Spatio-temporal variability in rainfall and wet-canopy evaporation within a small catchment recovering from selective tropical forestry

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Abstract

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Within tropical rainforest environments, rainfall pattern and canopy structure regulates the partitioning of water into wet-canopy evaporation and sub-canopy rainfall. These interrelated process then moderate atmospheric water vapour, plant water availability, runoff pathways and soil erosion. Forestry impacts on these atmospheric processes may, therefore, impact on a cascade of other environmental processes. This study, conducted within a 4 km^2 experimental catchment in the interior of Northeast Borneo, that was recovering from selective timber harvesting, sought to identify the spatial and temporal structure of the local rainfall, and the impact of forestry on wet-canopy evaporation and lumped, water-balance components. A total of 450 throughfall gauges, 50 raingauges and 40 stemflow gauges were installed and digitally surveyed within the catchment, mostly within a 0.44 km^2 tributary area. Data from these instruments were then supported by those from rainfall recorders and river gauges, and an enumeration of the vegetation patchwork present at 8-years post-logging.

Several approaches of statistical modelling were applied, and indicated that the rainfall during the 1997/8 drought-year was (1) highly localised in space, even for regions dominated by convective rainfall, (2) strongly moderated by the local undulating topography, with marked seasonal (monsoon) changes, and (3) delivered primarily as regular, short duration events of low intensity rainfall. The visually classified patchwork of canopy types (supported by a series of biophysical measurements), showed significant differences in rates of wet-canopy evaporation. Smaller quantities of sub-canopy rainfall were observed beneath the disturbed patches of vegetation, in comparison to those beneath undisturbed remnants of primary rainforest. This may have been caused by (i) a greater rate of wet-canopy evaporation, due to enhanced atmospheric turbulence and/or higher surface leaf densities, or (ii) disturbed forest blocks receiving less gross rainfall, due to sheltering by the higher undisturbed canopies. Modelling of the 8-year post-logging water balance data, indicated that both seasonal and inter-annual cycles (related to the El Nĩno Southern Oscillation) strongly affected the rainfall (P), riverflow (Q) and 'P-Q' dynamics. On removal of these cyclical components, the analysis indicated that there was no evidence of a change in evapotranspiration (strictly 'P-Q') with the 8-years of forest regeneration.

Some of these results were unexpected, and underlined the need for a new emphasis on 'canopy hydrology' within rainforests managed for development and conservation.

Declaration

No portion of the work embodied within this thesis has been submitted in support of an application for another degree or qualification at this or any other academic institution.

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Chapter 1

Introduction

... 'Tropical rain forests can be a sustained source of timber, renewed by re-growth after felling, so long as (and it is a vital proviso) man works within the limits of their natural dynamics' ... (Whitmore, 1990).

1.1. Importance of rainfall and wet-canopy evaporation studies within the humid tropics

The rainfall received by the catchment soils is the most fundamental hydrological quantity, as it is this that regulates (a) plant water availability (Black, 1996; Walsh, 1996), (b) transpiration losses to the atmosphere (Eschenbach *et al.*, 1988; Whitehead and Kelliher, 1991), (c) the relative importance of each runoff pathway (Kirkby, 1978, 1988; Elsenbeer and Cassel, 1990), (d) the rate of soil erosion and mass movement (Douglas, 1977; Douglas *et al.*, 1999), (e) the flashiness of rivers and catchment water yield patterns (Shaw, 1988; Bruijnzeel, 1990), and (f) the water resources potential of rivers (Shaw, 1988). The quantity of water received by the ground surface is itself moderated by (1) the character of the gross rainfall, and (2) the rate of wet-canopy evaporation (or 'interception loss') from vegetation surfaces above the ground.

Within tropical latitudes (± 23°), the hydrological impact of local variations in the temporal and spatial character of rainfall has received little research attention (Molicova and Hubert, 1994; Lyons and Bonell, 1992). Similarly, an understanding of the rates of wet-canopy evaporation is not complete within the humid tropics (Dykes, 1997), with the studies that do exist showing large differences not fully explained by deterministic theory (Bonell and Balek, 1993).

Given the high rate of vegetation change within the humid tropics, largely as a result of human activities (Pinard, 1995), there is an urgent need to understand the spatio-temporal patterns and dynamics of local rainfall and evaporation phenomena, and critically, the impact of our activities on these. Given that evaporative water transfer to the upper atmosphere within the humid tropics plays a significant role in the regulation of temperate climates, then there may be a wider significance for studies on tropical rainfall and evaporation. Current efforts to develop more 'sustainable' practices of forestry within the humid tropics, urgently demand research on rainfall and evaporation processes within model/example catchments (Douglas, 1999).

1.2. Research issues related to rainfall and wet-canopy evaporation within the humid tropics

While the nature of the spatio-temporal variability of rainfall across large regions of the humid tropics has been described (*e.g.*, Lyons and Bonell, 1992; Bonell and Balek, 1993; Kripalani and Kulkarni, 1997), data on variations over the scales of the 0.1 to 10 km^2 experimental catchment are, however, very sparse within the humid tropics (Bonell and Balek, 1993; Molicova and Hubert, 1994).

Spatial variability in rainfall over the scale of 0.1 to 10 km^2 may be important within the humid tropics for (a) understanding the distribution of drought stress, which itself affects the distribution of tree species (Ashton, 1964), (b) accurate modelling of rainfall-runoff behaviour (*cf.* Shah *et al.*, 1996; Chappell *et al.*, 1999), and (c) in the understanding of environmental differences between ecological monitoring plots distributed throughout a study region (*e.g.*, Ashton, 1964; Chapter 6). How 'localised' are the rainstorms will also be important to the extent and intensity of raingauge networks (Hersfield, 1965).

It is often assumed that rainstorms within the humid tropics are predominantly of high intensity and short duration, however, examination of the few studies that do exist, suggests that average intensities and durations are very variable across the region (Bonell and Balek, 1993). Perhaps, the largest contrasts occur between the equatorial tropics (*e.g.*, Borneo - Sulawasi, West Africa, Amazonia) and those regions affected by tropical cyclones (*e.g.*, Philippines - East Asia - South Asia, S.W. Pacific - N.E. Australia, Central America - Caribbean). This may have important implications for the spatial variations in rainfall-runoff dynamics across the tropics.

The development of tropical forests (a) as managed 'natural forests' or (b) by conversion to forest plantations, agricultural uses and urban settlements continues at a very high rate (Marshall, 1992). The popular view is that removal of the forest leads to a depletion of the water resources available in rivers. The scientific evidence from water balance studies undertaken within experimental catchments (0.1-10 km^2) generally contradicts this view, indicating that water yields increase following tree removal (Bruijnzeel, 1990, 1996). Some uncertainty does, however, remain even in the scientific community, about the impacts of (a) removing cloud forest, given the forest's 'cloud-stripping' capabilities (Bruijnzeel and Hamilton, 2000), and (b) 'selective forestry' where vigorous growth of pioneer-trees is encouraged. As ever, the uncertainties relate to a dearth of good catchment studies within such areas. Identifying why a water balance may change (notably through separate changes in the wet-canopy evaporation and transpiration components) is particularly difficult for a selectively managed forest, given the extreme heterogeneity of the vegetation cover that is produced (Tangki, In prep.). Worse still, there a few studies that fully document the characteristics of all vegetation components within terrain managed for selective forestry (Pinard *et al.*, 2000). Without a sound understanding of the component impacts of selective forestry on water yield, it becomes very difficult to justify detailed protocols for the 'sustainable' management of tropical forests; sustainable in terms of timber production and environmental conditions.

1.3. Aims of this study

Given the outstanding research issues surrounding the spatio-temporal characteristics of rainfall and wet-canopy evaporation within tropical forests, identified in the previous section, this study focused on a small (*i.e.*, 4 km^2) experimental catchment within equatorial Borneo, that was covered by selectively-managed natural forest.

The catchment is the drainage area of the Sapat Kalisun river (Figure 1.1). This river drains into the River Segama, which itself flows to the Northeastern coast of Sabah, Malaysian Borneo, where it enters the Sulu Sea. The catchment is located within a block of commercial forest - the Ulu Segama Forest Reserve, which itself lies within the 9,728 km^2 Yayasan Sabah timber concession. This concession is managed by the Forestry Upstream Division (Rakyat Berjaya Sdn Bhd.) for long-term commercial forestry and environmental conservation (*e.g.*, 438 km^2 Danum Valley Conservation Area and 390 km^2 Maliau Basin Conservation Area). Within the Ulu Segama Forest Reserve, the Sapat Kalisun Experimental Catchment lies within the 1998 and 1989 logging coupes (Greer *et al.*, 1996). Timber haulage road construction on the northern divide of the Sapat Kalisun Catchment, followed by roadside clearance to maintain road trafficability ('Matahari clearance') and then selective logging took place during 1988 and 1989.

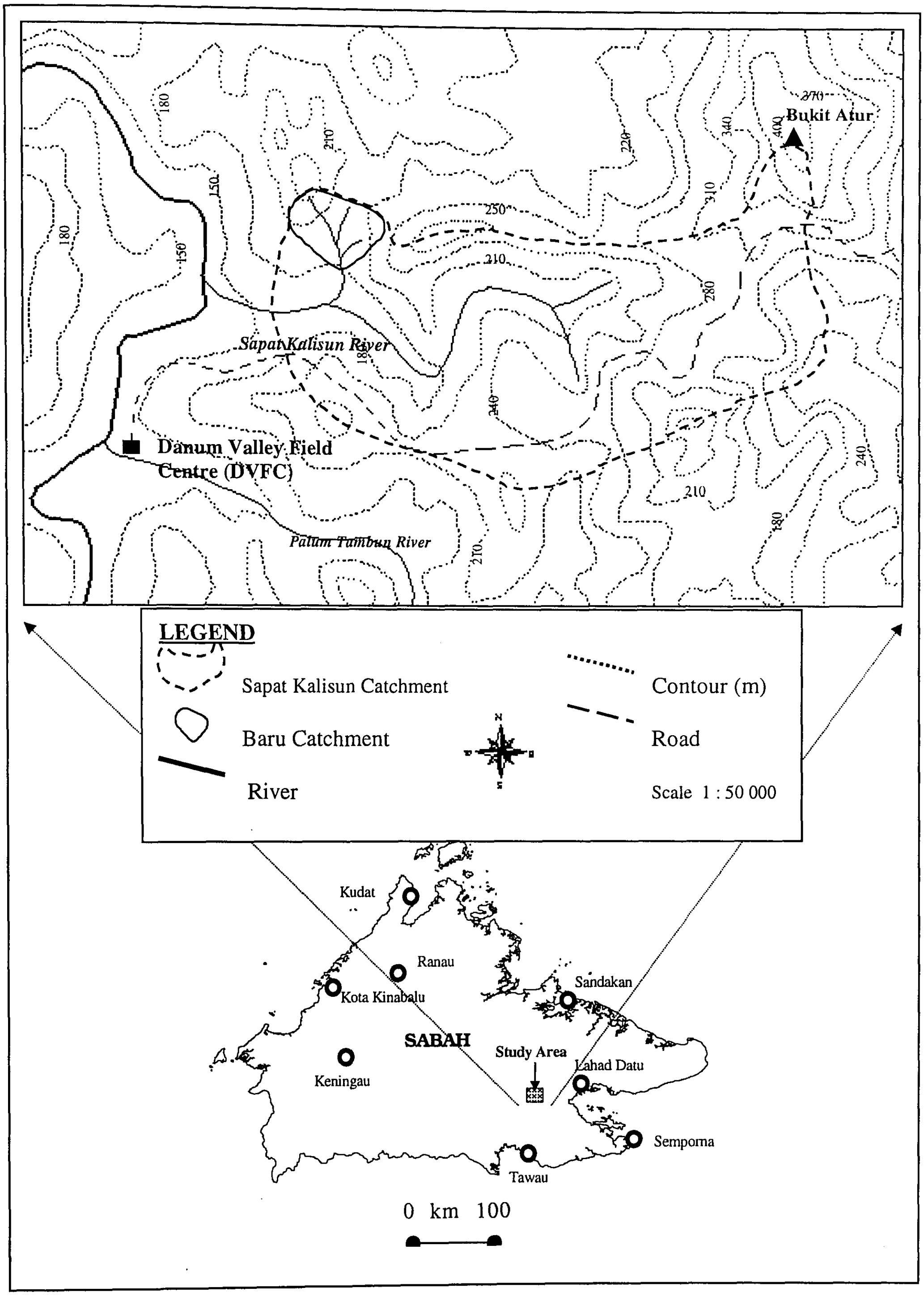


Figure 1.1: The study area within the Ulu Segama Forest Reserve of Sabah, Malaysia.

