : $Q_i \leq 0.07$ (mm h^{-1}), ▲ : $0.07 < Q_i < 0.1$ (mm h^{-1}), ■ : 0.1 (mm h^{-1}) $\leq Q_i$.

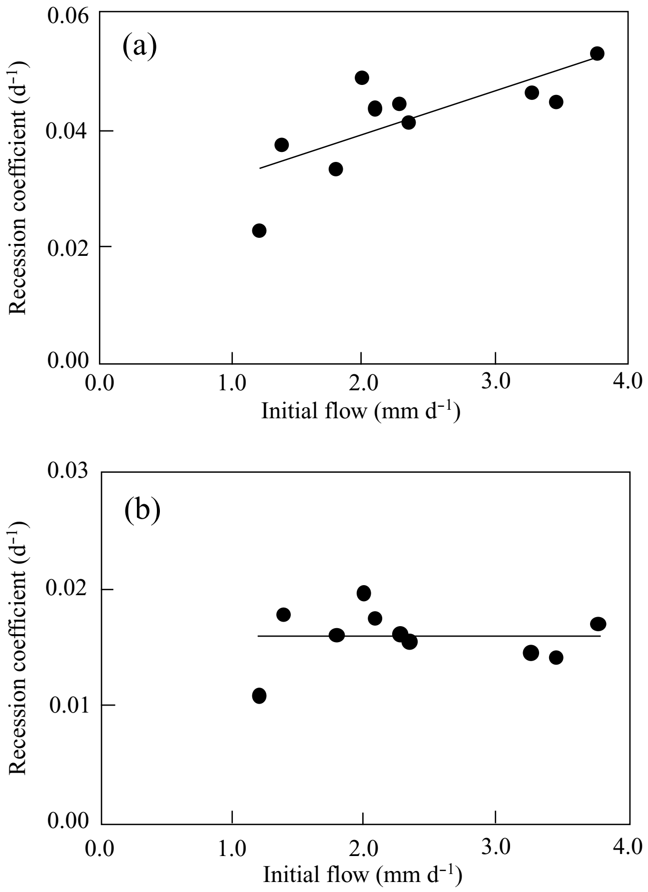

Fig. 3. Relationship between initial flow and recession coefficient
(a): Recession coefficient of confined groundwater.
(b): Recession coefficient of unconfined groundwater.

ficients at six watersheds in Japan. The values at each site exhibited seasonal differences. The value were in following order: summer > spring or autumn > winter. This is because evapotranspiration was higher in summer than in winter. Therefore, the recession coefficients in winter, less effected by evapotranspiration, have been used for analyzing in Japan. In contrast, evapotranspiration at BETW showed high potential (mean: 3.8 mm d^{-1}, SD: 0.57) through a year and no distinct seasonal variation based on 2-y observation[11]. Thus, we should consider that the recession coefficients at BTEW include the effect of evapotranspiration. In addition, Ando and Takahashi[1] proposed to use the recession coefficient, which was constant with the initial flow. Therefore, the recession coefficient of unconfined groundwater recession is used for analyzing hydrological characteristics in this study.

The discharge-duration curve is obtained from the daily discharge plotted according to the largest size of daily discharge for a year. The curve is affected by variation in rainfall, vegetation, area of catchment, soil physical properties, and geology. Plentiful runoff, ordinary runoff, low runoff, and scanty runoff are defined as the daily runoff on 95th, 185th, 275th, and 355th largest flow data of a year for flow regime characteristics. Fig. 4 shows discharge-duration curves at BTEW in 1992, 1993 and 1994. All flow in 1993 showed higher value than those in 1992 and 1994. The discharge-duration curve in 1994 varied more significantly than the curves in 1992 and 1993.

