Differences in stream responsiveness between a tropical montane cloud forest and a tropical lowland rainforest

A Nainar, K Kuraji, F Cleophas, V T Justine, N Maidin, K U Kamlun, K Bidin, L Majuakim, R Hassan and M Mahali*

1 Faculty of Tropical Forestry, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, Malaysia
2 University of Tokyo Forests, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1 Chome-1-1 Yayoi, Bunkyo City, Tokyo 113-8657, Japan
3 Sabah Parks, Block H, Level 1-5, Lot 45 & 46, Signature Office, KK Times Square, 88100, Kota Kinabalu, Sabah, Malaysia
4 Faculty of Science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, Malaysia
5 Institute for Tropical Biology and Conservation, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Sabah, Malaysia

* Corresponding author: marz@ums.edu.my

Abstract. Tropical Montane Cloud Forests (TMCF) have unique hydrology considering their high moisture, steep headwater terrain, shallow soils, frequent precipitation, and the presence of horizontal precipitation. While the hydrology of Tropical Lowland Rainforests (TLRF) has been given due attention, TMCF in Malaysia have been less explored. This study compares stream responsiveness and peak flow dynamics between TLRF (substation Inobong, 5.33 ha) and TMCF (substation Alab, 8.53 ha) in Crocker Range, Sabah, Malaysia. Streams in both study site were instrumented with water level sensors and dataloggers, and meteorological stations that records data at 10-minute intervals. Two hydrograph metrics namely $T_{res}$ (time taken from start of precipitation to hydrograph initiation) and $T_{peak}$ (time taken from start of hydrograph response to peak discharge) were assessed via a combination of the Mann-Whitney test and ANCOVA. TMCF took a longer time to achieve peak water level (mean $T_{peak}$=143 mins) compared to TLRF (mean $T_{peak}$=118 mins). Average rainfall intensity ($P_i$) was negatively correlated with $T_{peak}$. $T_{res}$ was higher in TMCF (mean=141 mins) than in TLRF (mean=51 mins) and was not affected by $P_i$ or $P$. Understanding such hydrological dynamics in TMCF is important for better headwater resource management and for flood prevention.

Keywords: Tropical, forest, hydrology, streamflow, peakflow.

1. Introduction

Due to being located in high altitudes and having a unique microclimate, tropical montane cloud forests (TMCF) are known to exhibit different hydrological characteristics than tropical lowland rain forests (TLRF). High altitude and mountainous terrain result in higher moisture and more frequent rainfall [1–3]. The frequent occurrence of fog and cloud results in frequent condensation on surfaces (leaves, stems, soils, rocks, etc.) and blocked solar radiation, which translate to lower vapour pressure deficit and lower leaf water potential. Under such conditions, evaporation and transpiration may be limited compared to lowland rainforest where solar irradiance is high, and conditions are relatively dry. In terms of surface runoff, such constant saturated conditions could mean that the primary runoff mechanism is saturation excess overland flow instead of infiltration excess (Hortonian) overland flow. At the tree scale, constant wet conditions coupled with frequent horizontal precipitation could result in frequent crown drip instead
of effective interception. The high altitude and location (montane) also reflect soil conditions whereby the soil layer is usually thin and poorly developed with abundant parent material. Compared to lowland terrain, these characteristics typically translate to higher streamflow responsiveness and runoff during storm events.

Although such characteristics are generally true for TMCF, variations and exceptions do exist and are not yet well-studied. The east Andean TMCFs show wetter conditions and less seasonal variation with altitude, indicating a positive relationship between altitude and fog persistence and precipitation just as with other TMCF [2]. With regard to streamflow, Ramirez et al. (2017) found that TMCF streamflow dynamics is a function of elevation and land cover, but those located at higher elevation are subjected to greater seasonality. Due to high precipitation, moisture, and low water loss, several studies found unusually high rainfall-runoff ratios [4]. Some were unable to balance the water budget, resulting in higher output than input [2,5,6]. Under such conditions, mechanisms for runoff generation are usually attributed to saturation excess overland flow. Other studies however found that streamflow is primarily sustained by soil water and groundwater, where rainwater rapidly percolates porous volcanic ash soil to recharge deep groundwater reservoirs [1,7,8,9].

Considering the diverse findings of hydrology in TMCF, more study is necessary to map its differing characteristics in different regions (differing elevation, vegetation, climate, and geology). In this study, we compared stream responsiveness in a TMCF against that in a secondary TLRF during storm events in Sabah, Malaysian Borneo by utilising two indicators of responsiveness namely the time from the start of precipitation to start in hydrograph initiation ($T_{res}$); and the time from hydrograph initiation to peak discharge ($T_{peak}$).