Detailed monitoring of rainfall and wet-canopy evaporation processes took place over the water-year 1st May 1997 to 30th April 1998, some eight years post forestry activities. Identifiable vegetation growth had taken place over these eight years (Douglas *et al.*, 1995; Tangki, in preparation). An intensive network of 450 raingauges was installed beneath the range of vegetation canopies observed within the region, together with 40 stemflow collars and 50 storage raingauges within large canopy openings. Measurements from these gauges were supplemented by continued monitoring and analysis of the data from a network of rainfall recorders installed during earlier projects (see Douglas *et al.*, 1992; Chappell *et al.*, 1999).

The 0.44 km^2 Baru Experimental Catchment lies within the Northwest corner of the Sapat Kalisun catchment (Figure 1.1). This area was more intensively monitored in comparison to other parts of the Sapat Kalisun catchment, and also provided data on riverflows and hence catchment water balance for this study.

This site and its monitoring network, allowed the project to address the following key aims:

1. How is gross rainfall spatially distributed across a small equatorial catchment, do the patterns change with time, and what are the possible causes?

2. What are the characteristics of the rainstorms within a small equatorial catchment within the interior of Borneo Island, and do these change with season?

3. Do the different patches of vegetation seen within a region recovering from the first episode of selective forestry have different rates of net rainfall (*i.e.*, sub-canopy rainfall) and wet-canopy evaporation?

4. Does the natural recovery of the forest and terrain since selective harvesting have a significant impact on the water yield, when set against the impacts of natural climatic fluctuations?

To answer these key aims, two further aims were required. These constituent aims were (a) what are the errors associated with the rainfall measurement, so that meaningful spatial rainfall patterns could be identified? and (b) can the complex patchwork of selectively managed forest be classified to allow representative plots to be established for wet-canopy evaporation studies ?

The study was undertaken during the 1997/8 water year, which turned out to be a severe drought associated with a trough in the El Nino Southern Oscillation (ENSO; Chappell *et al.*, 1998). The results of the study are, therefore expected to be more representative of the situation during ENSO troughs or other drought periods, than for very wet years.

1.4. Thesis structure

The thesis has been prepared as series of journal papers, each with some introductory material, though it is intended there is a logical progression through the series of chapters/papers presented with each chapter building on the former.

Chapter 2 begins by developing a classification of the vegetation cover with the 44 hectare Baru Experimental Catchment, and then tests this classification by looking to see if the biophysical characteristics of the principal vegetation elements within each class can be differentiated. This work is an essential precursor to the sampling of the region's forest for net-rainfall and wet-canopy evaporation.

The raingauges used to assess the spatial patterns of gross rainfall within the Sapat Kalisun Experimental Catchment, and the net rainfall and wet-canopy evaporation within one of its sub-catchments (i.e, the Baru Experimental Catchment) were designed specifically for the project. The aim was to minimise the costs of manufacture, while not losing too much accuracy in the catch. Chapter 3, therefore, details the results of a series of tests designed to assess the magnitude and source of any losses in accuracy associated with using a simplified raingauge design rather than commercially built raingauges. This quality assurance was required to ensure that the data on (a) the spatial patterns of gross rainfall, and (b) the differences in wet-canopy evaporation between different vegetation types was not over-interpreted.

Chapter 4 directly addressed the first key aim of the thesis - How is gross rainfall spatially distributed across a small equatorial catchment, do the patterns change with time, and what are the possible causes?

Chapter 5 then went on to examine the short-term, temporal dynamics in the gross rainfall, thus addressing the second key aim of the thesis - what are the characteristics of the rainstorms within a small equatorial catchment within the interior of Borneo Island, and do these change with season? This work sought to complement the analysis of the longer-term temporal dynamics in the rainfall at the same locality presented in Chappell *et al.* (2001). This paper was indeed, based upon data and interpretations collected as part of this thesis.

Following an understanding of (a) errors in the gross and net rainfall catch, (b) the spatial patterns in the gross rainfall, and (c) nature of the vegetation patterns, the thesis then goes on to address the spatial variations in the net-precipitation and wet-canopy evaporation. This section of the thesis - chapter 6, therefore, addresses the third key aim of the thesis - do the different patches of vegetation seen within a region recovering from the first episode of selective forestry have different rates of net rainfall (*i.e.*, sub-canopy rainfall) and wet-canopy evaporation?

Given that the study was undertaken some eight years after the cessation of selective timber harvesting, it was considered important to understand if the regeneration of the forest and other forms of vegetation over this period had had a significant effect on the riverflow and evapotranspiration. Chapter 7, therefore, applied a new Data-Based-Mechanistic (DBM) approach, known at the Dynamic Harmonic Regression (DHR) model (Young *et al.*, 1999) to the rainfall (P) and riverflow (Q) data for the Baru Experimental Catchment. Where catchment leakage (*i.e.*, exchange of subsurface flows across the catchment divides) and inter-annual storage are minimal, the annual difference between rainfall and riverflow (*i.e.*, P-Q) equates to the total evaporation or 'evapotranspiration' from a catchment. Thus the P-Q data-series was also modelled to see if inter-annual changes not associated with a dynamic climate (notably changing rainfall input) could be identified. Such changes, if they can be observed, might be changes in the loss of water by transpiration or wet-canopy evaporation with forest re-growth. As changes in the amount of water received by the ground surface (*i.e.*, net rainfall after wet-canopy evaporation changes) may change with forest re-growth, and the amount of water running over logging tracks may change as new vegetation establishes (Douglas *et al.*, 1995), then the rainfall-runoff flashiness of the catchment may change with time. This was, therefore, also addressed within Chapter 7 using a 'hydrograph separation technique' (Hewlett and Hibbert, 1967) implemented using an approach developed by Bidin and Greer (1997).

The final chapter of the thesis (Chapter 8) attempts to bring together the main findings of the thesis, draws tentative implications for forestry management and makes suggestions for new avenues of research that are needed.

Chapter 2

Classification of a 44 ha region of selectively-managed tropical forest for evaporation studies

To be submitted as Bidin, K., and Chappell, N.A., Classification of a 44 ha region of selectively-managed tropical forest for evaporation studies, *Journal of Tropical Forest Science*.

The mosaic of vegetation left after the first cycle of selective-logging of a Natural Forest within the humid tropics is highly heterogeneous. This chapter presents a new qualitative classification of the major elements of this vegetation patchwork within an area of lowland dipterocarp forest in Sabah, Malaysian Borneo. The six vegetation categories that can be clearly identified from their visual canopy characteristics are examined to see if they can distinguish using measurable biophysical characteristics. It can be seen that the different patches of vegetation cover that visually characterise selectively-managed lowland forest could identified on the basis of differences in either tree density, tree basal area, estimated biomass, vine density or canopy complexity (Shannon diversity index). Given that there are identifiable differences between the canopy patches within a selectively-managed forest, characterisation and subsequent stratified sampling becomes essential to studies that seek to estimate regional rates of wet-canopy evaporation.

2.1. Introduction

A major physical factor controlling rainfall interception process and wet-canopy evaporation is the 'forest structure', which includes the vegetation distribution, canopy density, and surface characteristics of the intercepting surfaces (Waterloo *et al.*, 1999). Disturbance of the forest structure as a result of 'selective timber harvesting', is therefore, expected to affect the rate of sub-canopy rainfall and wet-canopy evaporation, and as consequence rainfall-runoff behaviour and water resources (Bonell and Balek, 1993). Despite this, characteristics of the forest-cum-terrain within selectively-managed areas of tropical forest are rarely presented (Pinard, 1995; Nussbaum *et al.*, 1995). This study, therefore, makes a useful contribution to a field with only limited published information.

2.2. Study site

This study was conducted within the 44 ha area of logged-over forest within the Baru Experimental Catchment, a tributary area of the Sapat Kalisun Experimental Catchment (Figure 2.1). The study area is approximately 2-km away from the Danum Valley Field Centre (DVFC) at 5°01' North and 117°48.75' East, and lies within the 1989 logging coupe (known as 'Coupe 89') of the 'Ulu Segama Forest Reserve'. This commercial forestry area is within the Yayasan Sabah timber concession of the Malaysian State of Sabah, Borneo Island. The area has been subject of intensive sub-canopy rainfall and wet-canopy evaporation studies (Chapter 6).