The streamflow depended on variation of rainfall and soil moisture condition[7]. Annual rainfall in 1993 was larger (3,005 mm) than any other year (1992: 2,450 mm, 1994: 2,505 mm). In addition, monthly rainfall in 1993 was more than 100 mm through a year (Fig. 1). Therefore, the discharge-duration curve in 1993 showed higher than the curves in 1992 and 1994 (Fig. 4). Although annual rainfall and monthly rainfall on January (69 mm) in 1992 were as much as those (January: 84 mm) in 1994, we had much more rainfall on December 1993 (354 mm) than that on December 1991 (162 mm). It is suggested that much of the rainfall on December 1993 might contribute to the streamflow on January 1994. Antecedent precipitation is an index of soil moisture condition, which has an effect on streamflow. This is one of the reasons why the curve in 1994 showed higher value than the curve in 1992. Monthly rainfall in 1994 showed less than 100 mm for three months (January: 84 mm, July: 34 mm, December: 86 mm; Fig. 1). Especially, there was a dry spell in summer; the 30-day antecedent precipitation on 12 August 1994 was only 3.0 mm. Such extreme change of rainfall might have an effect on variation in the curve in 1994. These results suggest that the variation and amount of rainfall caused the difference of the curves in 1992, 1993, and 1994.

Fujieda[3] compared the stream regimen characteristics in Cuhna, Brazil with those of 15 forested watersheds in Japan. He showed that the runoff at Cuhna exhibited higher consistency of stream discharge than those at other watersheds in Japan. The maximum, minimum, and mean of plentiful, ordinary, low, and scanty runoffs were calculated using results by Fujieda[3]. The stream regimen at the BTEW varied within the range of results (Fig. 4).

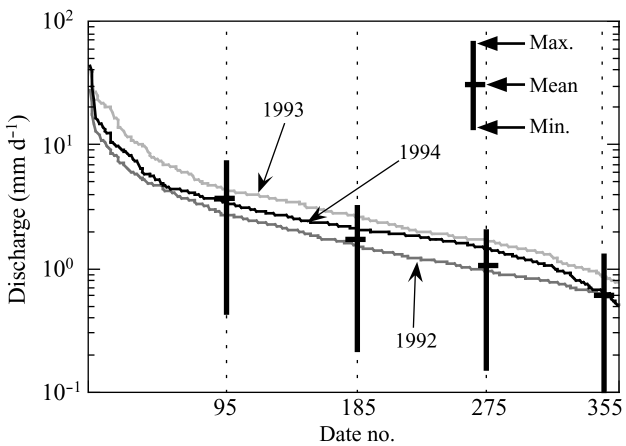

Fig. 4. Discharge-duration curves of BTEW C1 catchment
The maximum, minimum and average at plentiful, ordinary, low, and scanty runoffs were calculated using the results of 15 forested watersheds in Japan by Fujieda[2].

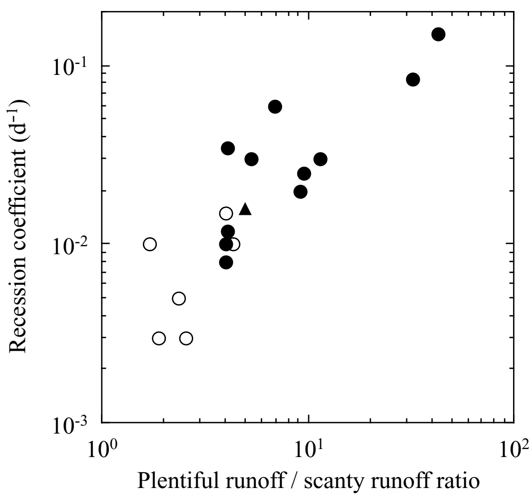

Fig. 5. Relationship between the ratio of plentiful runoff to scanty runoff and the recession coefficient of unconfined groundwater
○ : Granite, ● : Sedimentary rock,
▲ : Bukit Tarek.

Shimizu[13] calculated the ratio of plentiful runoff to scanty runoff at 70 watersheds in Japan. The ratio on Mesozoic, Paleozoic and tertiary formation watersheds was larger than the ratio on watersheds underlain by quaternary, tertiary volcanic rocks and granite rocks. It is suggested that the function of water recharge on watersheds underlain by quaternary, tertiary volcanic rocks and granite rocks is superior to that on Mesozoic, Paleozoic and tertiary formation watersheds. Fujieda[3] analyzed that relationship between recession coefficient and the ratio of plentiful runoff to scanty runoff in forested watersheds in Japan. He showed the ratio of plentiful runoff to scanty runoff and the recession coefficient of watersheds underlain by sedimentary rock was larger than those of watersheds underlain by granite rock. It is suggested that the function of water recharge on watersheds underlain by granite rock was superior to that on sedimentary rock. The relationship at BTEW was similar to the results by Fujieda[3] (Fig. 5). These results supports that bedrock of watershed plays an important role in production of groundwater flow.

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