Bull. Tokyo Univ. For., 113, 11–44 (2005)

# Inter-annual Variation in Rainfall Interception at a Hill Evergreen Forest in Northern Thailand

Nobuaki TANAKA *1, Chatchai TANTASIRIN *2, Koichiro KURAJI *3,
Masakazu SUZUKI *4 and Nipon TANGTHAM *2

## INTRODUCTION

Evaporation of intercepted rainfall is a distinct hydrological process in forested areas. Several studies have shown that rainfall interception by forest canopies had major significances to the water budget, comparing to other vegetative covers (*e.g.* CALDER, 1976, GASH and STEWART, 1977, PEARCE and ROWE, 1979, SUZUKI, 1991). Particularly an interception study in a flux study site, where water vapor and energy cycling are monitored and modeled, is required to quantify the confident observed amount of rainfall interception by the forest canopy. This interception amounts can be used both to parameterize and to validate the output from an evapotranspiration model, which describes the hydrological processes at a study site (CALDER *et al.*, 1986, SHUTTLEWORTH, 1988, TANAKA *et al.*, 2003, TANI *et al.*, 2003, KUMAGAI *et al.*, 2004). Furthermore, the interception data observed by LLOYED *et al.* (1988) in an Amazonian tropical forest were used to parameterize a land-surface model in GCM (DICKINSON and HENDERSON-SELLERS, 1988) and to validate the model output (LLOYD, 1990).

A number of observational studies of interception have shown that rainfall interception per individual rainfall event (hereafter event-based interception) varies remarkably. This variation in event-based interception presumably supports the understanding of unclear interception processes (KURAJI and TANAKA, 2003). However, interception models based on the Penman-Montieth equation, *e.g.* RUTTER *et al.* (1971, 1975), cannot explain the observed variation (HATTORI *et al.*, 1982, CALDER *et al.*, 1986, SCHELLENKENS *et al.*, 2000a, TANI *et al.*, 2003). Therefore, it is significant to distinguish between systematic variations that arises from measurement errors, and true variations caused by differences in rainfall and meteorological conditions during each rainfall event. Measurement errors in interception observation consist of gross rainfall and net rainfall, *i.e.* throughfall and stemflow. While a measurement of net rainfall is identified to be difficult, problems in measurement of rainfall are commonly ignored (CROCKFORD and RICHARDSON, 2000, KURAJI and TANAKA, 2003). In general, it is very difficult to find or establish a well-positioned clearing in a large forest reserve for a forest hydrological experiment. Normally any clearing used for rainfall observation is separate from interception study plots. CROCKFORD and RICHARDSON (2000) indicated that a event-based rainfall at a clearing and a study plot

---

*1 Department of Global Agricultural Sciences, Graduate School of Agricultural and Life Sciences, The University of Tokyo.
*2 Department of Conservation, Faculty of Forestry, Kasetsart University.
*3 University Forest in Aichi, University Forests, Graduate School of Agricultural and Life Sciences, The University of Tokyo.
*4 Department of Forest Science, Graduate School of Agricultural and Life Sciences, The University of Tokyo.

occasionally shows different amount due to the distance, and that the difference resulted in serious effects on the event-based interception, *e.g.* negative interception. On the other hand, differences of periodic rainfall between the 2 sites, such as annual rainfall or rainfall during a rainy season, tend to be small percentage of total rainfall (CROCKFORD and RICHARDSON, 2000). That is, a periodic rainfall at a clearing is more confident than an event-based rainfall for assigning to calculations of interception (SELLERS *et al.*, 1989).

KURAJI and TANAKA (2003) reviewed 106 observational interception studies exceeding 2 months in length in tropical and sub-tropical forests that were conducted using reliable methods. Most of the studies monitored interception for less than 12 months. This may cause following problems. For example, LLOYD *et al.* (1988) reported an interception rate for 14 months in 1984-1985 of 8 % at Ducke Reserve Forest, Brazil, while FRANKEN *et al.* (1982) reported 20 % for 14 months in 1976-1977 in the same forest. This reason for the difference was still unknown (KURAJI and TANAKA, 2003). Similarly, MANOKARAN (1979) and TANI *et al.* (2003) reported annual interception rates 21.8 and 16.9 %, respectively, at Pasoh Forest Reserve, in peninsular Malaysia. The difference was not accounted by TANI *et al.* (2003). An interception rate in a forest was often referred to literatures as a represented interception value for the forest type. Considering the above variations, it is important to examine an inter-annual variation in rainfall interception at one forest with a consistent methodology.

Kog-Ma watershed, which is covered by a hill evergreen forest in northern Thailand, is one of the flux study sites. We conducted an interception observation including rainfall observation at neighboring two sites at the watershed for four years. Then, the purposes of this study is 1) to quantify annual throughfall and stemflow, 2) to quantify confident annual interception for four years, 3) to evaluate the possible measurement errors of the presented interception, and 4) to examine the inter-annual variation in interception at the Kog-Ma watershed.

## STUDY SITE AND METHOD

### Study site and Climate

This study was carried out at the Kog-Ma watershed (at 18°45′ N, 98°54′ E, at 1,268 m.a.s.l) as a part of the Global Energy and Water Cycle Experiment Asian Monsoon Experiment (GEWEX-GAME), which is examining the role the Asian monsoon in the global climate system. The watershed is situated on an eastward-facing slope on Mount Pui (peak at 1,685 m.a.s.l.), 10 km west of Chiang Mai in northern Thailand (Fig. 1). According to the Preliminary Forest Land Use Assessment, conducted in 2000 by the Wildlife and Plant Conservation Department of Thailand, approximately 56 % of the land in northern Thailand (172,000 km$^2$) is classified as forest. The forest consists mainly of deciduous forests in the lowlands (73,000 km$^2$) and of evergreen forests in montane areas (20,000 km$^2$). Vegetation in the Kog-Ma watershed is an undisturbed hill evergreen forest, with canopy heights from 25 to 40 m (TANGTHAM, 1974). The forest is dominated by *Lithocarpus*, *Quercus* and *Castanopsis* spp. This forest can be classified as Tropical Montane Cloud Forest (hereafter TMCF, BRUIJNZEEL and PROCTOR, 1995), because fog/clouds

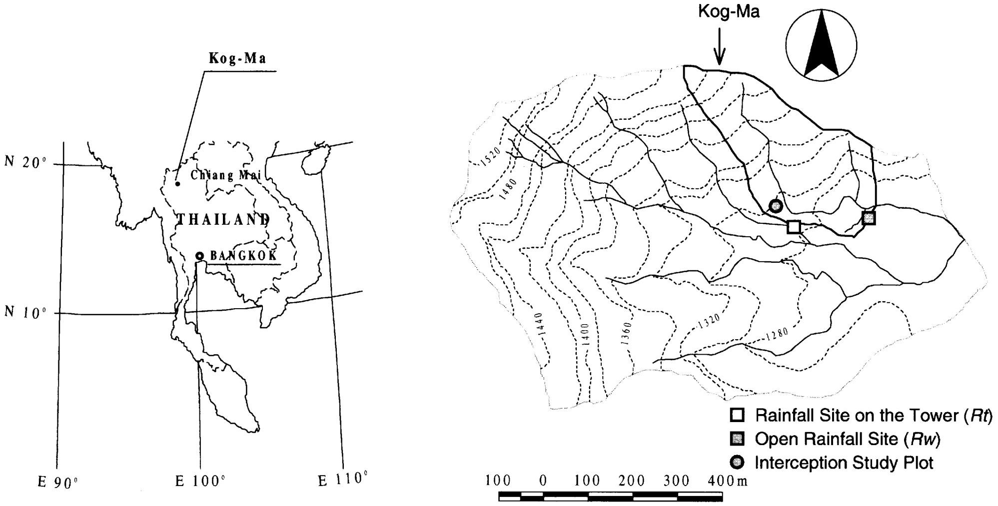

Fig. 1. Location and map of Kog-Ma watershed

occasionally covers the watershed. The occurrence of fog will affect the hydrological and ecological systems in the watershed.

The mean annual rainfall was 2084 mm for the 13-years from 1966 to 1978 (CHUNKAO et al., 1981). Seasonal change in rainfall is highly variable at this watershed. The dry season occurs from November to March, and most of the annual rainfall occurs during rainy season, which begins in April and continues until October. Temperature is constant year round. The annual mean temperature during the study period was 19.7 °C. Humidity shows large seasonality. The mean humidity during the 7-month rainy season and 5-month dry season was approximately 86 % and 68 %, respectively, during the study period.

## Method

Interception ($I$) is calculated from the following water balance equation in the forest canopy:

$$R = TF + SF + I \qquad (1)$$

where $R$ is rainfall, $TF$ is throughfall, and $SF$ is stemflow. Since the present forest is classified as TMCF, fog precipitation ($FP$) is probably input to the forest canopy in addition to the precipitation by rainfall. Therefore, Equation (1) should be changed to:

$$R + FP = TF + SF + I \qquad (2)$$

Equation (2) has been used for interception studies at cloud forests (*e.g.* HUTLEY et al., 1997). However, both a system that monitors fog water and an assumption to convert fog water (water volume, ml) to fog precipitation (water-depth equivalent, mm) are necessary to estimate fog precipitation at a cloud forest (GONZALÉZ, 2000). Therefore, we assume that the interception is referred to as a value, which is calculated from Equation (1) in this study. This assumption leads us to a definition that the interception amount, which will be reported in this paper, is the real interception minus *FP* in the Kog-Ma watershed.

### Study Plot

A 30 × 30 m study plot (at 1,300 m.a.s.l.) was established at a representative site near a 50-m observation tower in the Kog-Ma watershed (Fig. 1). The canopy projection in the study plot is shown in Fig. 2. The leaf area index (LAI) at the site is approximately 4; the seasonal change in LAI was not variable (TAKIZAWA *et al.*, 2001). There was no remarkable change in canopy condition at the interception study site, such as mortalities of the upper story trees or loss of the large braches, during the study period. AKSORNKAOE and BOONYAWAT (1977) describe the canopy structures at many sites with different altitudes on Mount Pui; BHUMINBHAMON and WASUWANICH (1970) describe the canopy of the Kog-Ma watershed. An inventory of all trees with DBH > 1 cm in the study plot was conducted in August and November 1998; 176 trees were found. The *Appendix* lists DBH, species, canopy height, and height at first living branch of all the trees. Table 1 shows the frequency distribution of DBH and tree height in the plot. Maximum DBH and tree height were 128.9 cm and 40.5 m, respectively. On the other hand, there are a lot of understory trees in the plot. In fact, approximately 77 % of the all trees had DBH < 10 cm; about 73 % of them had tree height < 5 m.

Although the species of 112 trees among 176 trees in the plot were identified, the species of the rest high trees were not identified mainly because of inaccessibility of their canopy. The species, which composed the upper story (canopy height > 20 m), were *Betula alnoides*, *Castanopsis acuminatissima*, *C. diversifolia*, *C. tribuloides*, *Elaeocarpus lanceifolius*, *Helicia nilagirica*, *Heliciopsis terminalis*, *Schima wallichii*, *Stereospermum colais*, and *Tarennoidea wallichii*. In addition, *Hiptage benghalensis* spp., *Lithocarpus elegans*, *Maesa ramentacea*, and *Phoebe lanceolata* were dominant in number among the understory of the study plot. *Ternstroemia gymnanthera* and *Turpinia nepalensis* appeared in both upper story and understory.

### Rainfall

In hydrological field experiments in forests, it is frequently difficult to find a large clearing. Fortunately, such a clearing exists at 1,268 m.a.s.l. about 250 m apart from the study plot. The clearing, with approximately 20 × 30 m open space, is surrounded by 30-m trees. Rainfall at this open site was measured with a storage-type rain gauge, which consisted of a plastic funnel (diameter 21.0 cm) and a plastic 10-L bottle. The storage water was measured daily with a 500-ml cylinder with 5-ml resolutions. Rainfall at this open site is hereafter referred to as *Rw*.

In addition, a standard rain gauge (NO.34-T, Ohta Keiki) with a 10-L bottle was installed at a site closer to the study plot to measure rainfall (hereafter *Rt*) starting in January 2000. This site

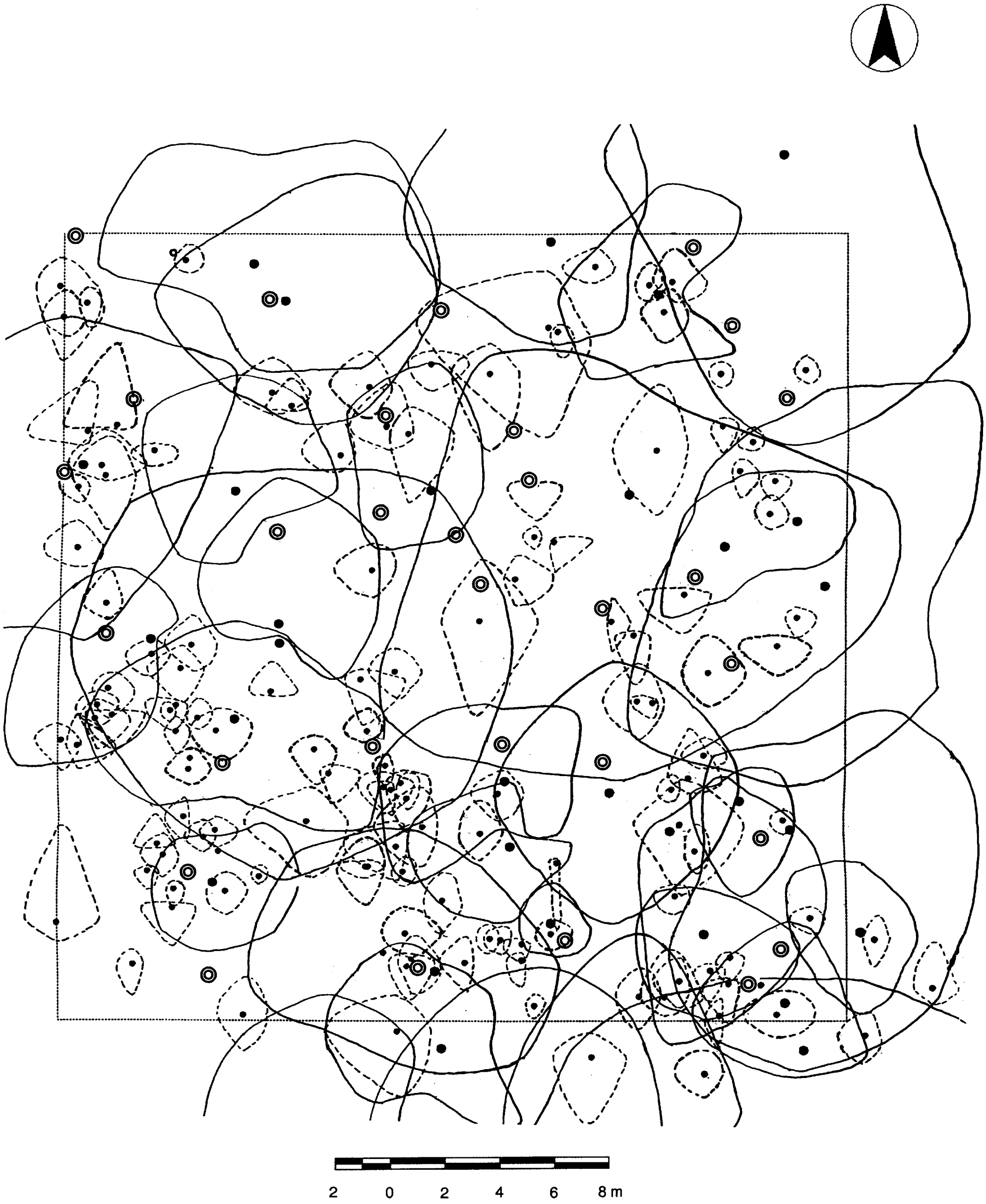

Fig. 2. Projection of canopy crowns, position of trunks (●), and location of 30 throughfall collectors (◎) in the interception study plot (30 m × 30 m) at Kog-Ma watershed. The canopy crowns of upper story and understory are expressed by solid lines and dot lines, respectively.