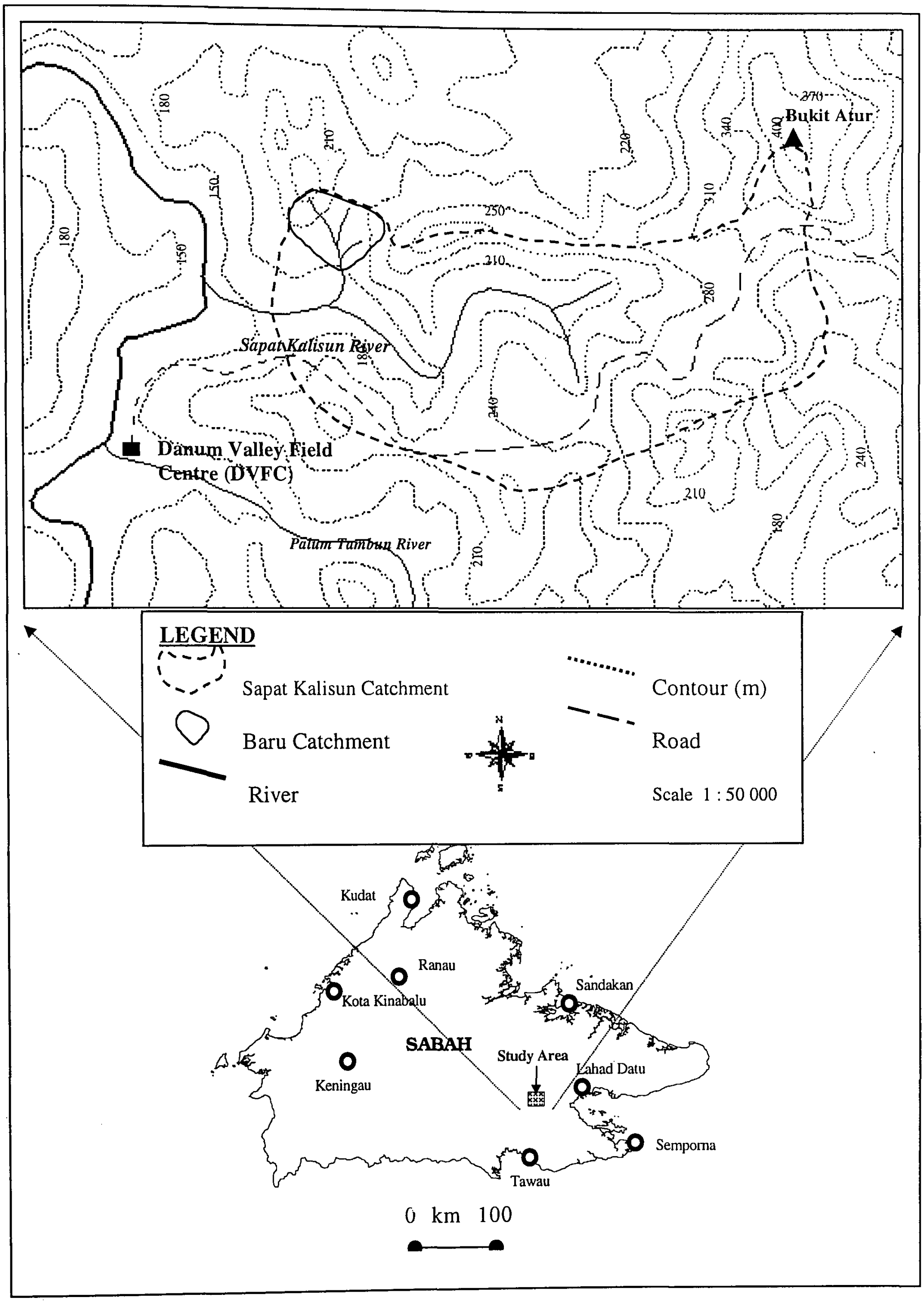


Figure 2.1. Location of the 44 ha Baru Experimental Catchment within the Sapat Kalisun Experimental Catchment, Sabah, Malaysian Borneo.

The study area was selectively logged in 1989 using both bulldozers and high-lead cable yarding systems (Conway, 1982) which left a complex and heterogeneous structure of regenerating forest patches, areas of Protection Forest and areas of highly damaged forest. The average volume of timber extracted from the area was 79.9 m^3ha^{-1} (Moura-Costa and Karolus, 1992). For the whole Sabah, an average of 8-15 trees per ha (giving 50-120 m^3ha^{-1} of timber) are felled by the selective-logging method, of which the Dipterocarpaceae family make up 90% of the total volume (Sabah Forestry Department, 1989).

This study aims to (i) apply a new classification to land-cover zones within an area of selectively-managed, lowland dipterocarp forest. It then seeks to (ii) examine the botanical characteristics of those zones containing climax or pioneer trees. The objective of this aspect of the work is the evaluation of the classification system suggested. Lastly the study, (iii) provides an estimate of the spatial extent of each of the land-cover classes.

2.3. Classification of selectively-logged tropical forest

Classification of all elements of vegetation cover within selectively-logged terrain is important for the regional estimation of sub-canopy rainfall and wet-canopy evaporation. Even in an undisturbed domain, rain forest has far from a uniform, unbroken canopy (Richards, 1952). Whitmore (1978) states that tropical forest consists of a mosaic of structural units each one at a different stage of development. For simplicity, this continuum of developmental stages in the forest growth cycle in undisturbed natural forest can be arbitrarily subdivided into gap, building, and mature phases. Such a subdivision has provided a convenient basis for the analysis of the structure of undisturbed forest in the vicinity of DVFC (Brown, 1990). Activities associated with Selective Forestry Management (SFM) within the Ulu Segama region and elsewhere in the tropics have, however, left an even more heterogeneous landscape requiring a different approach to classification of the whole vegetation cover (Nussbaum *et al.*, 1995).

An understanding of the forestry practices undertaken close to DVFC and more widely within the Ulu Segama Forest Reserve, suggests that six distinct categories of vegetation-terrain classes can be identified visually. Blocks of undisturbed forest canopy are found within selectively-managed forest, particularly in areas of 'Protection Forest' adjacent to rivers and very steep slopes (Nik *et al.*, 1997). Where direct or indirect disruption of a forest block during logging is relatively modest or regeneration is rapid, then the canopy may still be dominated by mature climax trees. This category could be described as 'moderately impacted forest canopy'. Within natural forests affected by selective harvesting, even those so called 'sustainable' or 'reduced-impact' practices, have some areas of very high impact. Some of these areas (i) continue to support some climax trees, but often these are draped in vines, others are colonised largely by (ii) *Macaranga* spp pioneer trees, or (iii) shrubs and herbs, while some areas remain as (iv) bare ground or support only grass. Areas of 'vine-covered forest canopy' are typical in areas close to high-lead yarding operations (Conway, 1982). *Macaranga* forest canopy areas are found along timber haulage roads, and on some landslides. Areas supporting shrubs and vines, here defined as 'sprawler-covered canopy gaps', are areas of local clearance only supporting plants of less than five metres in height. Areas of bare ground and grass are defined as 'canopy gaps' and are found in areas of former skid trails (used by tracked, bulldozer skidders), log landing areas and timber haulage roads (*cf.* Conway, 1982). In summary, the six categories are:

(1) undisturbed forest canopy (Figure 2.2),

(2) moderately impacted forest canopy (Figure 2.3),

(3) vine-covered forest canopy (Figure 2.4),

(4) *Macaranga* forest canopy (Figure 2.5),

(5) sprawler-covered canopy gap (Figure 2.6), and

(6) canopy gap (Figure 2.7).

Figure 2.2: Undisturbed forest canopy (canopy category 1) in the Danum Valley Conservation Area, 1 km Northwest of the Danum Valley Field Centre.

Figure 2.3: Moderately impacted forest canopy (canopy category 2) close to raingauge R3 within the Baru Experimental Catchment

Figure 2.4: Vine-covered forest canopy (canopy category 3). A small area of vine-covered canopy (centre right) is present near to the wall surrounding raingauge number 5 (centre left) within the Baru Experimental Catchment.

Figure 2.5: *Macaranga* forest canopy (canopy category 4). The photograph shows an area dominated by *Macaranga* spp. pioneer trees on the Northeastern slopes of Bukit Atur ('Atur Hill'), just to the Northeast of the Sapat Kalisun Experimental Catchment.

Figure 2.6: Sprawler-covered canopy gap (canopy category 5). The photograph shows the sprawler-covered canopy gap that surrounds raingauge tower number 6 within the Baru Experimental Catchment.

Figure 2.7: A canopy gap on top of Bukit Atur (canopy category 6). Bukit Atur ('Atur Hill') is in the foreground, and the old radiotelephone building on its summit can be seen within the large, bare canopy gap. The double peaked hill on the horizon is Mount Danum.

2.4. Forest inventory sampling

A combination of helicopter-based aerial photography taken in 1995 (e.g., Figure 2.2 to 2.7) and ground-based observations of the forest canopy in the Baru Experimental Catchment was used to identify the location of replicate plots characterising canopy categories 1 to 4, i.e., those categories containing large trees. Species enumeration and biophysical properties of each of these categories were then measured in four randomly located replicate plots, each 100 m^2 in area. The location of these plots is shown in Figure 2.8. These sampling areas were supplemented with sampling along a 750 m long by 3 m wide transect crossing the Baru Catchment (Figure 2.8).

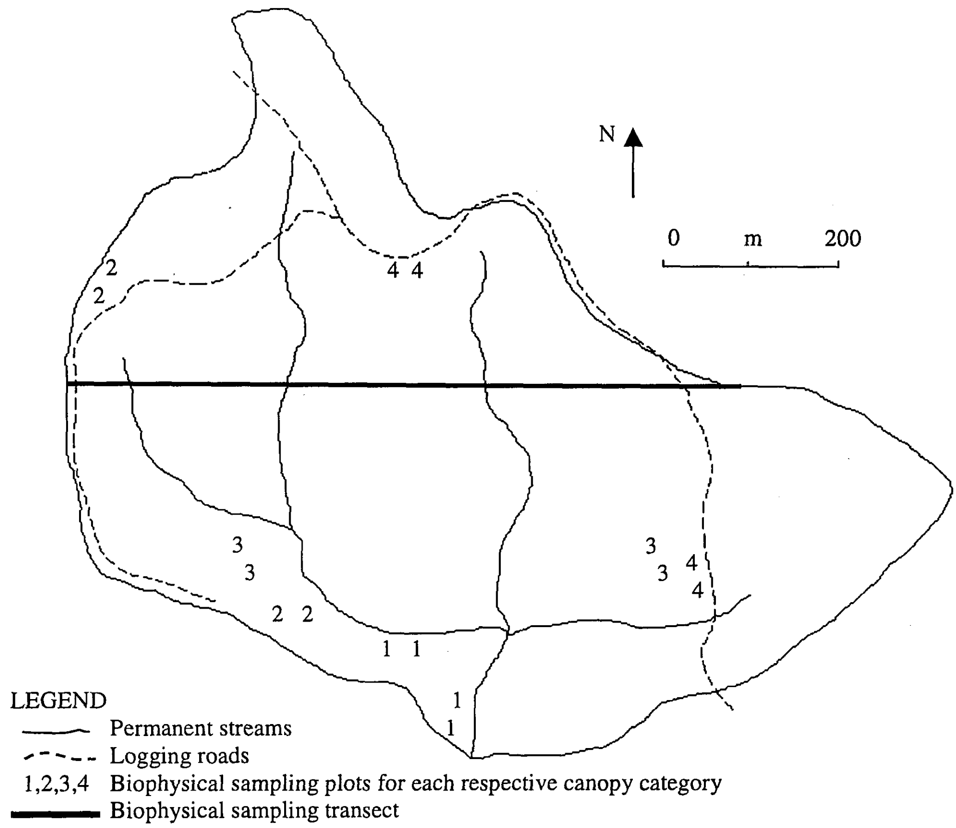


Figure 2.8: The 44 ha Baru Experimental Catchment showing the biophysical sampling plots

The girth (gbh) of all trees ≥ 2 cm in diameter (dbh) was recorded, and all trees ≥ 5 cm dbh (15.5 cm gbh) were identified. These measurements also allowed estimation of the local forest diversity, density, basal area, and timber biomass. Biodiversity was estimated using the Shannon Diversity Index (Pielou, 1977). The estimate of the timber biomass (dry weight) was derived from:

$$\text{Biomass (kg)} = [\exp(-2.134 + 2.530 * \ln(\text{dbh}))] \quad (2.1)$$

where dbh is the tree diameter breast height in cm (Brown, 1997). This equation is based on the average 'moist tropical tree species', so large uncertainties are likely, particularly for the *Macaranga* pioneer species of category 4.