2. Study area

The two catchments being compared in this study are the (i) Tropical Montane Cloud Forest (TMCF, 1,906 m.a.s.l) in Mount Alab, Tambunan; and the (ii) Tropical Lowland Rainforest (TLRF, 484 m.a.s.l) in Inobong. Both catchments are located slightly inland on the west coast along the Crocker Range in Sabah, Malaysia (Figure 1). These forests are managed by Sabah Parks – a local authority that oversees recreational and research activities in selected nature parks. TMCF is a primary virgin forest while TLRF is a secondary (selectively-logged, regenerated) forest.

In Mount Alab (TMCF), the general lithology is sandstones and mudstones of the Trusmadi association with main soil units comprising Gleyic and Orthic Acrisols, Gleyic Podzol, humic Gleysol, Dystric Histosol, and Lithosol. Inobong (TLRF) has a lithology of sandstones and mudstones of the Crocker association with Orthic Acrisol, Chromic and Dystric Cambisols, and Lithosol [10]. Both catchments are mountainous, but TMCF has higher proportions of steep slopes (Table 1).

The climate in Sabah is equatorial with high temperatures (annual mean: 26-28 °C) and rainfall (annual mean: 2,400 mm) throughout the year [10,11]. Distinct wet and dry seasons do not exist. However, in the west coast where the study sites are located, relatively higher rainfall occurs in May and October-November following the inter-monsoon periods [12]. Due to the inland and high-altitude nature of the studied catchments, they may be subjected to localised weather and increased rainfall. The TMCF has a mean annual rainfall of 3,527 mm (recorded 2007-2018), [13]; and daily temperature ranges between 13 and 25 °C. Daily averages of relative humidity is between 87 and 99.8% (recorded Aug 2010-Oct 2011). In the TLRF, mean annual rainfall is 4,189 mm and daily temperature ranges between 20 and 32 °C. Daily average relative humidity is 70-98% (recorded Oct 2010-Oct 2011).
Figure 1. Study area.

Table 1. Proportion of slopes in TMCF and TLRF.

| Slope (°) | TLRF | TMCF |
|-----------|------|------|
|          | Area (ha) | Area (%) | Area (ha) | Area (%) |
| ≤10       | 0.14  | 3.17  | 0.47  | 5.52   |
| 11 - 20   | 1.07  | 24.79 | 1.35  | 15.86  |
| 21 - 30   | 3.15  | 73.22 | 3.85  | 45.22  |
| 31 - 40   | 0.88  | 20.47 | 2.75  | 32.30  |
| 41 - 50   | 0.10  | 2.31  | 0.10  | 1.17   |
| ≥50       | 0.00  | 0.00  | 0.00  | 0.02   |

Vegetation comprises common species that can be found in tropical landscapes. TMCF is characterised by tropical montane species with the occurrence of stunted trees in higher elevation. Being a secondary forest, pioneer and successional species such as Macaranga is dominant in TLRF. A list of major species sorted by basal area is in Table 2.
Table 2. Major species in TMCF (Mount Alab) and TLRF (Inobong).

| Landscape | Species                  | Count (stem ha\(^{-1}\)) | Total BA (m\(^2\) ha\(^{-1}\)) | Rel. tree density (%) | Rel. BA (%) | Rel. dominance (%) |
|-----------|--------------------------|---------------------------|---------------------------------|-----------------------|-------------|-------------------|
| TMCF      | *Dacrydium xanthandrum*  | 120                       | 11.03                           | 0.47                  | 35.00       | 17.73             |
|           | *Leptospermum flavescens* | 80                        | 8.58                            | 0.31                  | 27.22       | 13.77             |
|           | *Adinandra acuminata*    | 40                        | 2.64                            | 0.16                  | 8.36        | 4.26              |
|           | *Lithocarpus bullatus*   | 40                        | 1.52                            | 0.16                  | 4.83        | 2.49              |
|           | *Litsea cylindrocarpa*   | 280                       | 1.33                            | 1.10                  | 4.23        | 2.66              |
|           | *Myrsine sp.*            | 240                       | 1.15                            | 0.94                  | 3.65        | 2.30              |
|           | *Tristaniopsis cf. obovata* | 960                      | 0.66                            | 3.76                  | 2.08        | 2.92              |
|           | *Adinandra sp.*          | 80                        | 0.30                            | 0.31                  | 0.95        | 0.63              |
|           | *Magnolia carsonii*      | 240                       | 0.27                            | 0.94                  | 0.85        | 0.90              |
| TLRF      | *Melastoma sabahense*    | 200                       | 0.22                            | 0.78                  | 0.69        | 0.74              |
|           | *Crypteronia paniculata* | 8                         | 4.54                            | 0.49                  | 17.44       | 8.97              |
|           | *Mallotus paniculatus*   | 208                       | 2.49                            | 12.78                 | 9.56        | 11.17             |
|           | *Ixonanthes reticulata*  | 4                         | 1.83                            | 0.25                  | 7.04        | 3.64              |
|           | *Eugenia napiformis*     | 12                        | 1.39                            | 0.74                  | 5.34        | 3.04              |
|           | *Macaranga triloba*      | 172                       | 1.31                            | 10.57                 | 5.04        | 7.80              |
|           | *Macaranga gigantea*     | 88                        | 1.29                            | 5.41                  | 4.95        | 5.18              |
|           | *Sandoricum koetjape*    | 4                         | 1.24                            | 0.25                  | 4.75        | 2.50              |
|           | *Macaranga pearsonii*    | 84                        | 0.92                            | 5.16                  | 3.54        | 4.35              |
|           | *Litsea sp.*             | 24                        | 0.87                            | 1.47                  | 3.33        | 2.40              |
|           | *Metadina trichotoma*    | 4                         | 0.61                            | 0.25                  | 2.33        | 1.29              |