Table 1. (a) DBH and (b) tree height distribution on all trees and trees for stemflow measurement in the interception study plot at the Kog-Ma watershed. This enumeration was conducted in August and November 1998.

| (a) DBH class (cm) | 1-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | >90 |
|---|---|---|---|---|---|---|---|---|---|---|
| All trees in the study plot (n=176 trees) | 135 | 16 | 5 | 5 | 6 | 3 | 1 | 1 | 2 | 2 |
| Trees for the measurement of stemflow (n=8 trees) | 0 | 2 | 1 | 0 | 1 | 0 | 2 | 1 | 1 | 0 |

| (b) Height class (m) | 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 | 30-35 | 35-40 | 40-45 | 45-50 |
|---|---|---|---|---|---|---|---|---|---|---|
| All trees in the study plot (n=175 trees*) | 128 | 11 | 9 | 7 | 12 | 3 | 4 | 0 | 1 | 0 |
| Trees for the measurement of stemflow (n=8 trees) | 0 | 0 | 2 | 1 | 1 | 2 | 1 | 0 | 1 | 0 |

* There was one climber in the study plot, the tree height of which could not be identified.

was situated on the top of the 50-m observation tower, which was based at 1285 m.a.s.l., 50 m apart from the interception study plot (Fig. 1). *Rt* was measured weekly until 21 August 2000, and daily thereafter, with the same cylinder as used at the open site.

Furthermore, tipping bucket rain gauges (NO.34-T, Ohta Keiki, resolution 0.5 mm) with a data logger (KADEC-PLS, Kona System Co.) were installed beside the rain gauges at the open site and on the tower to give the time distribution of rainfall with a resolution of 10 minutes. Manually measured *Rw* and *Rt* were also compared with the tipping bucket totals to check that *Rw* and *Rt* measured properly.

### Throughfall

The same storage-type rain gauge as *Rw* was used as a throughfall collector. The number of collectors was sixteen for the duration from January to March 1999, and thirty for the duration of March 1999 to December 2002. That is, the total area of throughfall collectors was 10,386 $cm^2$, which is within the range of a standard area for throughfall measurements in natural tropical forests. These collectors were randomly fixed in the plot, measured daily and never relocated during the study period. Several interception studies in tropical forest have relocated collectors periodically for the accurate estimation of throughfall (*e.g.* BRUIJNZEEL and WIERSUM, 1987, LLOYD and MARQUES, 1988, ASDAK *et al.*, 1998, MANFROI *et al.*, 2004). The collectors in our study were not relocated, because we sought to monitor rainfall interception for a long period with a consistent methodology. In addition, the total collecting area of this study is comparatively large enough for estimating throughfall properly. Missed throughfall was interpolated by the average throughfall for the rest of 29 collectors.

## Stemflow

Stemflow volumes measurements for 8 trees of 176 trees in the study plot (NO.1-8) started in 1998 as a preliminary experiment of this study. The species, DBH, height at the top and at the first living branch are summarized in Table 2. KURAJI *et al.* (1997) and MANFROI *et al.* (2004) describe in detail how the stemflow collector was attached to the trunks. Stemflow volume of larger trees (NO.1-6) was measured automatically by a covered tipping bucket rain gauge (NO.34-T, Ohta Keiki, resolution 15.7 ml) with a data logger (KADEC-UP, Kona System Co.), respectively. Stemflow discharge during a heavy shower shows an enormous water flux that may cause water loss from the tipping buckets. That is, the water volume per 1 tip becomes larger in a heavy rainfall than 15.7 ml. Thus, the relationship between the discharge rate (ml $10\text{min}^{-1}$) and the real water volume per 1 tip (ml $1\text{tip}^{-1}$) was precisely examined for every tipping bucket before the installation of this study. Stemflow volumes generated by Trees NO.7 and 8 were stored in 10-L plastic bottles and were measured manually as a part of the daily observation. The stemflow observation of each tree ended when the collector ceased functioning because of tree growth. The duration for the stemflow measurement of each tree summarized in Table 2. Stuffing often occurred inside the stemflow collector, judging from comparisons of time distribution of stemflow volume with that of rainfall. Such data were excluded from the analysis. Table 2 shows the number of rainfall event when the collector functioned properly for each tree.

A previous interception study at the Kog-Ma watershed (TANGTHAM, 1973) showed that the stemflow was only 0.90 % of gross rainfall. It was supposed that the upper story trees played a dominant role in generating total stemflow in the study plot. Therefore, trees with DBH >10 cm are selected for stemflow measurement in this study, although there are a lot of understory trees with DBH < 10 cm in the study plot (Table 1).

Table 2. DBH, height at the top and at the first living branch, the observation period and the number of rainfall events, for which stemflow was measured, of the each tree for stemflow measurement in the KogMa watershed

| Tree NO. | Spiecies | DBH (cm) | Height | | Period (Start/End) | Number of rainfall event[*2] (times) |
|---|---|---|---|---|---|---|
| | | | at the top (m) | at first living branch (m) | | |
| 1 | *Castanopsis acuminatissima* | 73.2 | 30.9 | 7.9 | Mar 1998 / May 1999 | 102 |
| 2 | not identified[*1] | 61.4 | 29.5 | 9.5 | Jun 1998 / Dec 1999 | 219 |
| 3 | not identified[*1] | 86.0 | 40.5 | 27.3 | Mar 1998 / Dec 1999 | 55 |
| 4 | *Helicia nilagirica* | 24.0 | 18.5 | 3.5 | Jun 1998 / Dec 2000 | 288 |
| 5 | not identified[*1] | 48.6 | 24.5 | 7.0 | Jun 1998 / May 1999 | 235 |
| 6 | not identified[*1] | 63.9 | 26.0 | 12.0 | Jun 1998 / Dec 1998 | 69 |
| 7 | *Elaeocarpus lanceifolius* | 13.7 | 13.0 | 8.0 | Jun 1999 / Dec 2000 | 170 |
| 8 | *Phrenaria garrettiana* | 19.7 | 12.0 | 5.5 | Jun 1999 / Dec 2000 | 171 |

*1 The species couldn't be identified, because the tree was too high to access the leaves.

*2 Number of rainfall event when the stemflow collector functioned properly.

## RESULT AND DISCUSSION

### Rainfall

Annual rainfall for 4 years is shown in Table 3. Mean annual rainfall during the study period was 1943.7 mm, which was approximately 140 mm less than the historical mean (CHUNKAO *et al.*, 1981). The maximum annual rainfall was 2481.2 mm in 2002 and the minimum was 1641.9 mm in 2000. This difference, exceeding 800 mm, reflects the large inter-annual variation in rainfall at the Kog-Ma watershed. Table 3 shows the annual rain time and the number of rainfall event in each year. In this study, it was defined that an individual rainfall event should have at least 3-hours dry period before and after the event. The annual rain time means a summation of durations of all rainfall events in a year. Annual rain time varied from 434 to 629 hours with a mean of 554 hours for 4 years. Number of rainfall event occurred in each year ranged from 191 to 253 times with a mean number of 222 times. Interestingly, annual rainfall in 1999 was not the maximum for 4 years, although the maximum rain time and number of rainfall event were observed in that year. This evidence suggests that distributions of rainfall size, rainfall intensity and rainfall duration in each year were not constant and varied year to year at this watershed.

Fig. 3(a) shows the monthly rainfall in each year and the mean monthly rainfall for 4 years. It is visible that a little rainfall was observed even in the dry season, and that there were two clear rainfall peaks in the rainy season, one in May and one in August and September. In these wet months, the rainfall normally exceeds 300 mm in the Kog-Ma watershed. In the drought year 2000, rainfall in September and November were remarkably small compared to the normal year. In 2002, the wettest year, rainfall in these two months was especially large. These evidences indicate that the variance in monthly rainfall in September and November is likely to be great in the Kog-Ma watershed.

Fig. 3(b) shows the diurnal variation in rainfall for each year. The rainfall in this watershed had a general peak between 1200-2200 hours, with a maximum between 1500-1700 hours. Rainfall in 2000, the driest year, was characterized by a distinct peak at 1600-1700 hours. By contrast, in 2002, the rainfall was likely to be greater at 1000-2200 hours compared to the normal year.

Table 3. Annual rainfall at the open site (*Rw*) and at the tower top (*Rt*), annual rain time, and number of rainfall events from 1999 to 2002 at the Kog-Ma watershed.

| Year | Rainfall | | Raintime (Hours) | Number of rainfall event* (Times) |
|---|---|---|---|---|
| | at Open Site (*Rw*) (mm) | at Tower Top (*Rt*) (mm) | | |
| 1999 | 1857.0 | — | 629 | 253 |
| 2000 | 1641.9 | 1629.5 | 434 | 204 |
| 2001 | 1794.5 | 1837.0 | 534 | 191 |
| 2002 | 2481.2 | 2503.9 | 621 | 239 |
| 4-years average | 1943.7 | — | 554 | 222 |

* In this study, it was defined that an individual rainfall event should have at least 3-hours dry period before and after the event.

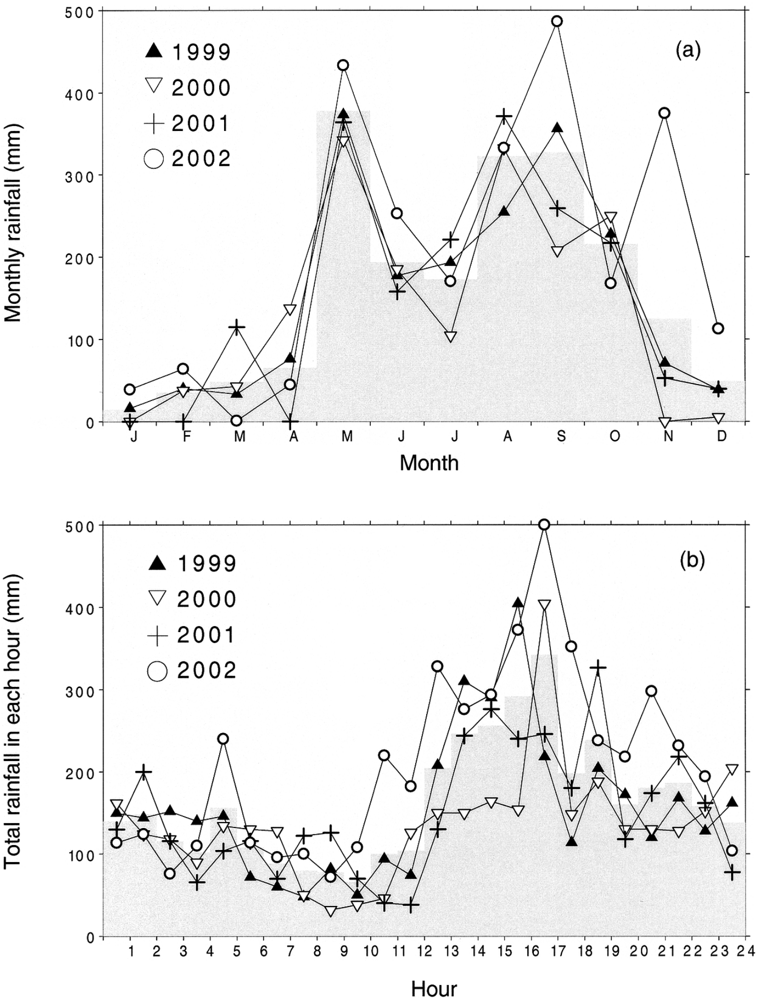

Fig. 3. (a) Seasonal and (b) diurnal variations in rainfall for 4 years at the Kog-Ma watershed. Gray bars indicate the mean rainfall for 4 years.

## Rainfall difference between two sites

Total rainfall for 3 years from 2000 to 2002 at the open site (*Rw*) and at the top of the tower (*Rt*) was 5917.6 mm and 5970.4 mm, respectively. Difference of the rainfall between two sites was 52.7 mm, or < 1 % of the total rainfall. *Rt* may be more suitable than *Rw* as *R* in the calculation of Equation (1), because the tower site is closer than the open site to the interception study site. However, it is possible that rainfall observations above the canopy caused serious systematic underestimations of rainfall due to the effect of wind (MANOKARAN, 1979, VALENTE *et al.*, 1997, CROCKFORD and RICHARDSON, 2000). Thus, more consideration should be necessary to assign *Rt* value to Equation (1).