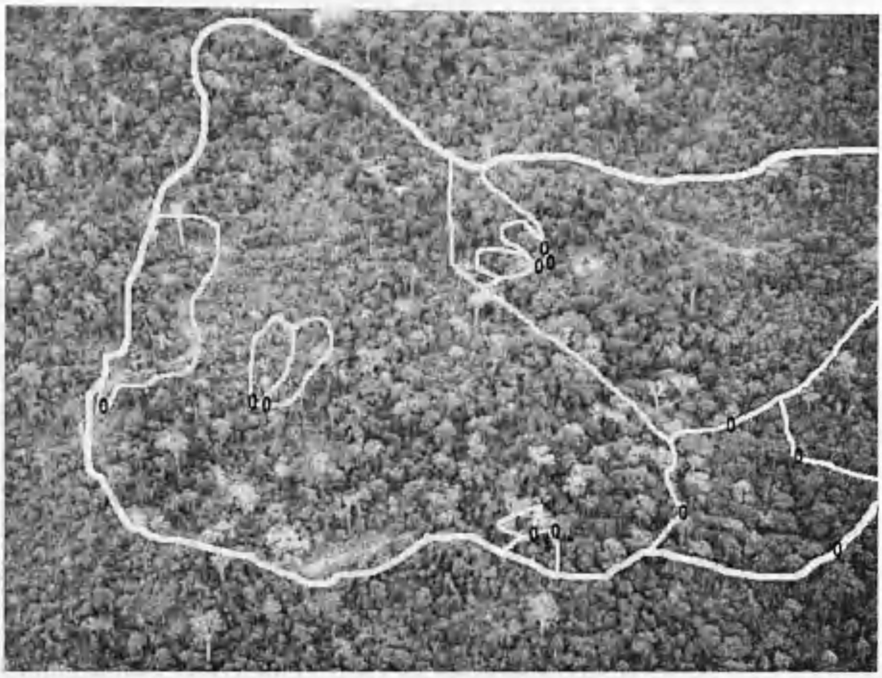


Figure 2.9: An aerial photograph showing the vegetation cover of all but the Eastern sector of the Baru Experimental Catchment. Sub-catchment areas are shown with white lines, with the stream gauging locations shown with an '0' symbol.

2.5. Botanical characteristics of each canopy category

The abundance of specific tree families and genera, together with the tree density, basal area, and biomass are all canopy characteristics that are likely to affect the rate of sub-canopy rainfall and evaporation.

2.5.1. Botanical diversity

At family level, Euphorbiaceae and Dipterocarpaceae trees dominated the 44 ha Baru Catchment area. Euphorbiaceae made up the highest percentage of the tree density within each of the canopy categories 1, 2, 4, and the transect accounting for 35.6%, 24.1%, 79.1%, and 23.3% respectively. Dipterocarpaceae became most dominant only in category 3, the vine-covered forest, with 16.3% abundance, followed by Euphorbiaceae at 10.5% (Table 2.1). These results are comparable with those of Hussin (1994) who reported that Dipterocarpaceae, Euphorbiaceae, Meliaceae, and Lauraceae accounted for 45.5% of the trees from the 44 dominant families within the whole 'Coupe 89' of the Ulu Segama Forest Reserve. There is, however, a slight difference, in that there is a higher percentage of Euphorbiaceae found in the present study, possibly resulting from continued regeneration of the selectively-logged forest since 1993. Within undisturbed natural forest adjacent to the study area enumeration of two 4 ha plots indicated that Euphorbiaceae is similarly dominant, followed by Dipterocarpaceae, Annonaceae, Lauraceae, and Meliaceae (Newbery *et al.*, 1992).

The vine-covered forest plots (category 3) are distinct from the undisturbed and moderately impacted forest, by having double the proportion (22%) of vines. The *Macaranga* forest canopy (category 4) is distinguished by the 79% abundance of *Maraganga* spp trees.

The blocks of *Macaranga* spp forest are characterised by a relatively low diversity index (Table 2.1). In contrast, the moderately-impacted and vine-covered canopies (categories 2 and 3) have greater Shannon diversity indices than the remnant blocks of undisturbed forest. This result is consistent with other enumeration studies within the Ulu Segama Forest Reserve (Tangki, In prep.) and elsewhere in the tropics (Urdabe, 1995; Uuttera *et al.*, 2000). Critically, the increased in local canopy complexity following disturbance may indicate that local variability in sub-canopy rainfall and evaporation may increase above that in the undisturbed forest.

2.5.2. Tree density

Within canopy categories 1, 2, and 3 the density of trees with a gbh ≥ 10 cm (Table 2.2) are all comparable to the 2,248 trees ha^{-1} measured by Newbery *et al.* (1992) in nearby undisturbed forest. The 699 trees ha^{-1} with a gbh ≥ 30 cm in the undisturbed forest (category 1) of the Baru Catchment is also comparable with studies undertaken in similar forest blocks throughout Borneo. For example, a density of 608 trees ha^{-1} was observed at Sepilok, Sabah (Nicholson, 1965), 628 trees ha^{-1} at Andalau, Brunei (Ashton, 1964), and 739 trees ha^{-1} at Mulu, Sarawak (Proctor *et al.*, 1983).

The tree density within areas dominated by the pioneer trees (*Macaranga* spp., canopy category 4) is, in contrast, considerably lower at 1,825 trees ha^{-1} (Table 2.2) than that within canopies 1, 2 and 3. Such a large difference in tree density may, therefore, affect the potential for rainfall interception and the resultant wet-canopy evaporation.

Table 2.1: Percentages with actual tree numbers (in brackets) of the most abundant trees at family and genus level for each canopy category. The top five abundance within each canopy is in bold.

Canopy category*	1	2	3	4	Transect
Family					
Annonaceae	0 (0)	**6.9 (4)**	4.7 (4)	0 (0)	1.8 (6)
Dilleneaceae	0 (0)	0 (0)	1.2 (1)	0 (0)	0.6 (2)
Dipterocarpaceae	**17.8 (13)**	**12.1 (7)**	**16.3 (14)**	1.2 (1)	**19.7 (65)**
Euphorbiaceae	**35.6 (26)**	**24.1 (14)**	**10.5 (9)**	**79.1 (68)**	**23.3 (77)**
Lauraceae	2.7 (2)	5.2 (3)	4.7 (4)	**2.3 (2)**	**5.8 (19)**
Leguminosae	2.7 (2)	0 (0)	3.5 (3)	**2.3 (2)**	2.1 (7)
Meliaceae	2.7 (2)	5.2 (3)	**7.0 (6)**	0 (0)	**5.8 (19)**
Moraceae	0 (0)	0 (0)	0 (0)	**3.5 (3)**	0.6 (2)
Myristieaceae	**4.1 (3)**	0 (0)	0 (0)	0 (0)	0 (0)
Myrtaceae	**9.6 (7)**	5.2 (3)	**7.0 (6)**	1.2 (1)	**4.5 (15)**
Polygalaceae	1.4 (1)	**6.9 (4)**	0 (0)	1.2 (1)	3.0 (10)
Rubiaceae	0 (0)	1.7 (1)	0 (0)	**3.5 (3)**	0.9 (3)
Tiliaceae	2.7 (2)	5.2 (3)	2.3 (2)	1.2 (1)	4.5 (15)
Vines[@]	**9.6 (7)**	**10.3 (6)**	**22.1 (19)**	2.3 (2)	+
Diversity Index[s]	2.0	2.5	2.6	1.6	2.8

Cont.'d..

Genus					
Aglaia	2.7 (2)	3.4 (2)	**5.8 (5)**	0 (0)	**5.8 (19)**
Aporusa	2.7 (2)	**5.2 (3)**	1.2 (1)	0 (0)	3.9 (13)
Dehassia	2.7 (2)	**5.2 (3)**	3.5 (3)	**2.3 (2)**	3.3 (11)
Ficus	0 (0)	0 (0)	0 (0)	**3.5 (3)**	0.3 (1)
Hopea	5.5 (4)	0 (0)	**8.1 (7)**	0 (0)	**11.2 (37)**
Knema	**6.8 (5)**	3.4 (2)	2.3 (2)	0 (0)	0.6 (2)
Koilodepas	**15.1 (11)**	0 (0)	2.3 (2)	0 (0)	0 (0)
Macaranga	0 (0)	0 (0)	0 (0)	**79.1 (68)**	**7.9 (26)**
Mallotus	**13.7 (10)**	**8.6 (5)**	4.7 (4)	0 (0)	**7.9 (26)**
Palaguim	4.1 (3)	0 (0)	0 (0)	0 (0)	0 (0)
Shorea	**6.8 (5)**	1.7 (1)	5.8 (5)	1.2 (1)	**6.1 (20)**
Vatica	4.1 (3)	**5.2 (3)**	2.3 (2)	0 (0)	1.2 (4)
Vines@	**8.2 (6)**	**10.3 (6)**	**22.1 (19)**	**2.3 (2)**	+
Xanthophyllum	1.4 (1)	**6.9 (4)**	0.0 (0)	1.2 (1)	3.0 (10)
Zyzygium	9.6 (7)	5.2 (3)	**7.0 (6)**	1.2 (1)	4.5 (15)
Diversity Index[s]	2.6	3.0	3.0	1.0	3.5

Notes:

* Trees/vegetations in canopy category 5 was not identified.

+ Vines were abundant but no measurement been taken.

@ Includes all type of lianas and climbers species.

[s] Shannon diversity index (Pielou, 1977)

Table 2.2: Tree density in number of tree ha^{-1} for different canopy categories in Baru Catchment. Values in brackets are coefficient of variation (CV%) from 4 replicate plots of each canopy category. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference. Canopy categories 5 and 6 do not contain trees, so are not shown.

	Canopy Category				Transect
gbh (cm)	1	2	3	4	
6 – 10	1325	1350	1380	325	na
10 – 30	1735	1725	1880	925	1074
≥ 10	2434	2200	2380	1500	1532
≥ 30	699	475	500	575	458
≥ 100	241	250	180	50	162
Total^{+}	3759 (20.0)	3550 (7.5)	3760 (39.2)	1825 (13.5)	1532^{++}
σ^2_{total+}	565504	70756	2172676	60516	-
Vines	554 (82.0)	775 (54.1)	1700 (50.3)	50 (150)	na
Mean difference[2]	ns				
Mean difference[3]	ns	ns			
Mean difference[4]	P<0.001	P<0.001	ns		

Notes:

na Not measured

ns Not significant at $P < 0.1$

[2] level of significance of the difference between mean total canopy category 2 and mean total canopy 1 (4 replicates)

[3] level of significance of the difference between mean total canopy category 3 and mean total canopy 1 and 2 (4 replicates)

[4] level of significance of the difference between mean total canopy category 4 and mean total canopy 1, 2, and 3 (4 replicates)

$^{+}$ not including vines

$^{++}$ not including vines and gbh class 6 – 10 cm

2.5.3. Basal area

The 58.3 m^2ha^{-1} basal area of trees with gbh ≥ 30 cm within the undisturbed forest canopy (category 1) of the Baru catchment (Table 2.3) was found to be slightly larger than that observed by other studies undertaken on Borneo Island. For example, the 35 m^2ha^{-1} of Asthon (1964), the 43 m^2ha^{-1} of Kamarudin (1986) and the 27 m^2ha^{-1} of Newbery *et al.* (1992) and the 31-35 m^2ha^{-1} of Tangki (In prep.). This greater basal area was measured in plots within 100 m of the main Baru Catchment stream. The greater likelihood of wetter soils in such downslope areas may have resulted in larger trees (*cf.* Newbery *et al.*, 1996).