Relative dominance was calculated by adding up rel. tree density and rel. BA and dividing by 2. Source: [14–16]

3. Methodology

In each catchment, a 90-degree v-notch weir was constructed at the outlet of the stream. Stream water level data was recorded at 10-minute intervals by means of a Hobo U20 pressure datalogger that is submerged in the stream and affixed inside a protective well made from a 15 cm diameter PVC pipe; used in conjunction with another similar datalogger outside the well recording ambient air pressure. With reference to the ambient air pressure, the pressure of the submerged datalogger was converted to water depth via the HOBOware Pro software. Rainfall data was collected at nearby weather stations (approximately 800 m away). Other meteorological data (temperature, relative humidity, solar irradiance) were sporadically measured whenever possible.

Data collection lasted between January 2015 and December 2020. From this raw dataset, storm event hydrographs were extracted via the software GFORTRAN 4.9.3 based on the following criteria: three consecutive increases in water level marks the start of a storm event; an event ends when water level drops to within 20% of its initial value [16]. Period of equipment malfunction were excluded from analysis. A total of 186 and 163 events were extracted from the TMCF and TLRF catchments, respectively. From each hydrograph, two key information pertaining to catchment responsiveness – the time taken from the start of precipitation to hydrograph initiation (\(T_{res}\)) and the time taken from hydrograph initiation to peak water level (\(T_{peak}\)) – were extracted. Differences in \(T_{res}\) and \(T_{peak}\) between TMCF and TLRF were assessed via the Mann-Whitney test. The Analysis of Covariance (ANCOVA) was also used to control for the effects of rainfall (\(P\)) and rain intensity (\(P_i\)) [16,17].

4. Results and discussion

\(T_{res}\) was significantly lower in TLRF compared to in TMCF as shown in Figure 2 (\(p < 0.05\)). Rainfall and average rain intensity did not significantly influence \(T_{res}\), hence ANCOVA was omitted. Lower \(T_{res}\) and \(T_{peak}\) values in TLRF translate to higher stream responsiveness compared to in TMCF. Considering
that soils are constantly wetter in TMCF and that the area is prone to saturation-excess overland flow, a more rapid runoff mechanism may be predominant in TLRF. A likely mechanism may be infiltration-excess overland flow found in similar secondary forests in the region [16,18,19]. Long dry periods and seasonal hydrophobicity that may also cause rapid runoff were however, never observed in TLRF.

Figure 2. $T_{\text{res}}$ in TMCF and TLRF.

Figure 3. $T_{\text{peak}}$ in TMCF and TLRF.

$T_{\text{peak}}$ was also significantly shorter in TLRF compared to in TMCF ($p > 0.05$) (Figure 3). $T_{\text{peak}}$ had a significant positive relationship with rainfall and a negative relationship with average rain intensity (Figure 4). Although both TMCF and TLRF were directly correlated to rainfall, slopes of $T_{\text{peak}}$ (rate of change) differed. In events of smaller magnitude ($\leq 18$ mm), $T_{\text{peak}}$ in TLRF was higher than that in TMCF. Beyond the switchover point of 18 mm, $T_{\text{peak}}$ in TMCF was higher (Figure 4b). This could be due to TLRF having higher rain intensities compared to TMCF in higher magnitude events.