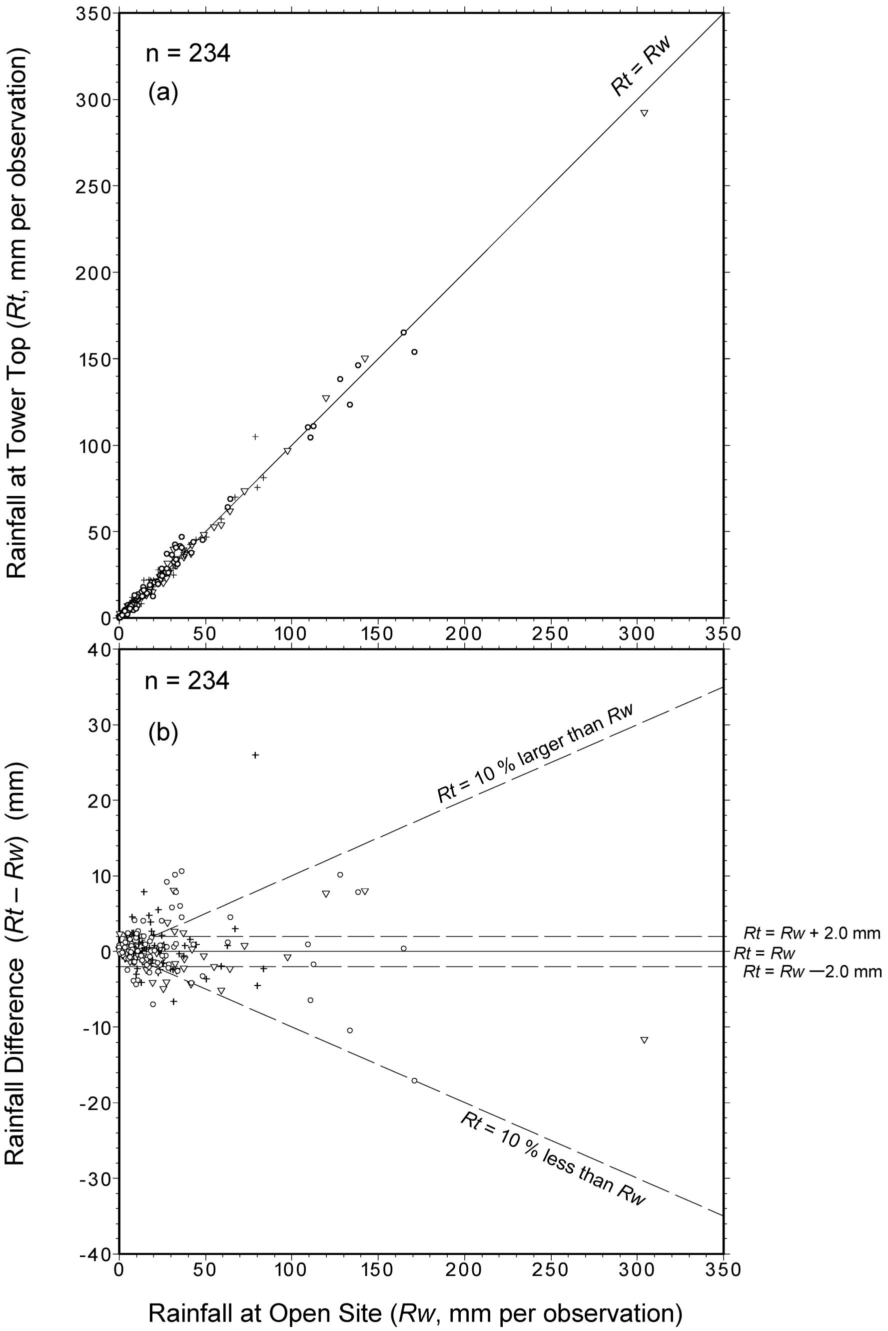

Fig. 4. Comparison of rainfall per observation at open site (*Rw*) with that at tower top (*Rt*). The vertical axis in (b) indicates the rainfall difference subtracting *Rw* from *Rt*. Rainfall in 2000, 2001 and 2002 are indicated by inverted triangles (▽), cross lines ( + ) and blank circles (○), respectively.

LABUDOMLERT *et al.* (1975) conducted rainfall observation for one year at ten sites with different altitudes from 1,300 to 1,600 m.a.s.l. in the Kog-Ma watershed, and derived the following relationship between annual rainfall and altitude:

$$Y = 1970.6 + 1.2 \cdot (X - 1300) \qquad (3)$$

where $Y$ is annual rainfall (mm) and $X$ is altitude (m.a.s.l.). The elevation difference between the open site and the tower basement in this study is approximately 20 m. Equation (3) predicts that the annual *Rt* should be 24 mm greater than the annual *Rw*. The observed rainfall differences between the two sites (*Rt* - *Rw*) in 2000, 2001, 2002, and for the 3-year total were –12.5, + 42.5, + 22.7, and + 52.7 mm, respectively. The differences in 2001 and 2002 were consistent with Equation (3), although some wind-induced loss of rainfall may have affected the *Rt* observation in 2000. However, the difference of + 52.7 mm for the three years agrees with Equation (3). Thus, we can conclude that no serious underestimation of rainfall occurred in the observation at the top of the tower.

*Rw* and *Rt* measured daily (hereafter observation-based *Rw* and *Rt*) for each year are plotted in Fig. 4(a). In general, these rainfall amounts are similar. Fig. 4(b), which emphasizes the difference between *Rw* and *Rt*, clearly shows the large variation in observation-based rainfall. Rainfall at two sites differed by less than 1 mm for 118 of 234 observations. However, it differed by more than 2 mm and 5 mm for 76 and 21 observations, respectively. Further, the rainfall differed by more than 10 % for 47 % of all observations. Table 4 summarizes the number of observations, the result of which showed $Rw < Rt$ and $Rw > Rt$, respectively. It is obviously found that the number of $Rw > Rt$ and $Rw < Rt$ observations are roughly equivalent in each year. There was no evidence that observation-based rainfall at one site systematically exceeded that at the other site, *i.e.*, there was no bias. This result suggests that the spatial variation in observation-based rainfall in the Kog-Ma watershed resulted in the rainfall difference between the two sites, even though the two sites are only 200 m apart. The annual rainfall at the two sites differed by only 1-2 %, because the differences of observation-based rainfall between the two sites was not accumulated systematically but was canceled with each other.

Table 4. Comparison between observation-times, when $Rt > Rw$ and $Rt < Rw$ for 3 years at the Kog-Ma watershed.

| Year | Number of comparable observations | | | Number of missing observations at *Rt* (not comparable) (times) |
|---|---|---|---|---|
| | Total (times) | $Rt > Rw$ (times) | $Rt < Rw$ (times) | |
| 2000* | 47 | 20 | 27 | 5 |
| 2001 | 82 | 48 | 34 | 12 |
| 2002 | 105 | 56 | 48 | 1 |
| Total | 234 | 124 | 109 | 18 |

* From January to August 2000, the observation at *Rt* was conducted weekly.

CROCKFORD and RICHARDSON (2000) conducted an event-based interception observation at a pine forest and a eucalypt forest, *i.e.* rainfall was observed at two sites, near Canberra, Australia. Annual rainfall at the site is about 680 mm. First, they noted that the rainfall per event differed by 15-20 % for 56 % of events with greater than 10 mm in size, although the two forests were only 500 m apart. Further, they found that difference of total rainfall for these events between the two forests resulted in only 0.8 % of the total rainfall (approximately 600 mm). Though the distance between the two sites in this study was closer than 500 m, the result of this study was similar to

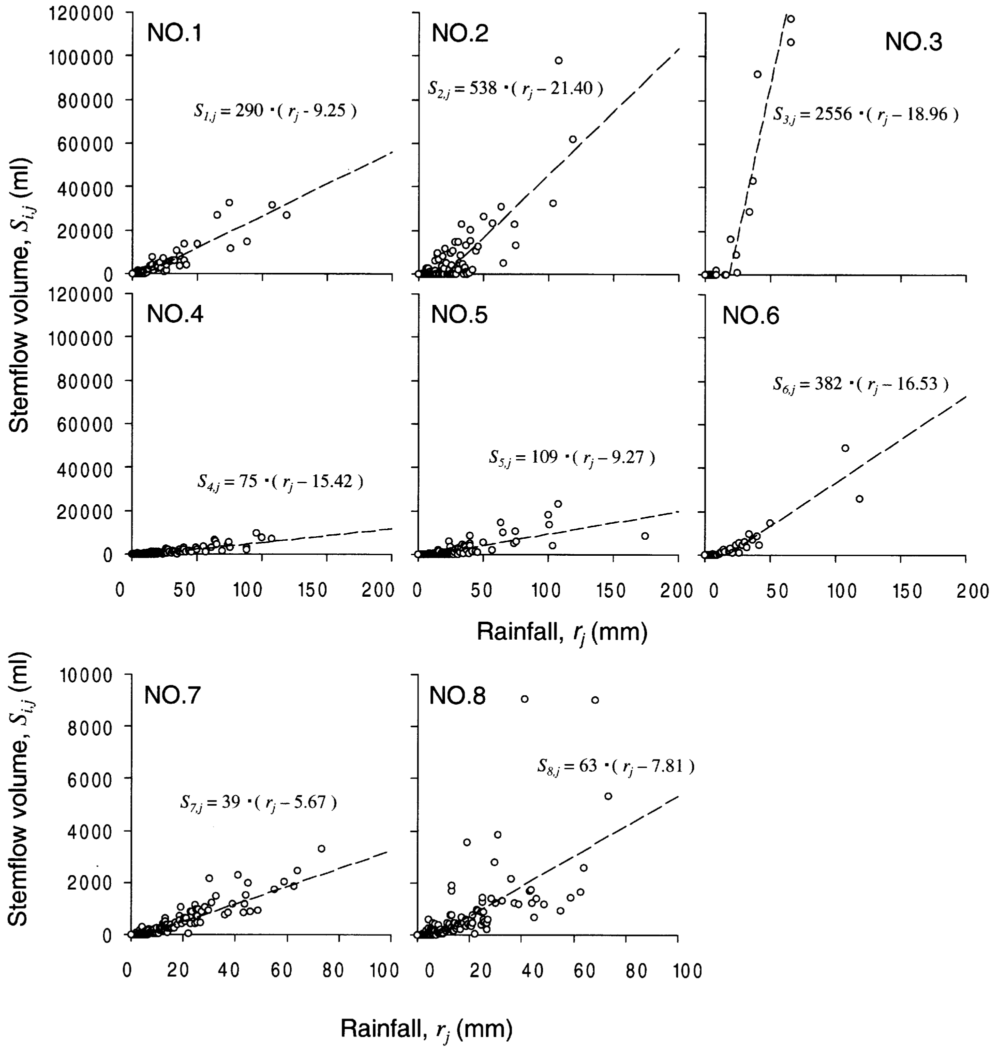

Fig. 5. Relationship between rainfall and stemflow volume generated by 8 trees. Regression lines determined from the relationships between the rainfall amount and measured stemflow generated by each tree.

that of Crockford and Richardson (2000). Second, they attributed an observed negative interception at the eucalypt forest to genuine difference in rainfall between a study plot and a rain gauge, which were only 50 m apart. The evidence suggests that the observation-based rainfall just above the interception study site of this study, which was 250 m and 50m apart from *Rw* and *Rt*, respectively, should be determined carefully. However, it may be considered that the annual rainfall, *i.e.* periodical rainfall, at just above the interception study site ranged between *Rt* and *Rw*.

## Stemflow

Fig. 5 shows the relationship between *Rw* and stemflow volume produced by each tree for each rain event. The number of data illustrated in each figure is shown in Table 2. Dot lines in Fig. 6 indicate regression lines of these relationships. The regression lines of trees with DBH > 20 cm (Trees NO.1-6) and DBH < 20 cm (Trees NO.7-8), were determined using stemflow volumes that were generated during rainfall events with totals exceeding 20 mm and 10 mm in size, respectively. The slope of each regression line (hereafter stemflow coefficient $a_i$, for Trees $i = 1$, 8) indicates the rate of stemflow volume generated per 1-mm rainfall, after the initial wetting of trunks terminated. The $x$-intercept of each regression line (hereafter stemflow coefficient $b_i$, for Trees $i = 1$, 8) reflects the critical amount of rainfall required for stemflow to start. Fig. 6(a) and 6(b) summarize $a_i$ and $b_i$ in relation to DBH of each tree, respectively. Stemflow coefficient $a_i$ is frequently correlated to basal area or DBH$^2$ (*e.g.* Crockford and Richardson, 1990, Kuraji *et al.*, 1997). However, stemflow coefficient $a_i$ correlated to DBH$^3$ better than to DBH$^2$ in this study. Therefore, the relationship between $a_i$ and DBH was expressed as a solid regression curve as shown in Fig. 6(a). Relationship between stemflow coefficient $b_i$ versus DBH shows a large variation (Fig. 6(b)). In this study, assuming that $b_i$ varies linearly with DBH for each tree, $b_i$ was expressed as a solid regression line in Fig. 6(b).

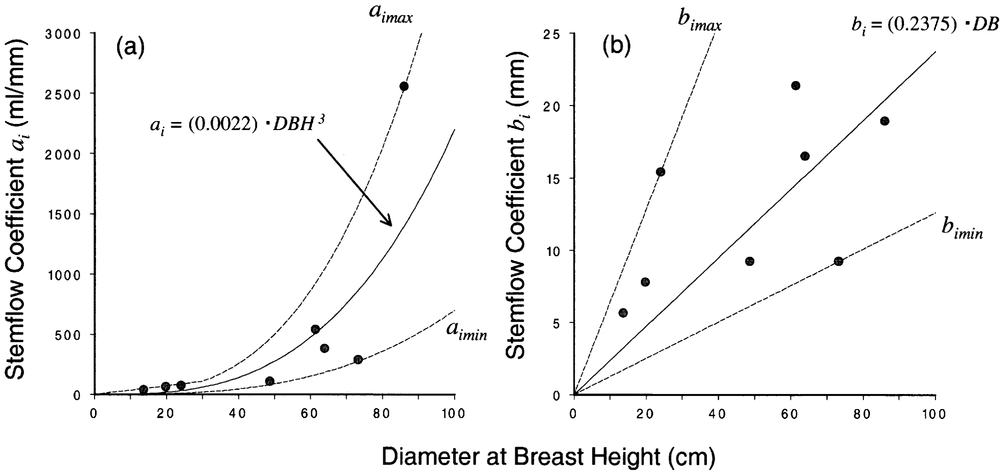

Fig. 6. Relationship between DBH and stemflow coefficients of 8 trees in the Kog-Ma watershed. (a) stemflow coefficient $a_i$, (b) stemflow coefficient $b_i$

To estimate stemflow volumes generated by the rest of 168 trees ($i$, from 9 to 176) in the interception study plot, stemflow coefficient $a_i$ and $b_i$ for these trees were determined by the regression curve and line shown in Fig. 6, respectively. Stemflow volume ($S_{i,j}$) generated during an individual rain event ($j$) for a tree ($i$) can be predicted using the following equation (4):

$$S_{i,j} = a_i \cdot ( r_j - b_i ) \quad \text{when } r_j \geq b_i \qquad (4)$$
$$S_{i,j} = 0 \quad \text{when } r_j < b_i$$

where $r_j$ is rainfall amount during an individual rainfall event($j$). Stemflow volumes (in ml) produced by all 176 trees during each rainfall event were calculated. If $S_{i,j}$ was observed properly, *i.e.*, stemflow volume shown in Fig. 5, the observed $S_{i,j}$ was used instead of the calculated $S_{i,j}$. Annual stemflow in water-depth equivalent ($SF$, in mm) can be obtained by dividing the annual total stemflow volume by the area of the study plot:

$$SF\,(\text{mm}) = [\Sigma\, \Sigma\, S_{i,j}\,(\text{ml}) \,/\, \{\, 3000\,(\text{cm}) \times 3000\,(\text{cm})\}] \times 10\,(\text{mm}) \qquad (5)$$

where $j$ (the number of rain events) in 1999, 2000, 2001, and 2002 is 253, 204, 191, and 239, respectively. The annual computed $SF$ for the Kog-Ma watershed in 1999, 2000, 2001, and 2002 was 28.4 mm, 25.1 mm, 27.5 mm and 37.9 mm, respectively, or 1.5 % of the annual rainfall in each year (Table 5). This fraction is remarkably small compared to $SF$ fractions reported for Japanese coniferous forests, *e.g.*, 10.0 and 12.0 % at cypress forests (HATTORI *et al.*, 1982, KURAJI *et al.*, 2001), and 6.0-6.6 % at a larch forest (MURAI, 1970). However, the present fraction was similar to reported $SF$ fractions for tropical forests in Southeast Asia and South America: 1.4 % (ASDAK *et al.*, 1998), 1.4 % (UBARANA, 1996), and 0.9 % for this watershed (TANGTHAM, 1973).