Table 2.3: Tree basal area in m^2ha^{-1} for different canopy categories in Baru Catchment. Values in brackets are Coefficient of Variation (CV%) from 4 replicate plots of each canopy category. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference.

	Canopy Category				Transect
gbh (cm)	1	2	3	4	
6 – 10	0.6	0.6	0.7	0.2	na
10 – 30	4.6	3.9	4.8	2.9	3.5
≥ 30	58.3	12.8	8.7	8.8	14.9
≥ 100	53.1	9.9	5.1	2.2	11.5
Total⁺	63.5 (88.2)	17.4 (44.2)	14.1 (42.9)	11.9 (9.1)	18.4⁺⁺
σ^2_{total+}	3136	59	36	1	
Vines	0.5	1.0	1.6	0.1	na
Mean difference[2]	ns				
Mean difference[3]	$P < 0.1$	ns			
Mean difference[4]	ns	$P < 0.05$	ns		

Cont.'d...

Notes:

na Not measured

ns Not significant at $P < 0.1$

[2] level of significance of the difference between mean total canopy category 2 and mean total canopy 1 (4 replicates)

[3] level of significance of the difference between mean total canopy category 3 and mean total canopy 1 and 2 (4 replicates)

[4] level of significance of the difference between mean total canopy category 4 and mean total canopy 1, 2, and 3 (4 replicates)

[+] not including vines

[++] not including vines and gbh class 6 – 10 cm

Within the disturbed canopy categories, the total basal area of trees is much lower than that in the undisturbed forest (Table 2.3). The average basal area for canopy categories 2, 3, 4, and along the transect is, however, comparable with the 9 m^2ha^{-1} found by Tangki (In prep.) within nearby areas of selectively-logged forest.

2.5.4. Estimated biomass

The timber biomass for trees with gbh $\geq$ 30 cm within the undisturbed forest plots is 809 t ha^{-1} (Table 2.4), and is higher than the 349-506 t ha^{-1} observed by Tangki (In prep.) within nearby plots of undisturbed forest. The range in biomass of 78-249 t ha^{-1} within the disturbed blocks of forest is, as expected, lower than that in the undisturbed forest, but is comparable with the average value of 174 t ha^{-1} for logging coupes within the Ulu Segama Forest Reserve found by Tangki (In prep.). Biomass within the logging Ulu Segama coupes logged by reduced-impact methods was, however, higher at 291-400 t ha^{-1} (Pinard, 1995).

Table 2.4: Tree biomass (in t ha^{-1}) for different canopy categories in Baru Catchment. Values in brackets are coefficient of variation (CV%) from 4 replicate plots of each canopy category. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference.

gbh (cm)	Canopy Category				Transect
	1	2	3	4	
6 – 10	1.6	1.6	1.7	0.4	na
10 – 30	18.6	15.1	19.3	12.3	14.9
≥ 30	809.2	97.8	57.0	60.2	145.5
≥ 100	779.6	80.4	36.6	21.0	125.8^{++}
Total^{+}	829.4 (104.6)	114.5 (59.8)	78.0 (55.9)	72.9 (22.4)	160.3
σ_{total+}	867.6	68.5	43.6	16.3	-
σ^2_{total+}	752730	4692	1901	266	
Total Vines	1.8	3.9	5.0	0.2	na
Mean difference ^{2}	ns				
Mean difference ^{3}	P < 0.1	ns			
Mean difference ^{4}	ns	P < 0.1	ns		

Notes:

na Not measured

ns Not significant at P < 0.1

^{2} level of significance of the difference between mean total canopy category 2 and mean total canopy 1 (4 replicates)

^{3} level of significance of the difference between mean total canopy category 3 and mean total canopy 1 and 2 (4 replicates)

^{4} level of significance of the difference between mean total canopy category 4 and mean total canopy 1, 2, and 3 (4 replicates)

$^+$ not including vines

$^{++}$ not including vines and gbh class 6 – 10 cm

2.6. Estimated spatial extent of each canopy category

The estimated area occupied by each canopy category was derived by combining an examination of the aerial photographs of the Baru Catchment, taken from heights of 50 m to over 1000 m above the forest, with several years of experience of working throughout the catchment. Table 2.5 shows the spatial extent of each category. The 18% of the catchment remaining in undisturbed forest blocks is very similar to that qualitatively estimated by Nussbaum *et al.* (1995) within Coupe 88 and 89. The Nussbaum *et al.* (1995) estimate of 30% of the Coupe 88 and 89 being occupied by log-landings and skid trails (haulage roads were not defined) is, however, larger than the areas defined as bare ground (category 6) and low vegetation (category 5) within the Baru catchment, and the category 5 canopy includes areas other than old log-landings and skid trails. Such differences are probably due to the large variations in harvesting impact over distances of several kilometres.

Table 2.5: Contribution of each canopy category within the 44 ha Baru Experimental Catchment, Ulu Segama Forest Reserve, Sabah, Malaysia

	Spatial extent of each canopy category					
	1	2	3	4	5	6
Best estimate (%)	18	25	30	10	10	7
Likely uncertain range (%)	± 3	± 3	± 5	± 4	± 3	± 2

2.7. Conclusions

The 44 hectare area of selectively-managed forest that comprises the Baru Experimental Catchment has been qualitatively classified into the six categories of: (1) undisturbed forest canopy, (2) moderately impacted forest canopy, (3) vine-covered forest canopy, (4) *Macaranga* forest canopy, (5) sprawler-covered canopy gap, and (6) canopy gap. Statistical analysis indicates that these categories, easily distinguishable from visual characteristics of their respective canopies, can be objectively identified using biophysical data.

The remnants of undisturbed forest canopy (canopy 1), which occupy 18 ± 3 % of the catchment, can be separated on the basis of their much higher tree basal area (i.e., >> 30 m^2 ha^{-1}) and estimated biomass (i.e., >> 300 t ha^{-1}). The density of vines might be able to be used to separated the 'moderately impacted forest canopy' (canopy category 2) from the 'vine-covered forest canopy' (canopy category 3). Within the areas categorised as 'vine-covered forest canopy' the basal area of vines >> 1.0 m^2 ha^{-1}. The patches of forest dominated by *Macaranga* spp. (i.e., 79 % of all tree genera), that occupy 10 ± 4 % of the catchment, have a characteristically low canopy complexity (i.e., Shannon diversity index of << 2.0) and tree density (i.e., << 300 t ha^{-1}). After some eight years following the first (and only) harvesting activity, 17 ± 4 % of the catchment remains without pioneer or climax trees (larger than saplings). As a result, these areas (canopy category 5 and 6) are easily distinguishable from the categories 1, 2, 3, and 4.

Given that the visual differences in the six canopy categories defined are supported by measurable differences in the biophysical properties, each canopy may intercept, store and release different quantity rainfall, and thereby result in different rates of wet-canopy evaporation (Chapter 6).

Chapter 3

Errors with simple storage raingauges under tropical forest conditions

To be submitted as Bidin, K., Chappell, N.A. and Dalimin, M.N. Errors with a simple storage rainagauges under tropical forest conditions. *Singapore Journal of Tropical Geography.*

Sub-canopy rainfall (*i.e.*, throughfall and stemflow) within rainforests, particularly those affected by selective harvesting, is highly heterogeneous, and requires very large numbers of gauges for accurate assessment. If a raingauge can be designed that is easy and inexpensive to build, yet does not significantly affect the accuracy of catch, then this would be of considerable value to studies addressing the spatial variability of rainfall, throughfall and wet-canopy evaporation within such tropical forest environments. This chapter presents the design of an inexpensive, storage raingauge that was used for studies on rainfall and evaporation variability (Chapters 4, 5, 6). Tests to identify the source and magnitude of the catch error were undertaken within an area of selectively-managed rainforest in Malaysian Borneo.

With the typical weekly or storm-based sampling associated with wet-canopy evaporation studies, errors due to gauge evaporation, gauge wetting and volumetric recording were seen to be very small (*i.e*, -0.54 %, -0.198 % and ± 0.025 %, respectively), as was the difference (-0.110 %) between the catch from these gauges and that of adjacent, commercially available raingauges. While the study incorporated only limited testing, such results indicate that catch errors with the simple raingauge design presented, remain within the 5 % error expected of commercial, storage raingauges.

3.1. Introduction

Studies addressing the local spatial variability of rainfall and wet-canopy evaporation in forested catchment require large numbers of rain-gauges and throughfall-gauges for accurate statistical quantification of the patterns and rates. If commercially available raingauges are required, then costs can be restrictive. An alternative solution is the self-construction of simple raingauges. As these are not likely to be built to the same exacting standards as commercial gauges, then robust error analysis is required to ensure that the increase in catch uncertainties have not become too large. It is worth noting, that raingauge errors are rarely quantified even in the most well supported studies of interception processes (*e.g.* Asdak *et al.,* 1998b).

This chapter, therefore, aims to describe the design of a simple storage raingauge used for measurement of gross- and net- rainfall within a region of equatorial rainfall in Malaysian Borneo (Chapter 6). The chapter then seeks to identify the catch errors associated with using the gauges within this environment and to propagate these errors to give a final uncertainty value. Such compound uncertainty estimates are required to prevent over-interpretation of maps of the local variability of rainfall (Chapter 4).

3.2. Design of a simple storage raingauge

The principal components of any storage raingauge are the collecting funnel and storage container (Winter, 1955). In this study, a 4-litre cylindrical plastic bottle, with the base removed, was used as funnel and 5-litre carbouy used as a storage container (Figures 3.1 and 3.2). The gauge was sat on the ground surface, and a metal stake driven 0.25 m into the ground to keep it vertical.

The funnel had a fall of 24 cm between the orifice and the base to reduce out-splash, and the orifice collected rainfall at a height of 54 cm above ground level to reduce in-splash (Struzer *et al.*, 1968). The orifice area is 180 cm^2. For comparison, the UK Meteorological Office Mark II standard gauge, as used by many meteorological departments throughout the world, has an orifice height of 30 cm above the ground, a funnel drop of 14.5 cm and an orifice area of 127 cm^2. As the dimensions of the simple gauge are larger than these, the simple gauge maybe less sensitive to in- and out- splash errors.

At the base of the funnel of the simple gauge, two 5 mm diameter holes (*cf.* Winter, 1955) channel the water into storage container. Their small size should help to reduce evaporation losses (Golubec, 1960). Additionally, the storage vessel of the raingauge is painted white to increase the albedo, and hence reduce the evaporation potential. The storage container can store the equivalent of about 280 mm depth of rainfall. As the greatest rainfall recorded at site (1986-2000) is 170 mm, the storage should be sufficient for daily sampling.