With regards the influence of rain intensity, $T_{\text{peak}}$ in TMCF showed a steeper rate of decrease than that in TLRF. In lower intensity events, TLRF had lower $T_{\text{peak}}$ values while in higher intensity events, TMCF had higher values. The switchover point was approximately 14 mm h$^{-1}$ (Figure 4d). Naturally, $T_{\text{peak}}$ would have had an inverse relationship with $P_i$. However, $T_{\text{peak}}$ in TMCF had a steeper rate of decrease compared to in TLRF, which may reflect its steeper mountainous terrain and higher moisture.
5. Conclusion
Being subjected to high rainfall in the tropics, both TMCF and TLRF had high responsiveness to rain events. Contrary to expectations, TLRF exhibited higher responsiveness compared to TMCF in our study sites. Both event rainfall and rain intensity affect stream responsiveness.

6. References
[1] Muñoz-Villers L E and McDonnell J J 2012 Runoff generation in a steep, tropical montane cloud forest catchment on permeable volcanic substrate. Water Resour. Res. 48(9) 9528
[2] Ramírez B H, Teuling A J, Ganzeveld L, Hegger Z and Leemans R 2017 Tropical Montane Cloud Forests: Hydrometeorological variability in three neighbouring catchments with different forest cover. J. Hydrol. 552 151–67
[3] Mahali M, Kuraji K, Uni Kamlun K, Bidin K, Nainar A, Repin R, Gunsalam G and Cleophas F 2020 Rainfall characteristics in a tropical montane cloud forest, Gunung Alab, Crocker Range Park, Sabah, Malaysia. Trans. Sci. Technol. 7 80–9
[4] Bruijnzeel L A, Mulligan M and Scatena F N 2011 Hydrometeorology of tropical montane cloud forests: Emerging patterns. Hydrol. Process. 25 465–98
[5] Clark K E, Torres M A, West A J, Hilton R G, New M, Horwath A B, Fisher J B, Rapp J M, Robles Caceres A and Malhi Y 2014 The hydrological regime of a forested tropical Andean catchment. Hydrol. Earth Syst. Sci. 18 5377–97
[6] Zadroga F 1981 The hydrological importance of a montane cloud forest area of Costa Rica. In: Tropical Agricultural Hydrology (Lal R and Russell E W (eds)). J. Wiley, New York, pp. 59–73
[7] Muñoz-Villers L E and McDonnell J J 2013 Interactive comment on Land use change effects on runoff generation in a humid tropical montane cloud forest region. Hydrol. Earth Syst. Sci. 17 2369–71
[8] Muñoz-Villers L E and McDonnell J J 2013 Land use change effects on runoff generation in a humid tropical montane cloud forest region Hydrol. Earth Syst. Sci. 17 3543–60
[9] Directorate of Overseas Survey 2010 The soils of Sabah - Kota Kinabalu (NB 50-10). Ordnance Survey
[10] Mojiol A R I 2006 Ecological Landuse Planning and Sustainable Management of Urban and Sub-urban Green Areas in Kota Kinabalu, Malaysia Cuvillier Verlag Göttingen
[11] Town and Regional Planning Department Sabah Coastal Zone Profile 1998 – 3 CLIMATE (Part I)
[12] World Meterological Organization World Weather Information Service - Kota Kinabalu
[13] Committee P R P 2010 Vegetation survey (Alab)
[14] Committee P R P 2010 Inobong vegetation survey
[15] Repin R, Majuakim L, Suleiman M, Nitus R, Mujih H and Gunsalam G 2012 Checklist of trees in Crocker Range Park Permanent Research Plot, Sabah, Malaysia. J. Trop. Biol. Conserv. 9 127–41
[16] Nainar A, Tanaka N, Bidin K, Annammala K V, Ewers R M, Reynolds G and Walsh R P D 2018 Hydrological dynamics of tropical streams on a gradient of land-use disturbance and recovery: A multi-catchment experiment. J. Hydrol. 566 581–94
[17] Nainar A, Tanaka N, Sato T, Mizuuchi Y and Kuraji K 2021 A comparison of hydrological characteristics between a cypress and mixed-broadleaf forest: Implication on water resource and floods. J. Hydrol. 595 125679
[18] Douglas I, Bidin K, Balamurugan G, Chappell N A, Walsh R P D, Greer T and Sinun W 1999 The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. Philos. Trans. R. Soc. B 354 1749–61
[19] Nainar A, Bidin K, Walsh R P D, Ewers R M and Reynolds G 2015 Variations in suspended sediment yield and dynamics in catchments of differing land-use in Sabah. Trans. Sci. Technol. 2 1–19

Acknowledgments
The authors thank the Crocker Range Park Permanent Research Plot Committee as well as rangers and research assistants of Sabah Parks for the establishment and maintenance of the study sites. This study was funded by University Malaysia Sabah internal grant (UMS SBK0373) and the Japan International Cooperation Agency - Bornean Biodiversity and Ecosystems Conservation II (JICA-BBEC II).