A recent interception research at a lowland tropical forest in Sarawak, Malaysia (MANFROI *et al.*, 2004) found a $SF$ fraction of 3.5 %, as a result of an intensive stemflow measurement for all trees with DBH > 1 cm in a 10×10 m plot. This fraction was more than double of the reported value in lowland tropical forests. Further, MANFROI *et al.* (2004) found that stemflow generated by understoty trees with DBH < 1 cm accounted for 77 % of total stemflow for that forest. In this study, stemflow produced by such small trees was not observed, but was estimated, although there were many understory trees in the study plot. Therefore, error in estimating stemflow at the Kog-Ma watershed was discussed as follows. The possible ranges of stemflow coefficients $a_i$ and $b_i$ can be expressed as the upper and the lower envelope curves in Fig. 6(a) and 6(b), respectively. Each curve shown in Fig. 6(a) and 6(b) were determined by eyesight and are expressed as follows:

$$a_{imax} = (0.0040) \cdot DBH^3 \quad \text{when } DBH \geq 30\ (\text{cm}) \qquad (6)$$
$$= (3.6) \cdot DBH \quad \text{when } DBH < 30\ (\text{cm})$$
$$a_{imin} = (0.0007) \cdot DBH^3$$
$$b_{imax} = (0.6423) \cdot DBH$$

$b_{imin} = (0.1264) \cdot DBH$

Possible maximum $S_{i,j}$ at the Kog-Ma watershed were calculated using Equation (4) and $a_{imax}$, which will generate more stemflow volume than the regression curve, and $b_{imin}$, which will generate stemflow with less rainfall than the regression line. Also, a possible minimum $S_{i,j}$ can be calculated using stemflow coefficients $a_{imin}$ and $b_{imax}$ in Equation (4). Table 5 summarizes the possible maximum and minimum stemflow at the Kog-Ma watershed. The estimated annual maximum stemflow was 55.4, 49.0, 53.6, and 73.9 mm for 1999, 2000, 2001, and 2002, respectively. These values are 20-40 mm greater than the annual stemflow estimated from the regression curves. The maximum *SF* increased to 3.0 % of the annual rainfall, which is close to the fraction reported in MANFROI *et al.* (2004). By contrast, the minimum stemflow at the Kog-Ma watershed is approximately 10 mm, or only 0.5 % of annual rainfall. This small value is identical to the stemflow in lowland tropical forest reported MANOKARAN (1979). Table 6 shows the stemflow contributions generated by each DBH class to the total stemflow for 4 years. The original estimate from the regression line shows that almost half of the total stemflow was produced by the two upper story trees with DBH > 90 cm. Only 0.1 % of the total stemflow was generated by understory trees with DBH < 10 cm. This small contribution by understory trees increases to 4.1 %, if the stemflow is calculated using the maximum combination of stemflow coefficients in Equation (4). However, the small contribution of understory trees is contrary to MANFROI *et al.* (2004). Stemflow observation problems in this study are attributed to the

Table 5. Annual amounts of estimated stemflow, the possible maximum stemflow and the possible minimum stemflow for 4 years at the Kog-Ma watershed.

| Year | Rainfall at Open Site (*Rw*) | Stemflow Estimated by | | | | | |
|---|---|---|---|---|---|---|---|
| | | The regression curves | | Maximum combination of stemflow coefficients | | Minimum combination of stemflow coefficients | |
| | (mm) | (mm) | (% *Rw*) | (mm) | (% *Rw*) | (mm) | (% *Rw*) |
| 1999 | 1857.0 | 28.4 | (1.5%) | 55.4 | (3.0%) | 9.0 | (0.5%) |
| 2000 | 1641.9 | 25.1 | (1.5%) | 49.0 | (3.0%) | 8.0 | (0.5%) |
| 2001 | 1794.5 | 27.5 | (1.5%) | 53.6 | (3.0%) | 8.7 | (0.5%) |
| 2002 | 2481.2 | 37.9 | (1.5%) | 73.9 | (3.0%) | 12.1 | (0.5%) |
| 4-years total | 7774.7 | 119.0 | (1.5%) | 231.9 | (3.0%) | (37.9) | (0.5%) |

Table 6. Contribution to the stemflow produced by each DBH class to the total stemflow at the Kog-Ma watershed for 4 years.

| Estimated by | DBH class (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | >90 |
| The regression curve (%) | 0.1 | 0.8 | 1.4 | 2.6 | 10.1 | 8.4 | 4.1 | 6.1 | 19.2 | 47.2 |
| The maximum combination of stemflow coefficients (%) | 4.1 | 3.1 | 1.7 | 2.4 | 9.4 | 7.8 | 3.8 | 5.7 | 17.9 | 44.0 |

extrapolation of stemflow coefficients of understory trees as shown in Fig. 6(a). Measurement and analysis of the stemflow by these small trees at the Kog-Ma watershed is a topic of future research.

As a result of an estimation annual stemflow in the study plot using the stemflow data for eight trees, it is found that 1.5 % of annual rainfall was partitioned as stemflow at the Kog-Ma watershed. Considering the error of the stemflow estimation, it is found that the possible maximum and minimum stemflow was 3.0 and 0.5 % of annual rainfall, respectively. Whether or not, the stemflow fraction was as small as the stemflow in the lowland tropical rain forests.

## Annual Throughfall

*TF* per observation was determined by the average value of 30 throughfall collectors. Annual *TF* and its 95 % confidence limit at the Kog-Ma watershed in 1999, 2000, 2001 and 2002 were 1857.0 ± 89.0, 1641.9 ± 76.5, 1794.5 ± 88.7, and 2481.2 ± 111.1 mm, respectively (Table7). The throughfall amounts showed large fractions of 86-91 % to annual *Rw*. Fig. 7 shows the cumulative *Rw* and *TF*. For understanding the spatial distribution of throughfall in the study plot, Fig. 7 illustrates the two cumulative throughfall, which were observed by collectors showing the maximum and minimum annual throughfall, respectively, and the cumulative standard deviation among 30 throughfall observed by each collectors (S.D.). It is clearly visible how the spatial

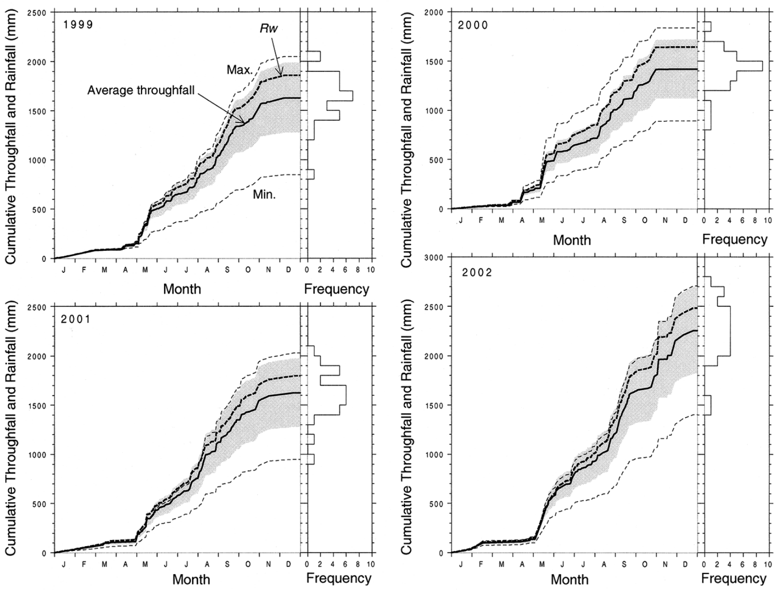

Fig. 7. The cumulative average throughfall (solid lines) and the *Rw* (thick dot lines) in each year at the Kog-Ma watershed. Ranges of cumulative standard deviations among 30 throughfall amounts measured by each collector (gray areas) and the cumulative throughfall of the collectors (thin dot lines), which showed the maximum and the minimum annual throughfall, are illustrated for indicating the distribution of throughfall. The frequency distribution of throughfall in each year are shown on the right of each cumulative figure.

Table 7. 4-years throughfall, its fraction to the annual rainfall and its coefficient of variation in the Kog-Ma watershed. Total number of observations conducted in every year and also number of observations, when the average of throughfall exceeded the rainfall at open site were shown in this table.

| Year | Rainfall at open site (*Rw*) | Throughfall | | | Number of observations | Number of observations, when the average throughfall exceeded *Rw* |
|---|---|---|---|---|---|---|
| | | Amount (mm) | Fraction to annual rainfall | Coefficient of Variation* | | |
| 1999 | 1857.0 | 1629.3 | 87.7% | 0.146 | 125 | 17 |
| 2000 | 1641.9 | 1418.5 | 86.4% | 0.144 | 77 | 4 |
| 2001 | 1794.5 | 1625.1 | 90.6% | 0.146 | 88 | 12 |
| 2002 | 2481.2 | 2255.9 | 90.9% | 0.132 | 91 | 11 |
| 4-years total | 7774.7 | 6928.8 | 89.1% | 0.126 | 381 | 44 |

* Coefficient of variation for 30 annual throughfall observed by individual gauge.

variation of throughall at the Kog-Ma watershed was great in every year. For example, not only the maximum throughfall but also *TF* + S.D. exceeded *Rw* in every year. In addition, the minimum throughfall amount in each year was only 46-56 % of annual *TF*. The coefficients of variation among 30 annual throughfall were almost 0.14 in each year. Although these coefficients were quite constant, the frequency distribution of throughfall in each year, shown in Fig. 7, was varied from year to year. These evidences suggest further attempt to consider errors or accuracies of the estimated throughfall will be important, because small errors in throughfall estimation will lead to large errors in estimated interception.

KURAJI and TANAKA (2003) reviewed 106 rainfall interception or hydrogeochemical studies at tropical forests. In 77 of the 106 studies, the area and the number of throughfall collectors were given. Fig. 8 shows the frequency distribution of the total area of the throughfall collectors. Studies in natural forests and logged natural forests, *i.e.*, the forest in the Kog-Ma watershed is a natural forest, are indicated by hatched areas. Fig. 8 shows a great variation in the total collecting area. CALDER *et al.* (1986) used the greatest collecting area, in their interception study in a tropical rain forest of West Java, Indonesia. They used two plastic net rain gauges, each with an area of 400,000 cm$^2$. However, it is found that the standard total collecting area of throughfall at the tropical forests normally ranges from 8,000 to 12,000 cm$^2$. The total collecting area of this study was 10,386 cm$^2$, which was within the standard range. In general, the increase in total collecting area of throughfall gauges reduces errors of the estimated throughfall. Therefore, it is possible to consider that *TF* in this study was enough confident to assign to Equation (1).

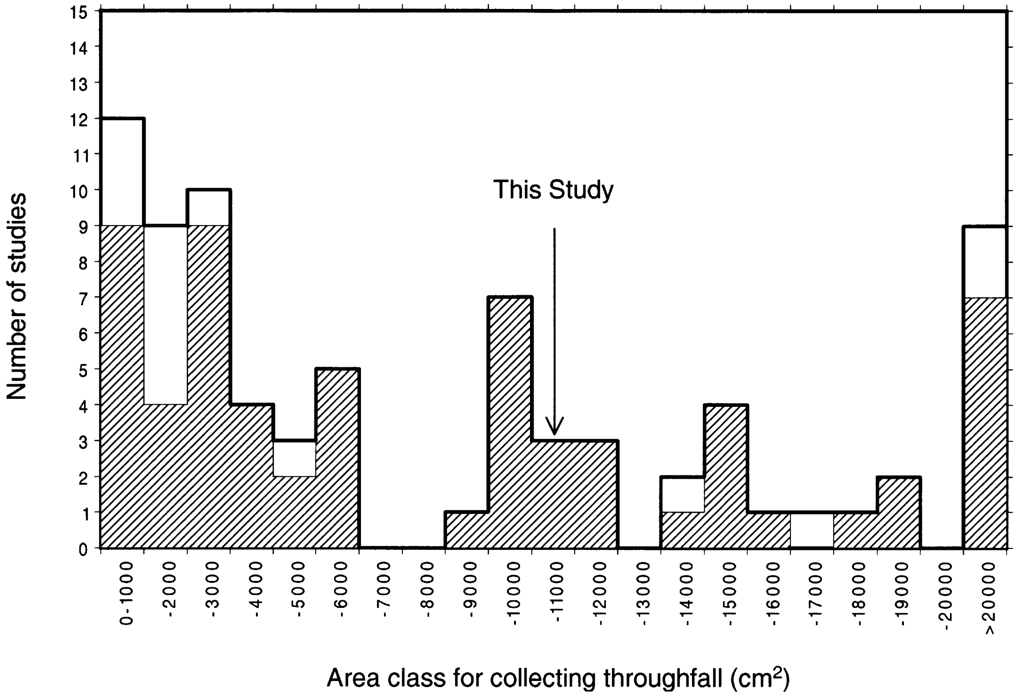

Fig. 8. Frequency distribuntion of total area for collecting throughfall in hydrological or ecological studies in tropical/subtropical forests all over the world (Number of studies, n = 77). Hatched area indicates the number of studies on natural forests or logged forests, while blank block means those on man-made forests. The total area of throughfall collector in this study are shown in the figure with an arrow. This figure are modified from KURAJI and TANAKA (2003).