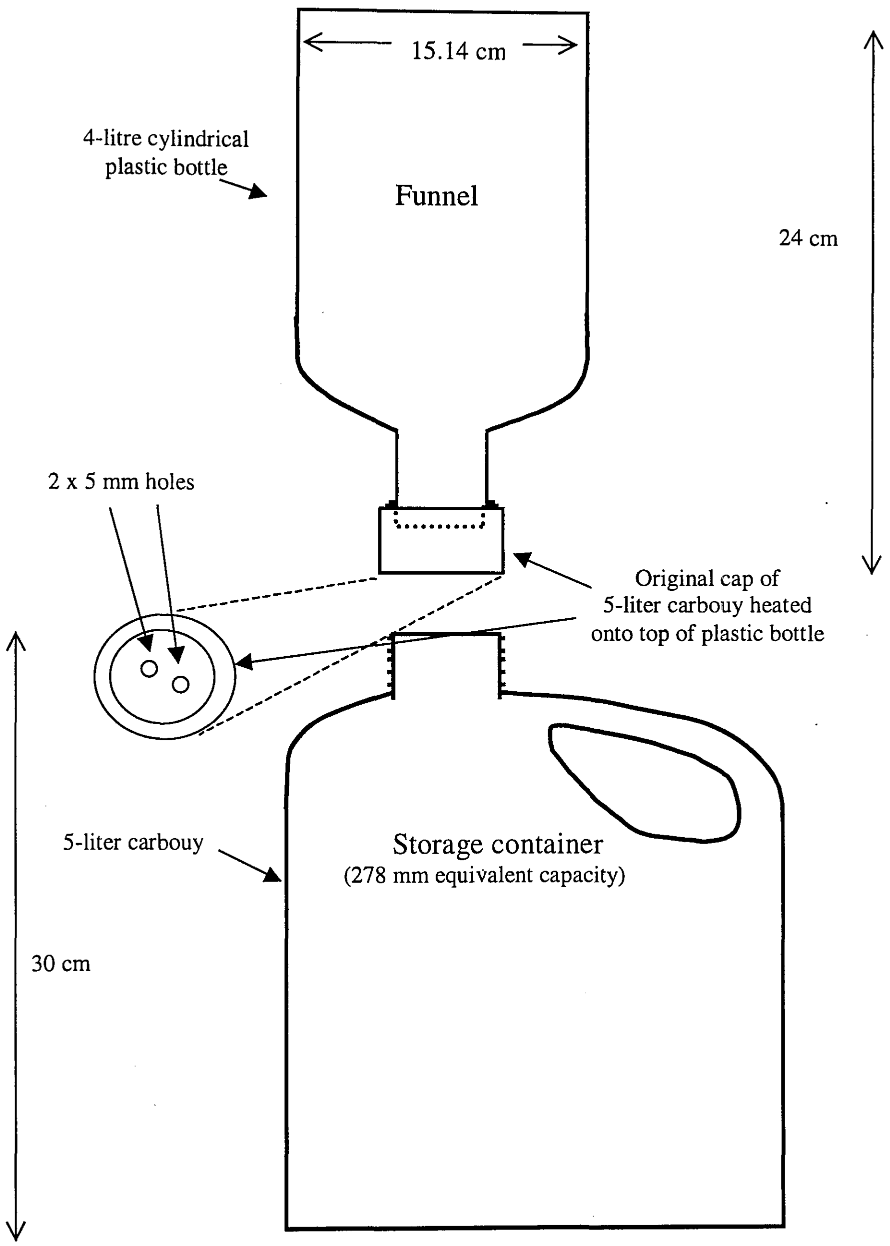


Figure 3.1: Schematic diagram of the simple storage raingauge tested within this study

Figure 3.2. Photograph of the simple storage raingauge tested within this study

3.3. Test conditions

The experiments were conducted at the vicinity of the Danum Valley Field Centre (DVFC) in the Malaysian state of Sabah on the Northeastern coast of Borneo Island (5°01' North and 117°48.75' East). The annual average rainfall totals recorded at the DVFC meteorological station (1986-2000) is 2,764 mm, with standard deviation of 466 mm. The two principal Southeast Asian monsoon wind directions in this part of Eastern Sabah – the Southwest monsoon (May-October) and Northeast monsoon (November-April) both deliver relatively similar totals (Chappell *et al.*, 2001; Chapter 5). The average daily maximum and minimum temperatures recorded at this site are 30.9 °C and 22.5 °C, respectively. The average relative humidity at 8 am is 94.5% and at 2 pm 72% (Marsh and Greer, 1992).

DVFC lies within the Brassey Range of hills in Eastern Sabah, where the highest peak, Mount Danum, is at 1,093 m a.s.l. (Marsh and Greer, 1992). Mount Danum is approximately 12.5 km Southwest of DVFC.

The natural vegetation within the DVFC region is 'lowland, evergreen dipterocarp' forest, with the upper canopy being dominated by *Parashorea malaanonan, P. tomentella* (both white Seraya), *Shorea johorensis* (Red Seraya) and *Rubroshorea spp.* (Marsh and Greer, 1992). These trees stand at height up to 70 m. Some commercial trees were, however, selectively removed from the region East of DVFC.

This study has sought to quantify the errors associated with the use of more than 450 of these simple storage gauges within the Sapat Kalisun Experimental Catchment adjacent to DVFC (Chapters 4 and 6).

3.4. Component errors

3.4.1. Effect of storage container evaporation

Many studies of wet-canopy evaporation (*e.g.* Lloyd and Marques 1988; Wong 1991; Asdak *et al.*, 1998) involve the emptying of net rainfall collected on a weekly basis. In hot climates there is the concern that some of the collected rainfall may evaporate from the storage container between capture and measurement (Kurtyka, 1953; Gill, 1960; Goodrich *et al.*, 1995). An experiment was undertaken with two simple storage gauges over the 5-month period from 1st November 1997 to 30th March 1998.

Both gauges were emptied at 8 am every day. One gauge was then left empty for subsequent catches, while exactly 1000 cm^3 was added to the second gauge. A volume of 1000 cm^3 is the equivalent to 5.56 mm depth of rainfall, the average daily rainfall recorded over the monitoring period November 1997 to March 1998. The average rate of evaporative loss over the same monitoring period was 3.60 mm.

During this same period, a nearby UK Meteorological Office Mark II raingauge recorded 657.6 mm of rainfall. The resultant percent error (ε_{bias}) is therefore:

$$100\left[\frac{-3.6mm}{657.6mm}\right] = -0.547\% \qquad [3.1]$$

As this period, was one of the driest on record, as a result of the particularly severe 1997/98 ENSO drought (Chappell *et al.*, 2001), this percent error may be larger than for a wet year. This figure is, however, smaller than the –1% to –1.5% evaporation error recorded by Gill (1960) in tropical conditions.

The small evaporation losses from the simple gauge in this study are probably the result of the small diameter of hole connecting the funnel to the storage collector. An evaporation rate over the same period for a 0.7 m diameter evaporation pan amounted to 190.3 mm. Thus, the simple gauge evaporated only 1/35 of the rate of an evaporation pan.

3.4.2. Effect of funnel and storage container wetting

Goodrich *et al.* (1995) states that for catch totals equivalent to only a few millimetre of rainfall, the adhesive effect of rainfall on the collector walls can be an area of concern. An experiment where exactly 1000 cm^3 of water was poured into and then out of the simple gauge then undertaken to see the recovery rate. An average of 2 cm^3 of water, equivalent to 0.011 mm of rainfall caught by the gauge, was not recovered. The average recording volume for the simple gauge during the studies described in Chapters 4 and 6 (*i.e.*, November 1997 to March 1998) was 5.56 mm. Thus the percentage bias error (ε_{bias}) due to raingauge wetting was, therefore:

$$100\left[\frac{0.011mm}{5.56mm}\right] = -0.198\% \qquad [3.2]$$

3.4.3. Effects of error in volumetric recording

A 250 cm^3 plastic measuring cylinder was used to measure the rainfall stored within the simple storage raingauges. The volume within this cylinder could be visually measured to ± 0.25 cm^3. As the typical sampling volume is 1000 cm^3, this gives a percent precision error ($\varepsilon_{precision}$) of :

$$100\left[\frac{\pm 0.25mm^3}{1000mm^3}\right] = \pm 0.025\% \qquad [3.3]$$

3.4.4. Compound error from evaporation, wetting and measurement

As the error associated with the measurement of the stored water (Section 3.4.3) is independent of the losses due to evaporation (Section 3.4.1) and losses due to surface wetting (Section 3.4.2), the errors can be added in quadrature (Taylor, 1982; Chappell and Ternan, 1997):

$$EWM = \sqrt{(\pm 0.025)^2 + (-0.547)^2 + (-0.198)^2} \qquad [3.4]$$

The total uncertainty (EWM) derived from the evaporation, wetting and measuring-cylinder errors identified is ± 0.582%.

3.5. Comparison with commercial raingauges

In addition to errors associated with the effect of evaporation from the storage container, wetting of raingauge surfaces, and measuring cylinder errors, the simple storage raingauges will be subject to associated with un-level raingauge orifices, and local turbulence at the orifice. The increase in catch error resultant from using the simple storage gauges rather than commercial (storage) raingauges were assessed in a further experiment.

Ten simple raingauges were used to derive a direct measurement of the total or compound catch error (ε_{total}). These gauges were installed about 10 m from the 3-standard gauges comprising of (i) a UK Meteorological Office MKII storage gauge, (ii) a siphoning-tank raingauge equipped with a chart recorder, and (iii) a second siphoning-tank raingauge where the siphoning mechanism had been replaced by a storage tank. All raingauges were measured daily throughout October 1997. A 250 ml measuring cylinder was used to measure the rainwater volume collected by the simple raingauges.

The arithmetic mean rainfall within October 1997 was 145.47 mm for the commercial raingauges and 145.31 mm for the simple storage gauges (Table 3.1). This short-term experiment, therefore, gave a total error (ε_{total}) of:

$$100\left[\frac{(145.31mm - 145.47mm)}{145.47mm}\right] = -0.110\% \qquad [3.6]$$

for the simple storage gauges against commercial gauges. For the catches greater than 20 mm, the coefficient of variation amongst the commercial gauges ranged from 0.8 to 2.8 %, while the simple gauge had a slightly larger uncertainty of 2.0 to 5.0 % (Table

3.1). Uncertainties in daily catches greater than 20 mm, therefore, have less than the 5 % which is consistent with the figures noted by Helvey and Patric (1965).

As expected, the errors for very small rainfall catches of a few millimetres per day are high, but decline exponentially (Figure 3.3), similar to the trend reported by Hutchinson (1969).

Table 3.1: Comparison of catches by 3 commercial raingauges with those of 10 simple storage gauges for raindays by October 1997.