## Observation-based Throughfall

Fig. 9 shows the relationship between observation-based *TF* and *Rw*. It is visible that *TF* occasionally exceeded *Rw* in every year. The number of observation, when *TF* exceeded *Rw*, in 1999, 2000, 2001, and 2002 was 17, 4, 12, and 11 times, respectively. That is, observation-based *TF* exceeded *Rw* in 12 % of all observations for 4 years. Two factors can explain these extra values. First, rainfall was occasionally underestimated, *i.e.*, the observation-based rainfall just above the interception study plot was occasionally greater than *Rw* (hereafter underestimation effect). This is quite possible to occur, as considering the observation-based rainfall difference between *Rw* and *Rt*. Such an effect has also been found not only at a eucalypt forest in Australia (CROCKFORD and RICHARDSON, 2000) but also at lowland tropical forests in Peninsular Malaysia (MANOKARAN, 1979) and Kalimantan, Indonesia (ASDAK *et al.*, 1998). Second reason is additional precipitation, which was produced by fog occurrence, to the forest canopy in the Kog-Ma watershed (hereafter fog effect). As mentioned in the site description of this paper, fog occasionally covered the Kog-Ma watershed. Although this study could not address the effect of such fog effect, a number of studies, conducted in other TMCFs, reported that throughfall sometimes exceeded gross rainfall because of the fog occurrence (*e.g.*, VENEKLAAS and VAN EK,

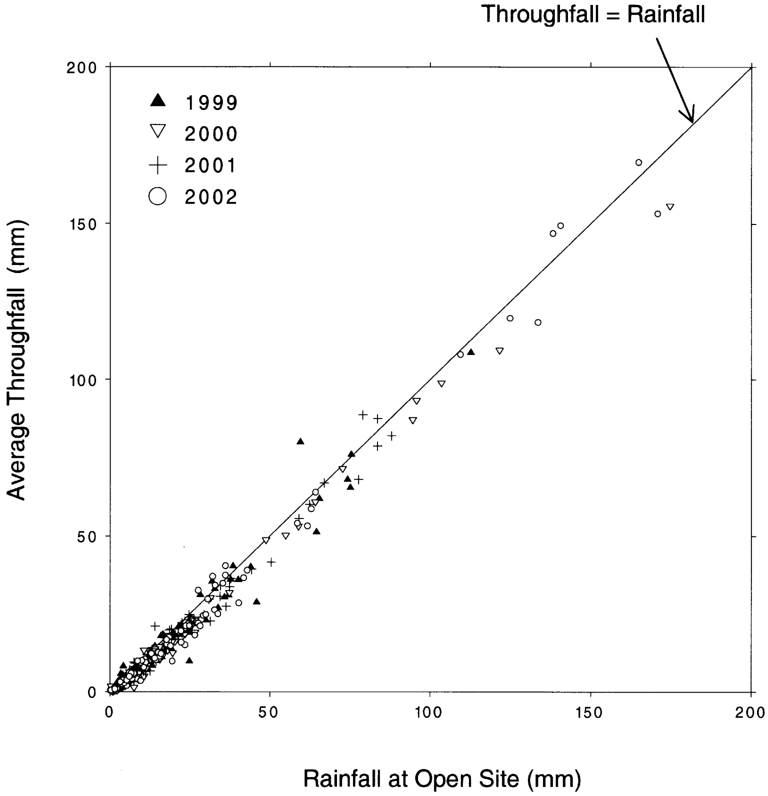

Fig. 9. Relationship between rainfall per a observation at open site (*Rw*) and the average throughfall observed in the Kog-Ma watershed for 4 years.

1990, CAVALIER *et al.*, 1997, HUTLEY *et al.*, 1997). The extra observation-based *TF* in this study should be caused by either of the effects or both. Also, it is supposed that not only the extra *TF* but also the rest *TF* with normal value might have the both effects. Further, the underestimation effect probably couple with ‘the overestimation effect’ simultaneously. Normal interception studies have analyzed the relationship between the event-based rainfall and throughfall (*e.g.* LLORENS *et al.*, 1997, LINK *et al.*, 2004), and presented the specific canopy storage capacity (*e.g.* KLAASSEN *et al.*, 1998). However, it is appropriate that the observation-based *TF* in the Kog-Ma watershed should be discussed after evaluating the two potential sources of error identified above. That is, further attempts to understand the spatial distribution of the observation-based rainfall at the Kog-Ma watershed, and to clarify the effects of fog precipitation, will be important.

## Rainfall Interception

Annual interception (*Iw*) in 1999, 2000, 2001, and 2002 at the Kog-Ma watershed, calculated using Equation (1) with *Rw*, was 199.3, 198.3, 141.9, and 187.4 mm, respectively (Table 8). There is a large variation in annual rainfall, though the variation in annual *Iw* was relatively small. The

Table 8. Annual rainfall, throughfall, stemflow and interception in Kog-Ma watershed

| Year | Rainfall | | Throughfall ($TF$) | Stemflow ($SF$) | Interception | | | |
|---|---|---|---|---|---|---|---|---|
| | at Open Site ($Rw$) (mm) | at Tower Top ($Rt$) (mm) | (mm) | (mm) | ($Iw$) (mm) | ($Iw$) (% to $Rw$) | ($It$) (mm) | ($It$) (% to $Rt$) |
| 1999 | 1857.0 | — | 1629.3 | 28.4 | 199.3 | 10.7% | — | — |
| 2000 | 1641.9 | 1629.5 | 1418.5 | 25.1 | 198.3 | 12.1% | 185.8 | 11.4% |
| 2001 | 1794.5 | 1837.0 | 1625.1 | 27.5 | 141.9 | 7.9% | 184.4 | 10.0% |
| 2002 | 2481.2 | 2503.9 | 2255.9 | 37.9 | 187.4 | 7.6% | 210.1 | 8.4% |
| 4-years total | 7774.7 | — | 6928.8 | 119.0 | 726.9 | 9.3% | — | — |

annual *Iw* in the drought year (2000) exceeded the annual *Iw* in 2001 and 2002. The annual *Iw* in 1999 and 2002 were almost identical, although annual *Rw* in the two years differed by approximately 600 mm. The similarity in *Iw* may reflect the similarity in the number of rainfall events and rain time in 1999 and 2002. In general, however, it is very difficult to relate the inter-annual variation in *Iw* to annual rainfall, annual rain time, and annual number of rainfall event in the Kog-Ma watershed.

The annual *Iw* was 10.7, 12.1, 7.9, and 7.6 % of the annual *Rw* for 1999, 2000, 2001, and 2002, respectively. Inter-annual variation in *Iw*/*Rw* ratio was variable at the Kog-Ma watershed, while the monitoring installation was consistent during the study period. This indicates that the relationship between annual rainfall and annual interception could not be expressed as a simple linear relationship for the Kog-Ma watershed. The result suggests that inter-annual variations in rainfall characteristics, meteorological conditions in rain time, and fog precipitation were presumably great at this watershed.

Five interception studies in tropical or sub-tropical forests, in which annual interception for several years were clearly described, were found. No clear account for the inter-annual variation in interception was found in these literatures. Three of the studies found larger annual interception in years with lager rainfall (PEREIRA, 1952, LUNDGREN and LUNDGREN, 1979, SCHELLENKENS *et al.*, 2000b). By contrast, ZULKIFLI (1996) found larger annual interception in years with less rainfall in secondly forest in Peninsular Malaysia. YADAV and MISHRAL (1985) studied at mix dry deciduous forest in India and found constant annual interception for 2 years, while the rainfall for the 2 years differed by 400 mm. Such variable results suggest that there is no consistent relationship between annual rainfall and annual interception. Interception ratio to annual rainfall at a specific forest is often cited in papers. However, the result of this study shows the risk of using such a value without considering its variability.

As mentioned in the result on rainfall observation in this study, it can be considered that the annual rainfall just above the interception study site ranged from annual *Rw* to *Rt*. Given that rainfall interception calculated by assigning *Rt* to Equation (1) is *It*, the annual interception at the Kog-Ma watershed ranged from *Iw* to *It*. Fig. 10 illustrates *Iw* and *It* in comparison with cumulative *Rw*, *Rt*, *TF* and *SF* for each year. Considering the observation error in annual rainfall,

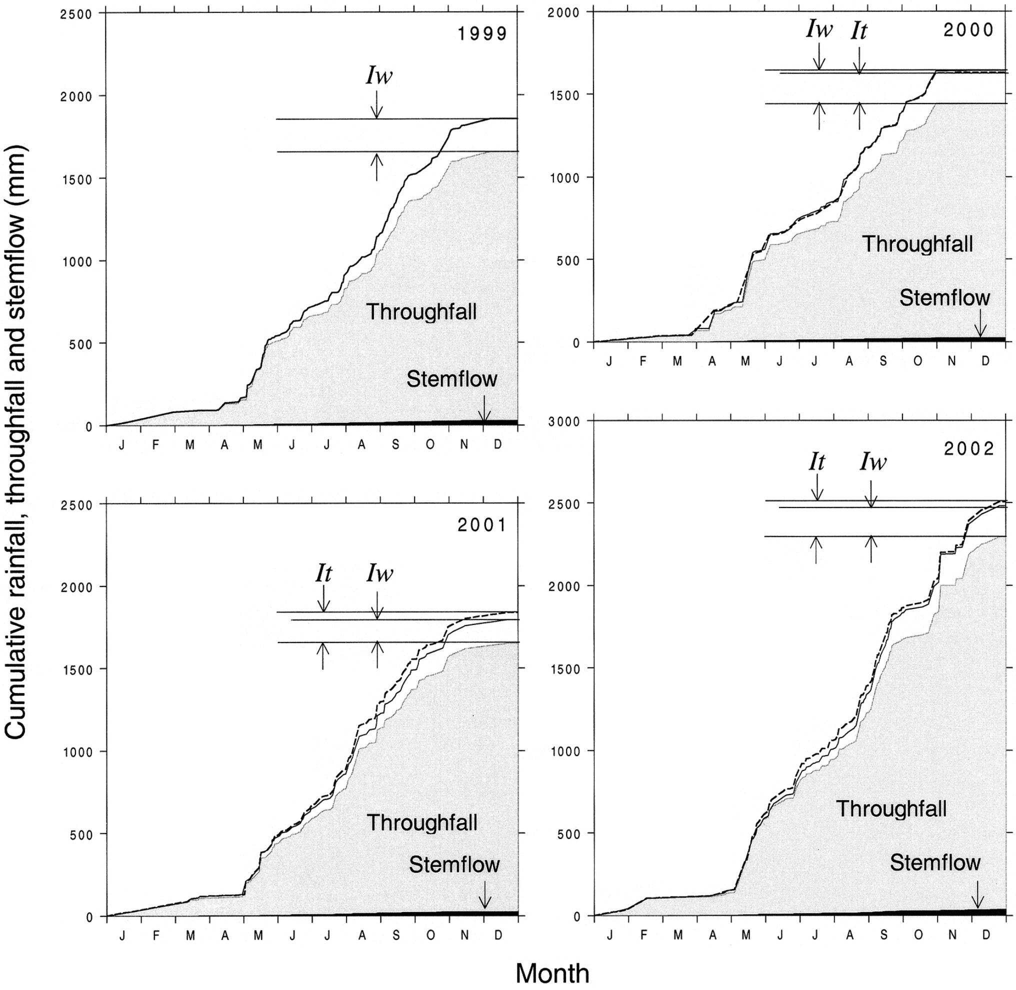

Fig. 10. Cumulative *Rw* (solid line), *Rt* (dot line), throughfall (gray area) and stemflow (black area) in each year at the Kog-Ma watershed. Annual interception in each year is shown as the difference between rainfall and the sum of throughfall and stemflow.

the possible range of annual interception at the Kog-Ma watershed in 2000, 2001, and 2002 was 185.8 to 199.8, 141.9 to 184.4, and 187.4 to 210.1 mm (Table 8). There is enough confidence in these ranges of rainfall interception in each year to apply them to a parameterization of a model that describes the evapotranspiration in the Kog-Ma forest.

Nevertheless, as described in the method section (see also Equation (2)), the presented interception can be defined as 'the apparent interception', which is the amount after *FP* has been subtracted from 'the genuine interception'. NAKAGAWA *et al.* (1998) conducted a hydrogeochemical study at the Kog-Ma watershed, in 1994, and indicated that annual rainfall and throughfall in 1994 were 2784 and 2969 mm, respectively. They attributed the difference to the

Table 9. Rainfall interception reports conducted in Thailand[*1] and lowland tropical forest in Southeast Asia.

| Forest Type | Fraction to annual rainfall (%) | | | Reference |
|---|---|---|---|---|
| | Interception | Throughfall | Stemflow | |
| Natural forest in Thailand | | | | |
| Hill evergreen | 5.10 | 94.00 | 0.90 | TANGTHAM (1973) |
| Hill evergreen | 10.7 | 87.8 | 1.5 | *This study* (in 1999) |
| Hill evergreen | 12.1 | 86.4 | 1.5 | *This study* (in 2000) |
| Hill evergreen | 7.9 | 90.6 | 1.5 | *This study* (in 2001) |
| Hill evergreen | 7.6 | 90.9 | 1.5 | *This study* (in 2002) |
| Moist evergreen | 8.90 | 91.30 | 0.52 | TAKAHASHI et al. (1983) |
| Dry evergreen[*2] | 4.10 | 37.80 | 0.97 | CHUNKAO et al. (1971) |
| Dry evergreen | 30.40 | 39.40 | 0.22 | WITTHAWATCHUTIKUL and SUKSAWANG (1987) |
| Deciduous with Teak[*2] | 62.70 | 37.40 | 0.02 | CHUNKAO et al. (1971) |
| Mixed Deciduous with Teak | 39.20 | 60.00 | 0.20 | CHUNPAGA and WACHIRAJUTIPONG (1977) |
| Dry dipterocarp[*2] | 61.00 | 39.10 | 0.01 | CHUNKAO et al. (1971) |
| Bamboo (*Gigantochloa nigruciliata*) | 69.80 | 24.10 | 6.10 | SAENGKOOVONG et al. (1985) |
| Bamboo (*Dendrocalamas membranaceus*) | 75.70 | 23.50 | 0.80 | SAENGKOOVONG et al. (1985) |
| Plantation in Thailand | | | | |
| *Acasia auriculaeformis* | 31.00 | 67.60 | 1.40 | PAUNGCHARCON (1987) |
| *E. camandulensis* (3-years old) | 15.70 | 82.10 | 2.20 | PUKJALOON et al. (1984) |
| *Hopea odorata* | 36.00 | 62.00 | 2.00 | SONGWATTANA et al. (1988) |
| *Tectona grandis*, Linn. f. (Teak) | 36.11 | 61.92 | 1.97 | CHAROENSUK et al. (1989) |
| *Melia azedarach* | 24.60 | 75.40 | 1.45 | JIRASUKTAVEEKUL et al. (1987) |
| *Leucaena Leucocephala* | 26.00 | 72.50 | 1.50 | PUKJALOON et al. (1985) |
| *Leucaena Leucocephala* | 26.06 | 72.52 | 1.42 | ONARSA (1995) |
| Unlogged lowland tropical forest in Southeast Asia | | | | |
| West Java, Indonesia | 20.87 | 79.13 | — | CALDER et al. (1986) |
| Unlogged forest at Central Kalimantan, Indonesia | 11.0 | 87.6 | 1.4 | ASDAK et al. (1998) |
| Brunei | 18.04 | 80.96 | 1[*3] | DYKES (1997) |
| Peninsular Malaysia | 21.80 | 77.56 | 0.64 | MANOKARAN (1979) |
| Peninsular Malaysia | 16.90 | 83.10 | 0.30 | TANI et al. (2003) |
| Sabah, Malaysia | 7.9 | 91.1 | 1[*3] | CHAPPELL et al. (2001) |
| Sarawak, Malaysia | 14.5 | 82.0 | 3.5 | MANFROI et al. (in press) |

[*1] This table are modified from TANGTHAM (1998).
[*2] The observations were conducted only for 2 months in early rainy season.
[*3] The proportion was determined by former reports.

input of fog precipitation in this watershed. In fact, the accuracy of observed throughfall amount in that study is debatable because they used only 5 collectors, each of which had a circular funnel with 22.5-cm diameter. However, this study suggests the significance of *FP* in hydrological processes at the Kog-Ma watershed.