	Simple storage gauges (N = 10)			Commercial gauges (N=3)		
DATE	Mean	SD (mm)	CV (%)	Mean	SD (mm)	CV (%)
4/10/97	0.89	0.20	22.46	1.13	0.35	30.99
6/10/97	49.32	1.81	3.66	48.83	0.40	0.83
7/10/97	5.91	0.20	3.44	5.83	0.25	4.31
9/10/97	1.57	0.25	15.93	1.73	0.31	17.63
11/10/97	10.71	0.46	4.28	10.97	0.31	2.79
16/10/97	9.93	0.51	5.12	11.13	1.04	9.35
19/10/97	21.66	1.08	4.97	20.67	0.45	2.18
23/10/97	21.33	0.43	2.02	20.80	0.56	2.68
24/10/97	9.31	0.54	5.77	9.40	0.26	2.81
26/10/97	9.76	0.44	4.51	9.67	0.64	6.57
28/10/97	4.91	0.36	7.27	5.30	0.36	6.80
Total	145.31	2.68	1.85	145.47	3.07	2.11

Notes:

SD – standard deviation

CV –coefficient of variation

N – number of gauges

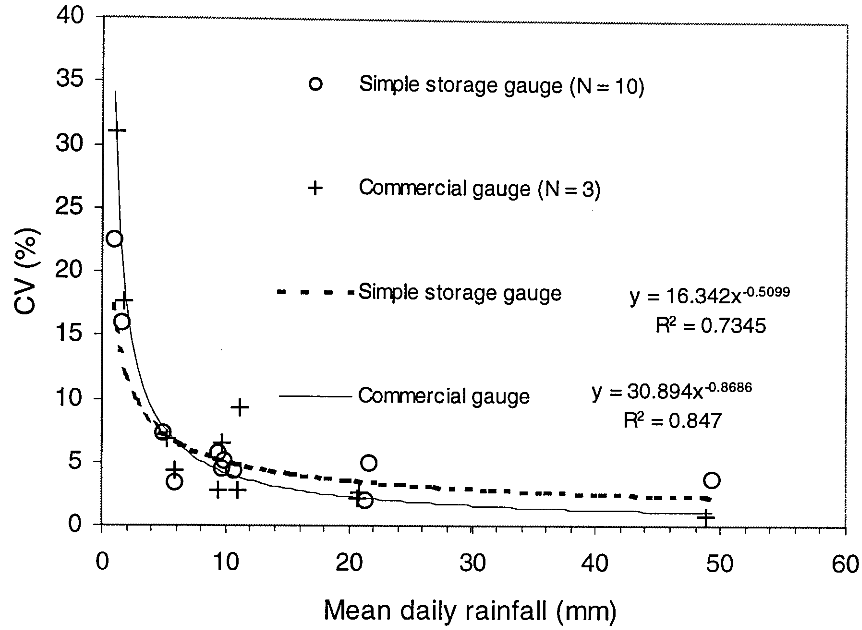


Figure 3.3: Daily rainfall catches showing the effect of rainfall size on the variation.

3.6. Conclusions

The simple raingauge design presented, based on the use of two inexpensive plastic bottles, did not give large catch errors when tested for evaporation losses (*i.e.*, only -0.54 % error per month), inner-surface wetting errors (*i.e.*, only -0.198 % error with weekly sampling) or volumetric recording (*i.e.*, ± 0.025 % error with sampling). Catch differences between these gauges and standard raingauges (*e.g.*, UK Meteorological Office Mark II gauge) were similarly small, at -0.110 % additional error, over a month's sampling. While more extensive testing needs to be undertaken with this simple raingauge design, the evidence so far suggests that weekly or storm-based catches from these gauges do not have significantly larger errors than the < 5 % error expected of commercially-built storage raingauges.

Chapter 4

Dynamic spatial pattern of rainfall within a 4-km^2 tropical catchment

To be submitted as Bidin, K., Chappell, N.A., Dalimin, M.N. and Sinun, W. Dynamic spatial pattern of rainfall within a 4-km^2 tropical catchment. *Agricultural and Forest Meteorology*.

An understanding of the spatial variability of rainfall at the scale of the 0.1 to 10 km^2 experimental catchment, particularly where rainfall is predominantly convective in nature, is essential for accurate rainfall-runoff modelling. With the increasing desire to model the impacts of land-use change on the behaviour of tropical catchments, comes a need for an understanding of magnitude and causes of local variations in rainfall.

This study analyses the spatial variability of rainfall across a network of 46 raingauges within a 4 km^2 rainforest catchment within the interior of Northeastern Borneo. Rainfall-runoff and sediment production and transport studies are taking place within the same area.

The inter-gauge correlation analysis undertaken shows that the region experiences a very high degree of rainfall variability, even when compared with other areas strongly affected by convective rainfall activity. Spatial structure is, however, apparent within the rainfall patterns when correlations between topographic variables of altitude and aspect are undertaken. Moreover, the patterns change dramatically from the Southwest monsoon (May-October) to the Northeast monsoon (November-April) as the dominant winds reverse. Physical interpretation of the rainfall patterns is only achieved with the aid of a conceptual model of wind field within undulating terrain of the area. Indeed, the work should be extended with the application of a numerical model to the local wind fields within the area.

4.1. Introduction

Increasing research efforts in both temperate and tropical environments are directed towards the topographic controls on eco-hydrological processes. Topography can exert a strong control on the patterns of soil moisture and the locations of returning subsurface water. Indeed, several catchment rainfall-runoff models, notably Topog_SBM and TOPMODEL, have been developed as a result of these empirical observations, and have been recently applied to data for tropical catchments (Chappell *et al.*, 1998b; Vertessy and Elsenbeer, 1999). The topographic control on soil moisture has also been shown to impact on tropical plant ecology, with some tree species preferring dry ridge top locations and others wetter streamside areas (Ashton, 1964; Newbery *et al.*, 1996). Clearly, if the topographic affect on the amount of rainfall received is significant at the scale of these modelling or ecological studies, then the spatial controls on the rainfall pattern must be characterised in order to separate them from the controls on the re-distribution of subsurface water.

As many hydrological and ecological research programmes, such as interception studies, are undertaken within experimental plots of a few metres square replicated over a region of a few hectares or square kilometres (*e.g.* Wong, 1991), then such studies would also benefit from an understanding of the local control of the rainfall pattern.

This study examines the spatial variability in rainfall over a network of 51 storage gauges sited within the 4-km^2 Sapat Kalisun Experimental Catchment (Figure 4.1). This catchment is within a region, centred on the Danum Valley Field Centre (DVFC), which is a focus for research on hydrological flows, erosion, plant ecology and physiology. These research programs would greatly benefit from a greater understanding of rainfall pattern.

4.2. Experimental region

The Sapat Kalisun Experimental Catchment (ca. $4^{o}58'$N and $117^{o}48'$E) is located approximately 50 km west from the Eastern coast of Sabah, Malaysian Borneo (Chappell *et al.*, 2001). Outflows from the Sapat Kalisun Experimental Catchment enter the River Segama, in its headwater reaches. This major river then drains to the Sulu Sea off the Northeast coast of Sabah.

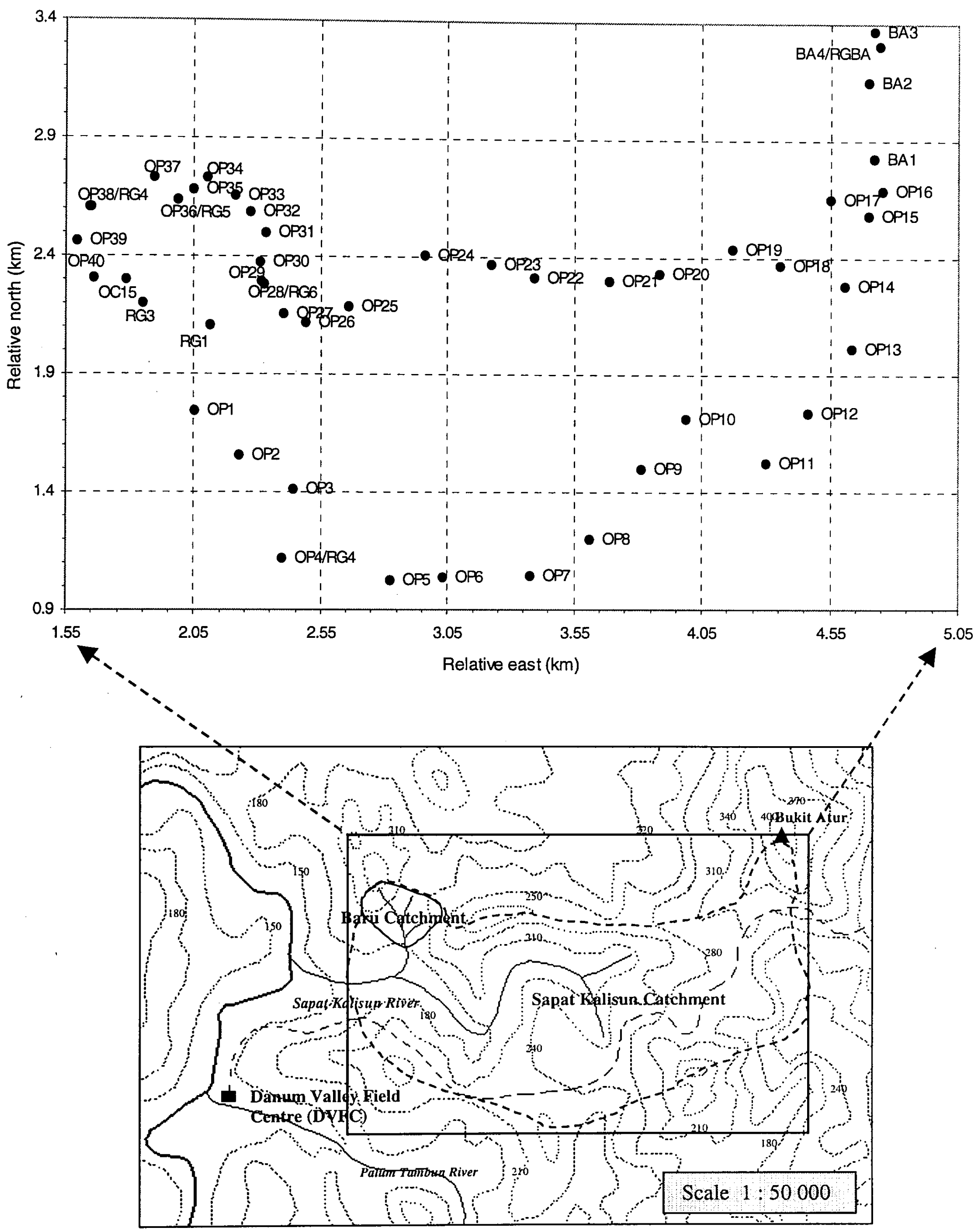


Figure 4.1: Distribution of the simple storage raingauges (OP, BA, OC) and the recording raingauges (RG) monitoring rainfall within the 4-km^2 Sapat Kalisun Experimental Catchment. The gauge number begins with a symbol, where OP is roadside gap site, BA is an opening on Atur Hill (Bukit Atur) and OC is canopy gap away from haulage roads.

4.2.1. Climate

The average annual rainfall total recorded at the DVFC meteorological station (1986-1999) is 2,712 mm, with standard deviation of 435 mm. The two principal Southeast Asian monsoon wind directions – the Southwest monsoon (May-October) and Northeast monsoon (November-April) both deliver relatively similar totals in this part of Sabah (Chappell *et al.*, 2001; Table 4.2). Air temperatures and relative humidity is also measured at the DVFC meteorological station, which is located in a large forest clearing by the River Segama. The average daily maximum and minimum temperatures recorded at this site are 30.9 °C and 22.5 °C, respectively. The average relative humidity at 8 am is 94.5% and at 2 pm 72% (Marsh and Greer, 1992).