TANGTHAM (1998) reviewed the local reports on rainfall interception by various forest types in Thailand. In addition to this reviewed reports, the results both of this study and of the interception studies at natural lowland tropical forests in Southeast Asia are summarized in Table 9. Lowland forests in Thailand, such as a dry depterocarp forest and mixed deciduous forests, including most of plantations, have interception rates greater than 20 %. By contrast, most interception studies at montane forests in Thailand, such as hill evergreen forests, found interception ratios less than 10 %. KURAJI and TANAKA (2003) reviewed 106 reports of rainfall interception at tropical forests in the world and found that almost all of the observed interception rates ranged from 10 to 20 %. In fact, most of the interception rates that were indicated in Table 9 range from 10 to 20 %. Therefore, rainfall interception by forests in Thailand could be characterized by a contrast in interception rates between lowland forests and montane forests.

## CONCLUSION

A four-years observation of rainfall, throughfall, and stemflow at a hill evergreen forest in northern Thailand found the followings:

(1) The annual rainfall was variable at the Kog-Ma watershed during the study period, ranging from 1641.9 to 2481.2 mm. The annual rainfall at the two neighboring sites differed by only 1-2 %. The difference could be accounted by the altitudinal increase in annual rainfall, which was presented by a previous study at Kog-Ma watershed. On the other hand, the observation-based rainfall at two sites differed by more than 10 % in half of all observations. These results indicated that spatial distribution of rainfall in the Kog-Ma watershed caused the difference in observation-based rainfall between the two sites, even though the two sites are only 200 m apart. However, the annual rainfall at the 2 sites was similar, because the rainfall difference per observation between 2 sites did not accumulated but canceled with each other. We confirmed that annual rainfall at the two sites for each year was confident, and that the annual rainfall just above the interception study site ranged between the annual rainfall at the two sites.

(2) Stemflow observations for 8 trees presented the relationship between tree size and stemflow coefficients, which were determined by regressing stemflow volume vs. rainfall. An attempt to estimate the total stemflow in the study site showed that 1.5 % of annual rainfall, or 25-40 mm per year, was partitioned as stemflow at the Kog-Ma watershed. The estimation error suggests that the possible maximum and minimum stemflow was 3.0 and 0.5 % of annual rainfall, respectively. The stemflow fraction of annual rainfall was as small as the stemflow fractions in lowland tropical rain forests. However, a comparison with a recent report on stemflow at a natural lowland tropical forest in Borneo suggests the significance of measurements and analysis of stemflow for understory trees at the Kog-Ma watershed.

(3) Throughfall observation using 30 collectors showed that 1857.0, 1641.9, 1794.5, and 2481.2 mm of rainfall was partitioned as throughfall at the Kog-Ma watershed in 1999, 2000, 2001 and 2002, respectively. These throughfall amounted to 86-91 % of the annual rainfall. The spatial distribution of througfall within 30×30 m plot was great in every year, which highlights the importance of considering errors or accuracies of the observed throughfall. In addition, it was found that observation-based throughfall occasionally exceeded rainfall every year. These extra throughfall amounts were caused by the occasional underestimations of observation-based rainfall just above the interception study site and by the additional precipitation, which was produced by fog occurrence, to the forest canopy in the Kog-Ma watershed. These problems in analyzing the observation-based throughfall at the Kog-Ma watershed were clarified and confirmed by this study.

(4) Annual interception in 1999, 2000, 2001, and 2002 at the Kog-Ma watershed, was 199.3, 198.3, 141.9, and 187.4 mm, or 10.7, 12.1, 7.9, and 7.6 % of the annual rainfall, respectively. The relationship between annual rainfall and annual interception could not be expressed as a simple linear relationship at the Kog-Ma watershed. The variation in the interception rates over four years suggested the risk in referring a reported interception rate, which was obtained from one-year observation, as a representative value of a forest. Moreover, a consideration of measurement error in annual rainfall just above the interception study site gave the possible range of annual interception at the Kog-Ma watershed. These ranges were 185.8 to 199.8, 141.9 to 184.4, and 187.4 to 210.1 mm for 2000, 2001, and 2002, respectively. These ranges of rainfall interception were confident enough to be applied to the parameterization of the model, which describes the evapotranspiration at the Kog-Ma forest. We assumed that only rainfall contributed to the total precipitation in the forest canopy, although fog precipitation also presumably occurred. That is, underestimations of annual interception could occur if fog precipitation in the Kog-Ma watershed was remarkably large. The significance of analyzing the rainfall interception with respect to fog occurrence was confirmed by this study. Comparison of interception rates between natural lowland tropical forests in Southeast Asia except Thailand and forests in Thailand showed remarkable contrasts. The interception rates at the natural lowland tropical forests in Southeast Asia normally ranged from 10 to 20 %. However, the lowland forests in Thailand showed higher rainfall interception rate than 20 %, while montane forests in Thailand indicated lower rate than 10 %.

## Acknowledgements

This study was funded by Prof. Katsumi MUSHIAKE of Fukushima University (GEWEX Asian Monsoon Experiment in Tropics Project). We thank Hideki TAKIZAWA, the head of field activity, in Nihon University, Natsuko YOSHIFUJI, and Tomonori KUME at the University of Tokyo for supporting our research activities. We thank the local assistants and the driver for daily maintenances in the field and logistical support. We also thank the staffs of Royal Forest

Department for assisting our activity and the staffs of Dui Pui National Park for identifying the tree species. This study is ongoing with funding from the JST (Japan Science and Technology Agency) as CREST research project "Effects of rainfall variability on water cycle and ecosystem in tropical forest under Asian monsoon climate".

## Summary

Rainfall, throughfall, and stemflow at Kog-Ma watershed, which is situated in a hill evergreen forest in northern Thailand, were examined for 4 years 1) to quantify annual throughfall and stemflow, 2) to quantify confident annual interception for four years, 3) to evaluate possible measurement errors of the presented interception, and 4) to understand inter-annual variation in interception. The annual rainfall was variable at the Kog-Ma watershed during the study period, ranging from 1641.9 to 2481.2 mm. The annual rainfall at the two neighboring sites differed by only 1-2 %. The difference could be accounted by the altitudinal increase in annual rainfall, which was presented by a previous study at Kog-Ma watershed. On the other hand, the observation-based rainfall at two sites differed by more than 10 % in half of all observations. These results indicated that spatial distribution of rainfall in the Kog-Ma watershed caused the difference in observation-based rainfall between the two sites, even though the two sites are only 200 m apart. Stemflow observations for 8 trees presented the relationship between tree size and stemflow coefficients, which were determined by regressing stemflow volume vs. rainfall. An attempt to estimate the total stemflow in the study site showed that 1.5 % of annual rainfall, or 25-40 mm per year, was partitioned as stemflow at the Kog-Ma watershed. The estimation error suggests that the possible maximum and minimum stemflow was 3.0 and 0.5 % of annual rainfall, respectively. Throughfall observation using 30 collectors showed that 1857.0, 1641.9, 1794.5, and 2481.2 mm of rainfall was partitioned as throughfall at the Kog-Ma watershed in 1999, 2000, 2001 and 2002, respectively. These throghfall amounted to 86-91 % of the annual rainfall. In addition, it was found that of observation-based throughfall occasionally exceeded rainfall every year. These extra throughfall amounts were caused by the occasional underestimations of observation-based rainfall just above the interception study site and by the additional precipitation, which was produced by fog occurrence, to the forest canopy in the Kog-Ma watershed. Annual interception in 1999, 2000, 2001, and 2002 at the Kog-Ma watershed, was 199.3, 198.3, 141.9, and 187.4 mm, or 10.7, 12.1, 7.9, and 7.6 % of the annual rainfall, respectively. The relationship between annual rainfall and annual interception could not be expressed as a simple linear relationship at the Kog-Ma watershed. Moreover, a consideration of measurement error in annual rainfall just above the interception study site gave the possible range of annual interception at the Kog-Ma watershed. These ranges were 185.8 to 199.8, 141.9 to 184.4, and 187.4 to 210.1 mm for 2000, 2001, and 2002, respectively. These ranges of rainfall interception were confident enough to be applied to the parameterization of the model, which describes the evapotranspiration at the Kog-Ma forest. We assumed that only rainfall contributed to the total precipitation in the forest canopy, although fog precipitation also presumably occurred. That is, underestimations of annual interception could occur if fog precipitation in the Kog-Ma watershed was remarkably large. The significance of analyzing the rainfall interception with respect to fog occurrence was confirmed by this study. Comparison of interception rates between natural lowland tropical forests in Southeast Asia except Thailand and forests in Thailand showed remarkable contrasts. The interception rates at the natural lowland tropical forests in Southeast Asia normally ranged from 10 to 20 %. However, the lowland forests in Thailand showed higher rainfall interception rate than 20 %, while montane forests in Thailand indicated lower rate than 10 %.

**Key words:** rainfall interception by forest canopy, stemflow, throughfall, hill evergreen forest, and spatial distribution of rainfall

## References

AKSORNKAOE, S. and BOONYAWAT, S. (1977) Structure of hill-evergreen forest along the altitude at Doi Pui, Chiengmai. Kog-Ma Watershed Research Bull. No.32, 47pp, Department of Conservation, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

ASDAK, C., JARVIS, P. G., van GARDINGEN, P., and FRASER, A. (1998) Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indoneshia. J. Hydorol. 206: 237-244.

BHUMIBHAMON, S. and WASUWANICH, P. (1970) The structural characteristics of Huay Kog-Ma forest (in Thai with an English abstract). Kog-Ma Watershed Research Bull. 22pp, Department of Conservation, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

BRUIJNZEEL, L. A. and WIERSUM, K. F. (1987) Rainfall interception by a young *Acacia auriculiformis* (A. Cunn) Plantation forest in west Java, Indonesia: Application of Gash's analytical model. Hydrol. Proc. 1: 309-319.

BRUIJNZEEL, L.A., and PROCTOR, J. (1995) Hydrological and biogeochemistry of tropical montane cloud forest: What do we really know? *In* Tropical Motane Cloud Forests. Hamilton, L.S., Juvik, J. O., and Scatena F.N. (eds.), 407pp, Springer-Verlag: New York, 38-78.

CALDER, I. R. (1976) The measurement of water losses from a forested area using a 'natural' lysimeter. J. Hydrol. 30: 311-325.

CALDER, I. R., WRIGHT, I. R., and MURDIYARSO, D. (1986) A study of evaporation from tropical rain forest—west Java. J. Hydrol. 89: 13-31.

CAVELIER, J., JARAMILLO, M., SOLIS, D., and de LEÓN, D. (1997) Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama. J. Hydrol. 193: 83-96.

CHAPPELL, N., KAWI, B., and WLODEK, T. (2001) Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest. Plant Ecol. 153: 215-229.

CHAROENSUK, S., JIRASUKTAVEEKUL, W., and ONARSA, S. (1989) rainfall intercepted by teak plantation. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by Nalanpoon, A., Thitirojanawat, P., and Tippharot, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 39.

CROCKFORD, R. H. and RICHARDSON, D. P. (2000) Partitioning of rainfall into throughfall, Stemflow and interception: Effect of forest type, groud cover and climate. Hydrol. Proc. 14: 2903-2920.

CHUNKAO, K., TANGTHAM, N., and UNGKULPAKDIKUL, S. (1971) Measurements of rainfall in early wet season under hill-and-dry evergreen, natural teak, and dry depteterpcarp forests of Thailand (in Thai with an English abstract). Kog-Ma Watershed Research Bull. No.10. 31pp, Department of Conservation, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

CHUNKAO, K., TANGTHAM, N., BOONYAWAT, S., and NIYOM, W. (1981) Watershed management research on moutanous land (in Thai with an English abstract). 15-year Tentative Report 1966-1980. 32pp, Department of Conservation, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

CHUNPAGA, U. and WATCHIRAJUTIPONG, T. (1977) Interception, throughfall and stemflow of mixed deciduous with Teak forest. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by Nalanpoon, A., Thitirojanawat, P., and Tippharot, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 27.

DICKINSON, R.E. and HENDERSON-SELLERS, A. (1988) Modelling tropical deforestation: a study of GCM land-surface parameterization. Q. J. R. Meteorol. Soc. 114: 439-462.

DYKES, A. P. (1997) Rainfall interception from a lowland tropical rainforest in Brunei. J. Hydrol. 200: 260-279.

FRANKEN, W., LEOPOLDO, P. R., MATSUI, E, and RIBEIRO, M. N. G. (1982) Estudo da interceptação da água de chuva em cobertuna florestal Amazônica do tipo terra firme (in Portuguese with English Summary). Acta Amazonica 12: 327-331.

GASH, J.H.C. and STEWART, J.B. (1977) The evaporation from Thetford Forest during 1975. J. Hydrol. 35: 385-396.

GONZáLEZ, J. (2000) Monitoring cloud interception in a tropical montane cloud forest of the southeastern Colombian Andes. Advances in Environmental and Monitoring and Modelling 1(1): 97-117.

HATTORI, S., CHIKAARASHI, H., and TAKEUCHI, N. (1982) Measurement of the rainfall interception and its meteorological analysis in a Hinoki stand (In Japanese with English abstract). Bull. For. & For. Prod. Res. Inst. 318: 79-102.

HUTLEY, L.B., DOLEY, D., YATES, D.J., and BOONSANER, A. (1997) Water balance of an Australian subtropical rainforest at altitude: The ecological and physiological significance of intercepted cloud and fog. Aust. J. Bot. 45: 311-329.

JIRASUKTAVEEKUL, W., CHAROENSUK, S., and WITTHAWATCHUTIKUL, P. (1987) Rainfall intercepted by *Melia azedarach* Linn. Plantation. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by Nalanpoon, A., Thitirojanawat, P., and Tippharot, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 29.

KLAASSEN, W., BOSVELD, F., and de WATER, E. (1998) Water storage and evapotration as constituents of rainfall interception. J. Hydrol. 212-213: 36-50.

KUMAGAI, T., KATUL, G. G., SAITOH, T. M., SATO, Y., MANFROI, O. J., MOROOKA, T., ICHIE, T., KURAJI, K., SUZUKI, M. and PORPORATO, A. (2004) Water cycling in a Bornean tropical rainforest under current and projected precipitation scenarios. Water Resour. Res., 40(1): W01104, doi:10.1029/2003WR002226.

KURAJI, K., TANAKA, N., SHIRAKI, K., KARAKAMA, I., and OHTA, T. (1997) Effects of windspeed on stemflow volume in masure *Cryptmeria japonica* and *Chamaecyparis obtusa* stand (in Japanese with English abstract). J. Jpn. Sor. Soc. 79: 215-221.

KURAJI, K., TANAKA, Y., TANAKA, N., and KARAKAMA, I. (2001) Generation of stemflow volume and chemistry in a mature Japanese cypress forest. Hydrol. Proc. 15: 1967-1978.

KURAJI, K. and TANAKA, N. (2003) Rainfall interception studies in the tropical forests (in Japanese with English abstract). J. Jpn. For. Soc. 85(1): 18-28.

LABUDOMLERT, P., BOONYAWAT, S., and CHUNKAO, K. (1975) Rainfall variation of small difference elevation of Kog-Ma watershed research station, Chiengmai. Kog-Ma Watershed Research Bull. No.22. 19pp, Department of conservation, Faculty of forestry, Kasetsart University, Bangkok, Thailand.

LINK, T. E., UNSWORTH, M., and MARKS, D. (2004) The dynamics of rainfall interception by a seasonal temperate rainforest. Agric. For. Meteorol. 124:171-191.

LLORENS, P., POCH, R., LATRON, J., and GALLERT, F. (1997) Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area 1. Monitoring design and results down to event scale. J. Hydrol. 199: 331-345.

LLOYD, C. R. and MARQUES, F. A. de O. (1988) Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. Agric. For. Meteorol. 42: 63-73.

LLOYD, C. R., GASH, J. H. C., SHUTTLEWORTH, W. J., and MARQUES, A. de O. (1988) The measurement and modeling of rainfall interception by Amazonian rainforest. Agric. For. Meteorol. 43:277-294.

LLOYD, C. R. (1990) The temporal distribution of Amazonian ranfall and its implications for forest interception. Q. J. R. Meteorol. Soc. 116: 1487-1494.

LUNDGREN, L. and LUNDGREN, B. (1979) Rainfall, interception and evaporation in the Mazumbai forest reserve, west Usambara MTS., Tanzania and their importantce in the assessment of land potential. Geogr. Ann. 61 A: 157-178.

MANFROI, O.J., K. KURAJI, N. TANAKA, M. SUZUKI, M. NAKAGAWA, T. NAKASHIZUKA, and C. LUCY. (2004) The stemflow of trees in a Bornean lowland tropical forest. Hydrol. Proc., doi: 10.1002/hyp.1474.

MANOKARAN, N. (1979) Stemflow, throughfall and rainfall interception in a lowland tropical rain forest in peninsular Malaysia. Malays. For. 42: 174-200.

MURAI, H. (1970) Studies on precipitation interception by forest vegetations (In Japanese with English abstract). Bull. Gov. For. Exp. Sta. 232: 25-64.

NAKAGAWA, Y., PAMPASIT, S., KHAMYONG, S., TAKEDA, H., and IWATSUBO, G. (1998) Hydrobiogeochemistry of a hill-evergreen forest in nothern Thailand. Tropics. 8: 81-92.

PAUNGCHAREON, C. (1987) Rainfall interception in *Acasia auriculaeformis* Plantation. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 30.

ONARSA, S. (1995) Rainfall interception of Leuocena leucouphara Lam De Wit at Pasak watershed research station, Pechabun province. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 55.

PEARCE, A.J. and ROWE, L.K. (1979) Forest management effects on interception, evaporation, and water yield. J. Hydrol. (N.Z.), 18: 73-87.

PEREIRA, H. C. (1952) Interception of rainfall by cypresss plantations. East Afr. Agric. J. 18: 73-76.

PUKJALOON, V., PONGBOUN, K., and ROUYSUNGNERN, S. (1984) Rainfall interception by *Eucalyptus camaldulensis*. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 16.

PUKJALOON, V., PONGBOUN, K., and ROUYSUNGNERN, S. (1985) Rainfall interception by *Leucaena leucocephala*. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 21.

RUTTER, A. J., KERSHAW, K. A., ROBINS, P. C., and MORTON, A. J. (1971) A predictive model of rainfall interception in forests: 1. Deriviation of the model from observations in a plantation of Corsican pine. Agric. Meteorol. 9: 367-384.

RUTTER, A. J., MORTON, A.J., and ROBINS, P.C. (1975) A predictive model of rainfall interception in forests 2. Generation of the model and comparison with observations in some conferous and hardwood stands. J. Appl. Ecol. 12: 367-380.

SAENGKOOVONG, P., RUNGROJWANICH, S., and ROUYSUNGNERN, S. (1985) Rainfall interception by bamboo. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 21.

SCHELLEKENS, J., SCATENA, F. N., BRUIJNZEEL, L. A., and WICKEL, A. J. (2000a) Modelling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico. J. Hydrol. 225: 168-184.

SCHELLEKENS, J., BRUIJNZEEL, L. A., SCATENA, F. N., BINK, N. J., and HOLWERDA, F. (2000b) Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. Water Resour. Res. 36: 2183-2196.

SELLERS, P. J., SHUTTLEWORTH, W. J., DORMAN, J. L., DALCHER, A., ROBERT, J.M. (1989) Calibrating the simple biosphere model for Amazonian tropical forest field and remote sensing data. Part 1: average calibration with field data. J. Appl. Meteorol. 28(8): 727-259.

SHUTTLEWORTH, W. J. (1988) Evaporation from Amazonian rainforest. Proc. R. Soc. Lond. B233: 321-346.

SONGWATTANA, V., ROUYSUNGNERN, S., and ONNOM, V. (1988) Rainfall interception by some tree species in forest plantation. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 34.

SUZUKI, M. (1991) Evapotranspiration from forests (In Japanese and the title are tentatively translated from the original Japanese one by the authors of this paper). J. Japan Soc. Hydrol. & Water Resour. 4: 9-22.

TAKAHASHI, T., NAGAHORI, C., MONGKOLSAWAT, C., and LOSIRIKUL, M. (1983) Runoff and soil loss. *In* Shifting Cultivation - An Experiment at Nam Phron, Notheast Thailand. KYUMA, K. and PAIRINTRA, C. (ed.), Ministry of Science, Technology and Energy, Bangkok, Thailand, 84-109.

TAKIZAWA, H., SUZUKI, M., TANAKA, N., KOSAKA, I., YOSHIHUJI, N., TANAKA, K., TANTASIRIN, C., and TANGTHAM, N. (2001) The general climate at hill evergreen forest of tropical monsoon area in northern Thailand. *In* Proc. Inter. 5th Study Conference on GEWEX and GAME. 823pp, Nagoya, Japan, 619-623. (GAME Publ. NO.31(3))

TANAKA, K., TAKIZAWA, H., TANAKA, N., KOSAKA, I., YOSHIFUJI, N., TANTASIRIN, C., PIMAN, S., SUZUKI, M., and TANGTHAM, N. (2003) Transpiration peak over a hill evergreen forest in northern Thailand in the late dry season: Assessing the seasonal changes in evapotranspiration using a multilayer model. J. Geophys. Res. 108(D17): 4533, doi:10.1029/2002JD 003028.

TANGTHAM, N. (1973) Ecosystem of Kog-Ma wastershed research station, Kog-Ma Watershed Research Bull. No.12. Department of conservation, Faculty of forestry, Kasetsart University, Bangkok, Thailand.

TANGTHAM, N. (1974) Preliminary study of the ecosystem of hill evergreen forest in northern Thailand. Ph.D. thesis. Pennsylvania state university, University park, Pennsylvania, USA.

TANGTHAM, N. (1998) Hydrological roles of highland watershed in Thailand. *In* Proc. Inter. Symposium on Highland Ecosystem Management. Angkang, Thailand, 25-31.

TANI, M., NIK, A.R., YASUDA, Y., NOGUCHI, S., SYAMSUDDIN, S.A., SAHAT, M.M., and TAKANASHI, S. (2003) Long-term estimation of evapotranspiration from atropical rain forest in Peninsular Malaysia. *In* Water Resources SystemWater Availability and Global Change. FRANKS, S., BLSOCHL, G., KUMAGAI, M., MUSHIAKE, K., and ROSBJERG, D. (eds.), Sapporo, 267-274. (IAHS Publ. No.280.)

UBARANA, V. N. (1996) Observations and modeling of rainfall interception at two experimental stes in Amazonia. In Amazonian deforesration and climate. GASH, J. H. C., NOBRE, C. A., ROBERTS, C. A., and VICTORIA, R. L. (eds.), 611 pp, Wiley, New York, 152-162.

VALENTE, F. DAVID, J. S., and GASH, J. H. C. (1997) Modelling interception loss for two sparse eucalypt and pine forests in Central Portugal using reformulated Rutter and Gash analytical models. J. Hydrol. 190: 141-162.

VENEKLAAS, E.J. and Van EK, R. (1990) Rainfall interception in two tropical montane rain forests, Colombia. Hydrol. Proc. 4: 311-326.

WITTHAWATCHUTIKUL, P. and TANGTHAM, N. (1987) Rainfall intercepted in logged-over dry evergreen forest at Huay Ma Fuang, Rayong Province. *In* Abstract of Research Works in Watershed Management in Thailand (compiled by NALANPOON, A., THITIROJANAWAT, P., and TIPPHAROT, P. in 1997). 58pp, Forest Environment Reseach and Development Division, Forest Resaerch Office, Royal Forest Department, Bankok, Thailand, 38.

YADAV, A. K. and MISHRA, G. P. (1985) Distribution of precipitateon under a tropical dry deciduous forest stand of central India. J. Trop. For. 1: 181-197.

ZULKIFLI, Y. (1996) Nutrient cycling in secondary rain forest catchments of Peninsular Malaysia. Ph. D. Thesis, University of Manchester.

*Appendix* :Summary of complete enumeration in the interception study plot (30 m × 30 m) in Kog-Ma watershed. Species, heights at top of canopies and at the first living branch and DBHs of all tree (n=176) are shown. The survey was conducted in August 1998.

| Species | Height | | DBH (cm) |
|---|---|---|---|
| | at the Top (m) | at the First Living Branch (m) | |
| *Betula alnoides* | 33.0 | 15.0 | 128.9 |
| not identified* | 29.3 | 0.7 | 93.3 |
| not identified* | 40.5 | 27.3 | 86.0 |
| *Schima wallichii* | 32.5 | 6.5 | 82.8 |
| *Castanopsis acuminatissima* | 30.9 | 7.9 | 72.6 |
| not identified* | 26.0 | 12.0 | 63.7 |
| not identified* | 29.5 | 9.5 | 58.9 |
| *Castanopsis diversifolia* | 24.0 | 14.5 | 56.7 |
| *Ternstroemia gymnanthera* | 21.0 | 0.5 | 51.6 |
| not identified* | 33.9 | 27.9 | 49.3 |
| *Heliciopsis terminalis* | 21.0 | 11.0 | 48.4 |
| not identified* | 24.5 | 7.0 | 48.1 |
| *Stereospermum colais* | 25.0 | 14.0 | 46.8 |
| *Mischocarpus pentapetalus* | 25.0 | 11.0 | 45.8 |
| *Tarennoidea wallichii* | 23.0 | 10.5 | 44.6 |
| not identified* | 23.0 | 7.5 | 34.4 |
| *Turpinia nepalensis* | 11.0 | 1.5 | 32.5 |
| *Castanopusis tribuloides* | 24.7 | 10.6 | 31.2 |
| *Castanopsis diversifolia* | 23.5 | 7.5 | 30.6 |
| *Turpinia nepalensis* | 13.0 | 5.5 | 30.2 |
| *Lithocarpus elegans* | 23.0 | 13.0 | 29.6 |
| *Elaeocarpus lanceifolius* | 22.0 | 18.0 | 27.7 |
| *Acronychia pedunculata* | 15.7 | 8.6 | 27.1 |
| *Helicia nilagirica* | 18.5 | 3.5 | 23.9 |
| *Lithocarpus elegans* | 15.5 | 5.5 | 20.7 |
| *Phrenaria garrettiana* | 12.0 | 5.5 | 19.7 |
| *Turpinia nepalensis* | 17.0 | 10.0 | 19.7 |
| *Turpinia pomifera* | 13.0 | 3.0 | 16.9 |
| not identified* | 19.0 | 11.0 | 16.2 |
| *Turpinia nepalensis* | 8.5 | 3.0 | 15.0 |
| *Styrax benzoides* | 15.0 | 12.0 | 15.0 |
| not identified* | 16.5 | 6.5 | 14.6 |
| not identified* | 17.0 | 10.5 | 14.6 |
| *Eugenia tetragona* | 12.5 | 6.0 | 14.0 |
| *Elaeocarpus lanceifolius* | 13.0 | 8.0 | 13.7 |
| *Hiptage benhalensis spp.* | 7.5 | 1.5 | 13.1 |
| *Turpinia nepalensis* | 9.5 | 4.0 | 12.7 |
| not identified* | 14.0 | 8.0 | 12.1 |
| *Castanopsis acuminatissima* | 15.0 | 6.0 | 11.8 |
| climber* | — | — | 11.8 |
| *Castanopsis diversifolia* | 9.0 | 4.5 | 10.5 |
| *Eugenia tetragona* | 5.0 | 2.0 | 7.3 |
| not identified* | 8.0 | 4.0 | 7.0 |
| *Hiptage benghalensis ssp.* | 6.5 | 1.5 | 7.0 |
| not identified* | 6.5 | 2.5 | 6.0 |
| *Hiptage benghalensis ssp.* | 5.5 | 0.5 | 6.0 |
| *Hiptage benghalensis ssp.* | 6.5 | 1.0 | 5.7 |
| not identified* | 4.0 | 2.0 | 5.4 |
| not identified* | 4.5 | 2.5 | 5.1 |
| not identified* | 4.0 | 2.0 | 5.1 |
| *Hiptage benghalensis ssp.* | 4.5 | 1.5 | 4.8 |
| *Michelia floribunda* | 4.5 | 2.5 | 4.5 |
| not identified* | 8.0 | 3.5 | 4.5 |
| *Hiptage benghalensis ssp.* | 3.5 | 1.0 | 4.5 |
| *Hiptage benghalensis ssp.* | 3.5 | 1.5 | 4.1 |
| *Hiptage benghalensis ssp.* | 4.0 | 0.1 | 3.5 |
| *Hiptage benghalensis ssp.* | 3.5 | 0.0 | 3.5 |
| *Meliosma pinnata ssp. Arnottiana* | 5.5 | 3.5 | 3.5 |
| *Phoebe lanceolata* | 3.5 | 1.0 | 2.1 |
| not identified* | 4.0 | 1.5 | 2.1 |
| *Eriobotrya bengalensis* | 3.5 | 2.0 | 2.1 |
| *Cinnamomum iners* | 3.5 | 1.5 | 2.1 |
| *Hiptage benghalensis ssp.* | 2.5 | 0.1 | 2.1 |
| *Hiptage benghalensis ssp.* | 3.5 | 3.0 | 2.1 |
| *Hiptage benghalensis ssp.* | 2.0 | 1.0 | 2.1 |
| *Phoebe lanceolata* | 3.5 | 1.5 | 2.1 |
| *Ternstroemia gymnanthera* | 3.0 | 1.5 | 2.0 |
| not identified* | 3.0 | 1.5 | 2.0 |
| not identified* | 3.5 | 1.5 | 2.0 |
| *Hiptage benghalensis ssp.* | 3.5 | 0.0 | 2.0 |
| *Phoebe lanceolata* | 4.0 | 2.0 | 2.0 |
| not identified* | 3.0 | 1.0 | 1.9 |
| *Ternstroemia gymnanthera* | 3.0 | 1.5 | 1.9 |
| *Ternstroemia gymnanthera* | 3.5 | 1.5 | 1.9 |
| not identified* | 4.0 | 2.0 | 1.9 |
| *Castanopusis acuminatissima* | 2.5 | 1.5 | 1.9 |
| *Styrax benzoides* | 3.5 | 1.5 | 1.9 |
| *Turpinia nepalensis* | 3.0 | 1.5 | 1.9 |
| *Turpinia nepalensis* | 3.0 | 1.5 | 1.9 |
| *Hiptage benghalensis ssp.* | 2.0 | 1.5 | 1.8 |
| *Ternstroemia gymnanthera* | 3.0 | 2.0 | 1.8 |
| not identified* | 3.0 | 2.0 | 1.8 |
| *Hiptage benghalensis ssp.* | 3.5 | 1.0 | 1.8 |
| not identified* | 3.0 | 1.5 | 1.8 |
| *Acronychia pedunculata* | 3.5 | 1.0 | 1.8 |
| *Phoebe lanceolata* | 4.0 | 1.5 | 1.8 |
| *Ternstroemia gymnanthera* | 3.0 | 1.5 | 1.8 |
| *Acronychia pedunculata* | 2.5 | 1.0 | 1.7 |
| not identified* | 3.5 | 1.5 | 1.7 |
| *Acronychia pedunculata* | 3.0 | 1.5 | 1.7 |
| *Mischocarpus pentapetalus* | 3.5 | 2.0 | 1.7 |
| *Hiptage benghalensis ssp.* | 2.5 | 2.0 | 1.6 |
| *Hiptage benghalensis ssp.* | 2.0 | 1.5 | 1.6 |
| not identified* | 3.5 | 2.5 | 1.6 |
| *Castanopusis diversifolia* | 3.0 | 2.0 | 1.6 |
| *Meliosma pinnata ssp. arnottiana* | 2.5 | 1.0 | 1.6 |
| *Ternstroemia gymnanthera* | 3.0 | 1.5 | 1.5 |
| *Ternstroemia gymnanthera* | 3.0 | 1.5 | 1.5 |
| *Lithocarpus elegans* | 3.0 | 1.0 | 1.5 |
| *Lithocarpus elegans* | 3.0 | 1.0 | 1.5 |
| *Maesa ramentacea* | 2.5 | 1.5 | 1.5 |
| not identified* | 2.5 | 1.5 | 1.5 |
| not identified* | 3.5 | 1.5 | 1.5 |
| not identified* | 2.5 | 1.5 | 1.4 |
| *Ternstroemia gymnanthera* | 2.0 | 1.5 | 1.4 |
| not identified* | 3.0 | 1.5 | 1.4 |
| not identified* | 2.5 | 2.0 | 1.4 |
| not identified* | 3.5 | 2.0 | 1.4 |
| not identified* | 3.0 | 2.0 | 1.4 |
| *Turpinia nepalensis* | 2.5 | 1.5 | 1.4 |
| *Turpinia nepalensis* | 3.0 | 1.5 | 1.4 |
| *Turpinia nepalensis* | 3.0 | 2.0 | 1.4 |
| not identified* | 3.0 | 2.0 | 1.4 |
| *Litsea salicifolia* | 3.0 | 1.0 | 1.3 |
| *Maesa ramentacea* | 3.0 | 2.0 | 1.3 |
| not identified* | 2.5 | 1.0 | 1.3 |

*Appendix* :Summary of complete enumeration in the interception study plot (30 m × 30 m) in Kog-Ma watershed. Species, heights at top of canopies and at the first living branch and DBHs of all tree (n=176) are shown. The survey was conducted in August 1998. (Continued)

| *Species* | Height | | DBH (cm) |
|---|---|---|---|
| | at the Top (m) | at the First Living Branch (m) | |
| *Hiptage benghalensis ssp.* | 4.5 | 3.5 | 3.5 |
| *Hiptage benghalensis ssp.* | 3.5 | 1.0 | 3.5 |
| *Hiptage benghalensis ssp.* | 4.0 | 1.0 | 3.5 |
| *Rhus chinensis* | 4.0 | 3.0 | 3.3 |
| *Rhus chinensis* | 3.0 | 1.5 | 3.2 |
| *Hiptage benghalensis ssp.* | 3.0 | 1.5 | 3.2 |
| not identified* | 3.5 | 1.5 | 3.2 |
| not identified* | 4.0 | 3.0 | 3.2 |
| not identified* | 5.0 | 2.0 | 3.2 |
| not identified* | 4.0 | 2.5 | 2.9 |
| not identified* | 4.0 | 2.0 | 2.9 |
| *Hiptage benghalensis ssp.* | 3.0 | 1.0 | 2.9 |
| not identified* | 4.0 | 2.0 | 2.9 |
| *Prunus arborea var montana* | 4.0 | 1.5 | 2.7 |
| *Hiptage benghalensis ssp.* | 3.5 | 3.0 | 2.7 |
| *Hiptage benghalensis ssp.* | 4.5 | 3.5 | 2.7 |
| *Maesa ramentacea* | 3.5 | 2.0 | 2.7 |
| *Ternstroemia gymnanthera* | 4.0 | 1.5 | 2.5 |
| *Phoebe lanceolata* | 3.5 | 1.5 | 2.5 |
| not identified* | 4.0 | 2.0 | 2.5 |
| *Maesa ramentacea* | 4.0 | 1.5 | 2.5 |
| *Hiptage benghalensis ssp.* | 3.5 | 2.5 | 2.5 |
| not identified* | 3.0 | 1.0 | 2.5 |
| not identified* | 2.5 | 1.5 | 2.5 |
| *Acronychia pedunculata* | 4.0 | 1.0 | 2.5 |
| not identified* | 3.0 | 1.0 | 2.5 |
| not identified* | 3.0 | 2.5 | 2.4 |
| *Hiptage benghalensis ssp.* | 1.5 | 1.0 | 2.2 |
| *Michelia floribunda* | 3.5 | 1.5 | 2.2 |
| *Mischocarpus pentapetalus* | 3.0 | 1.5 | 1.3 |
| not identified* | 2.0 | 0.5 | 1.2 |
| not identified* | 2.5 | 1.5 | 1.2 |
| *Eurya nitida var. siamensis* | 3.0 | 1.0 | 1.2 |
| *Ternstroemia gymnanthera* | 2.5 | 1.0 | 1.2 |
| not identified* | 2.5 | 1.5 | 1.2 |
| not identified* | 2.5 | 2.0 | 1.2 |
| not identified* | 3.0 | 1.0 | 1.2 |
| not identified* | 2.0 | 1.5 | 1.2 |
| not identified* | 3.0 | 1.5 | 1.2 |
| not identified* | 2.5 | 1.5 | 1.2 |
| *Memecylon plebejum* | 4.5 | 2.5 | 1.1 |
| *Maesa ramentacea* | 2.5 | 1.5 | 1.1 |
| not identified* | 3.0 | 1.5 | 1.1 |
| *Maesa ramentacea* | 2.5 | 1.5 | 1.1 |
| *Styrax benzoides* | 2.5 | 1.0 | 1.1 |
| not identified* | 2.5 | 1.0 | 1.1 |
| not identified* | 3.5 | 1.5 | 1.1 |
| not identified* | 2.0 | 1.0 | 1.1 |
| not identified* | 2.5 | 1.0 | 1.1 |
| not identified* | 3.0 | 1.5 | 1.0 |
| *Maesa ramentacea* | 2.0 | 1.0 | 1.0 |
| *Ternstroemia gymnanthera* | 2.5 | 1.5 | 1.0 |
| *Engelhardia spicata var. spicata* | 1.5 | 1.0 | 1.0 |
| not identified* | 2.5 | 1.5 | 1.0 |
| not identified* | 2.0 | 1.0 | 1.0 |
| not identified* | 2.5 | 1.0 | 1.0 |
| *Artocarpus lanceolata* | 2.0 | 1.5 | 0.9 |
| *Maesa ramentacea* | 2.5 | 2.0 | 0.9 |
| *Eugenia tetragona* | 2 | 1 | 0.9 |
| not identified* | 2.5 | 1.5 | 0.9 |

* The species could not be identified.

(Received Jun. 30, 2004)
(Accepted Nov. 8, 2004)

# タイ北部の丘陵性常緑林における 4年間の樹冠遮断量とその年々変動

田中延亮*1・チャチャイタンタシリン*2・蔵治光一郎*3・
鈴木雅一*4・ニポンタンタム*2

*1 東京大学大学院農学生命科学研究科農学国際専攻
*2 カセツァート大学林学部保護学科
*3 東京大学大学院農学生命科学研究科附属科学の森研究センター愛知演習林
*4 東京大学大学院農学生命科学研究科森林科学専攻

## 要　旨

タイの丘陵性熱帯季節林における森林フラックスサイト（コグマ試験地）における年間樹冠遮断量，その測定誤差，およびその年々変動を明らかにすることを目的として，4年間にわたって降水量，樹幹流下量，および樹冠通過雨量を観測した．その結果，以下のことが整理された．

（1）4年間の年降水量の最小値と最大値はそれぞれ1641.9 mmと2481.2 mmとなり，その年々変動の幅が大きいことが確認された．樹冠遮断観測プロット近辺に設けた互いに約200 m離れた2地点での年降水量の差は，各年とも1 %～2 %の範囲内であった．この差は，コグマ試験地でおこなわれた既往研究で報告されている年降水量の標高依存性で説明できる範囲であった．一方，2地点での観測毎の降水量は，約半数の観測において，降水量に対して10 %以上の差を示していた．これら観測毎の降水量の差は，コグマ試験地内の降水量の空間分布が生み出したと考えられた．また，2地点での年降水量がほとんど等しかった理由として，両地点における降水量の大小関係は観測毎に入れ替わり，1年間の積算降水量を比較した場合は，個々の観測での降水量差はキャンセルされていることが挙げられた．樹冠遮断観測プロットは2地点の降水量観測点からそれぞれ50 mと250 m離れていたが，そのプロットの真上における年降水量は，2地点での年降水量の範囲であるとして差し支えないと判断された．

（2）樹冠遮断観測プロット内で8本の樹木が生成する樹幹流下量を測定した．各樹木から生成される樹幹流下量と雨量の回帰直線より得られる係数と各樹木の大きさとの関係を明らかにした．また，その関係を用いて，プロット全体に供給される樹幹流下量を推定した結果，毎年の樹幹流下量は25 mmから40 mm（年降水量の1.5 %）という結果を得た．また，本試験地で想定される樹幹流下量を最大限に見積もった結果，本試験地での樹幹流下量は，たかだか各年に50 mmから75 mm（年降水量の3.0 %）であるということが明らかになった．ただし，ボルネオ島の低地熱帯林での最近の報告と本研究が上層木の樹幹流下量のみを実測対象としたことをあわせて考えると，今後，コグマ試験地においても下層樹木が生成する樹幹流下量についての調査の必要性が示された．

（3）30個のコレクターを用いて樹冠通過雨量を測定した結果，1999年から2002年の4年間に生じた年間樹冠通過雨量は，1857.0 mm，1641.9 mm，1794.5 mmおよび2481.2 mm（年降水量

の86 to 91 %）であった．ただし，30個のコレクターが示した樹冠通過雨量の空間分布は非常に大きく，その部分についての詳細な検討は今後の課題となった．また，観測毎に観測される樹冠通過雨量が降水量を上回るという現象が毎年確認された．その原因の一つとして，コグマ試験地での降水量の空間分布の不均一性により，樹冠遮断観測プロットより250 m離れている露場の降水量が，樹冠遮断観測プロットの真上の降水量より小さかったことが挙げられた．また，その他の原因として，霧の発生により本試験地の森林の樹冠部に降雨以外の水分供給（precipitation）があったことが挙げられた．コグマ試験地での樹冠通過雨量には，以上の2つの要因が影響していることが特徴である．この2つの影響度を個別に明らかにしたうえで，コグマ試験地での観測毎の樹冠通過雨量を解析する必要性が示された．

（4）コグマ試験地での4年間の年樹冠遮断量は，199.3 mm（1999年），198.3 mm（2000年），141.9 mm（2001年）および187.4 mm（2002年）となった．これらは，それぞれの年降水量に対して，10.7 %（1999年），12.1 %（2000年），7.9 %（2001年），7.6 %（2002年）という割合を示した．樹冠遮断量の年降水量に対する割合の年々変化が大きかったことから，コグマ試験地において各年に発生する降雨イベントの降雨特性，イベント中の気象条件，あるいは霧により流域への水分供給量が，年々変動することが示唆され，これらと関連させて解析することが今後の課題となった．また，その割合の年々変化の大きさは，特定の森林の樹冠遮断量を特定の1年間の樹冠遮断率だけで表現することの危険性を示唆した．また，樹冠遮断観測プロットの真上における年降水量は2地点（プロットから250 m離れた露場と50 m離れた樹冠上）における年降水量の間にあったと考え，観測された遮断量の測定誤差の範囲を求めた．その結果，185.8～199.8 mm（2000年），141.9～184.4 mm（2001年），187.4～210.1 mm（2002年）という誤差範囲が示された．本研究では，森林の樹冠部への水分供給源（precipitation）は降雨だけであると考え，各年の樹冠遮断量の算出をおこなった．本報告では検討できなかったが，もしコグマ試験地で霧による水分供給（fog precipitation）が顕著であった場合，本報告で示された樹冠遮断量は過小評価されているはずである．熱帯山岳雲霧林（TMCF）に分類されるコグマ試験地では，霧の寄与を含めた樹冠遮断量の解析の必要性が確認された．また，本研究で得られた観測結果とタイ国内で報告されていた樹冠遮断の観測結果をとりまとめ，タイの森林における樹冠遮断率の特徴を明らかにした．

**キーワード：** 樹冠遮断量・樹幹流下量・樹冠通過雨量・丘陵性常緑林・降雨の空間分布