4.2.2. Topography

The Sapat Kalisun Experimental Catchment lies within the Brassey Range of hills in Eastern Sabah, where the highest peak, Mount Danum, is at 1093 m a.s.l. (Marsh and Greer, 1992). Mount Danum (or 'Gunung Danum') is approximately 19.5 km Southwest of the centre of the Sapat Kalisun Catchment. The altitudinal range within Sapat Kalisun Experimental Catchment itself is 132 to 436 m, the highest point being the summit of Atur Hill or 'Bukit Atur' (Figure 4.1).

4.2.3. Vegetation

The natural vegetation within the Sapat Kalisun Catchment is 'lowland, evergreen dipterocarp' forest, with the upper canopy being dominated by *Parashorea malaanonan, P. tomentella* (both White Seraya), *Shorea johorensis* (Red Seraya) and *Rubroshorea spp.* (Marsh and Greer, 1992). Some commercial trees were, however, selectively removed from the Sapat Kalisun Experimental Catchment during the period 1988-89 (Greer *et al.*, 1995) and from its Southwest corner in the early 1980s (Waidi

Sinun pers. comm). This commercial forestry activity has left a mosaic of land cover (Chapter 2). As a consequence, the canopy surface and its properties such as albedo are very uneven, thereby potentially affecting local wind fields and evaporative transfers.

4.3. Raingauge network and sampling

A total of 51 storage raingauges were installed within the 4-km^2 Sapat Kalisun Experimental Catchment. The gauges were designed specifically for the project, and the point measurement errors for storm rainfalls evaluated and found to be < 5 % (Chapter 3). The records from five of these gauges were not used, due to regular damage by elephant and wild boar. Most of the gauges were located along forestry haulage roads, typically at a distance of 250 to 400 m apart. The large canopy opening (typically with a minimum width of 20-40 m) along the roads minimised the sheltering effects of the forest canopy. Fifteen of the raingauges were clustered within the 44 ha Baru Experimental Catchment (equivalent to 1 gauge for every 3 ha), a tributary area for Sapat Kalisun (Figure 4.1) that has been subject to intensive hydrological and erosion studies (*e.g.* Douglas *et al.*, 1992 & 1999; Greer *et al.*, 1995; Chappell *et al.*, 1998ab, 1999). The precise location of all of these gauges was measured using a Total Station, which is a combined electronic theodolite and laser distance system (Leica TC400). Closed-loop traverses were used to both quantify and minimise the errors. The minimum slope distance amongst the gauges in a pair was 17 m, the average was 1.52 km and maximum 3.3 km.

The gauges were monitored every 11 days on average throughout the water year 1st May 1997 to 30th April 1998. This period was in fact the driest 12-months period on record (1986-1999), being strongly affected by the regionally extensive 1997/98 drought related to the El Niño-Southern Oscillation or 'ENSO' (Kane, 1999).

A UK Meteorological Office Mark II (storage) raingauge is located at the DVFC, approximately 2-km Southeast of the centre of Sapat Kalisun Experimental Catchment. The daily rainfall totals, recorded at this site since 1986, will be used to place the Sapat Kalisun Experimental Catchment within the long-term (*i.e.*, inter-annual) setting. Rainfall intensity data-series derived from a siphoning-tank raingauge and eight datalogged, tipping-bucket raingauges (RG on Figure 4.1) are also available for Sapat Kalisun Experimental Catchment (see *e.g.*, Chappell *et al.*, 1999), though these data are not analysed within this Chapter.

4.4. Location-independent spatial variability

During the water-year 1st May 1997 to 30th April 1998, the DVFC raingauge recorded 1,520.7 mm precipitation. This figure is 1.7 percent more than the average rainfall of 1,495.8 mm recorded across the 46 reliable gauges within the Sapat Kalisun Experimental Catchment (Table 4.1). With the DVFC rainfall total being only 42.3 percent of the normal rainfall over 1986-1998 period, then the patterns in the statistical and spatial distribution of rainfall may be representative only of those patterns associated with an ENSO drought.

Table 4.1: Descriptive statistics of rainfall totals for individual time of measurements and periods of monitoring. The 'paired two samples for mean' of the South-west and North-east monsoons totals was significant in different at $P < 0.001$ ($t=10$, $df = 32$).

Sampling Period (Days)	N_d	Sampling Day	ξ (mm)	Min (mm)	Max (mm)	σ (mm)	CV%	σ_y (mm)
13	1	13/05/97	8.2	3.6	12.9	2.3	27.6	0.3
7	6	20/05/97	113.9	83.8	158.3	18.5	16.3	2.8
6	2	26/05/97	10.7	4.9	22.3	4.4	41.3	0.7
6	1	01/06/97	22.4	4.9	37.2	8.7	38.9	1.5
17	3	18/06/97	10.3	0.4	27.0	7.9	77.3	1.2
8	4	26/06/97	35.6	12.4	63.5	13.1	36.7	1.9
12	6	08//07/97	73.2	0.4	96.7	15.1	20.7	2.4
3	2	11/07/97	54.0	27.8	120.1	22.7	42.0	3.4
10	5	21/07/97	89.1	60.8	119.1	14.9	16.7	2.2
5	2	26/07/97	14.6	0.4	25.0	4.8	32.6	0.7
4	2	30/07/97	24.0	13.8	41.6	6.6	27.4	1.0
12	4	11/08/97	51.8	18.5	98.9	19.9	38.3	3.0
8	4	19/08/97	26.8	13.2	44.0	7.9	29.5	1.2
18	3	06/09/97	54.2	31.8	80.3	12.7	23.4	1.9
7	2	13/09/97	26.9	13.9	43.4	5.7	21.2	0.8
4	3	17/09/97	14.1	3.6	36.8	7.7	54.5	1.2
6	2	23/09/97	84.7	40.8	128.6	28.6	33.7	4.3
13	5	06/10/97	46.1	33.9	63.7	7.6	16.5	1.1
2	2	08/10/97	17.4	5.8	27.3	5.8	33.5	0.9
13	5	21/10/97	48.4	33.2	61.5	5.9	12.1	0.9
15	7	05/11/97	49.2	29.9	69.7	10.1	20.4	1.5
6	5	11/11/97	93.0	75.8	122.4	12.2	13.2	1.8
16	nc	27/11/97	40.8	29.0	59.4	6.3	15.4	0.9
12	nc	09/12/97	63.3	45.6	104.4	10.4	16.4	1.5
7	nc	16/12/97	18.1	6.6	29.7	6.1	33.8	0.9
6	nc	22/12/97	20.4	14.7	26.4	2.8	13.8	0.4
14	nc	05/01/98	68.4	49.0	95.1	10.7	15.6	1.6
7	nc	12/01/98	12.1	6.0	22.3	2.7	21.9	0.4
29	nc	10/02/98	98.6	64.8	139.6	17.4	17.6	2.6
15	nc	25/02/98	85.1	48.9	108.5	13.2	15.5	2.0
16	nc	13/03/98	60.4	27.7	90.7	18.7	31.0	2.8
29	nc	11/04/98	60.0	40.3	72.0	5.9	9.9	0.9
19	nc	30/04/98	14.9	6.7	24.7	4.9	32.7	0.7
		Average	45.8	25.8	68.9	10.4	27.2	1.6
Periods of Monitoring		Southwest monsoon	860.3	669.0	1098.4	103.8	12.1	15.5
		Northeast monsoon	635.1	555.7	770.2	55.3	8.7	8.2
		Calendar year	1495.8	1300.9	1726.6	92.5	6.2	13.8

Notes:
nc = not counted; N_d = number of daily events in data; ξ = mean catch
CV% = Coefficient of variation; σ = Std. Deviation; σ_y = Std Error

The data distribution of storm-based rainfall totals across Sapat Kalisun Experimental Catchment is seen to be Guassian for both 6-month and 12-month integration periods (Figure 4.2). The catchment-average rainfall totals for the Southwest monsoon were, however, seen to be statistically different ($P < 0.001$) to those for the Northeast monsoon of the 1997/98 water-year (Table 4.1). In contrast, there is no statistical difference ($P < 0.1$) in the DVFC-gauge rainfall total between the two 6-month periods if all of the 13-year records from May 1986 to April 1998 are examined (Table 4.2). It may be concluded, therefore, that in this region of North-eastern Borneo the proportion of the annual rainfall appearing within each monsoon may change dramatically from year to year, and that one monsoon is not consistently wetter than the other.

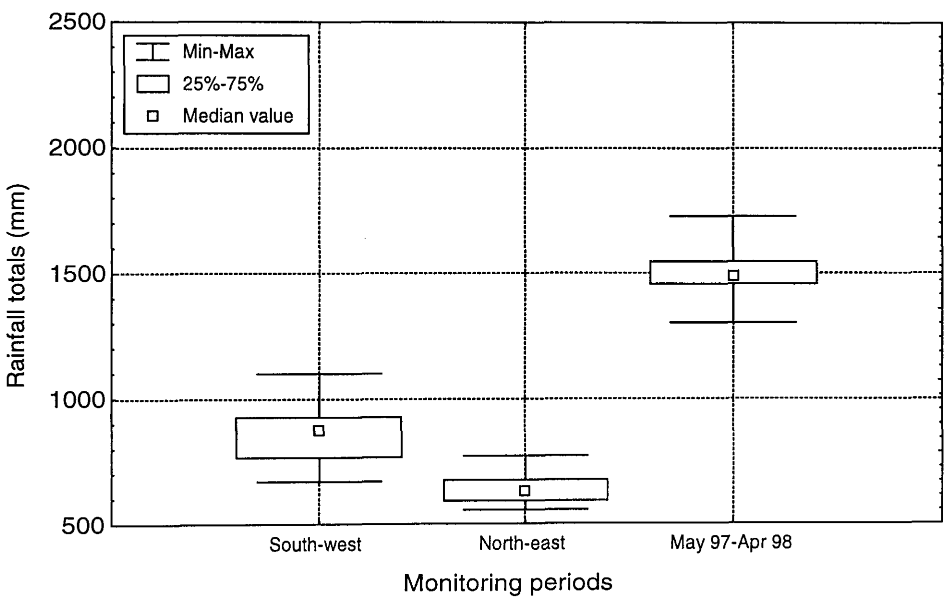


Figure 4.2: Box-and-whisker plots (Wrinkler and Hays, 1975) of the statistical distribution of 6-month and 12-month rainfall totals during the Southwest monsoon (1 May 1997 to 31 October 1997), Northeast monsoon (1 November 1997 to 30 April 1998) and water year 1 May 1997 – 30 April 1998.

The coefficient of variation (CV) for the rainfall totals in Sapat Kalisun Experimental Catchment varies between the 6-month integration periods. The Southwest monsoon has a CV of 12.1 percent, while the Northeast monsoon has a CV of only 8.7 percent

(Table 4.1). The large CV for Southwest monsoon also can be seen in the larger range, with the highest catch of 1,098.4 mm (OP17) receiving 64.2 percent more rainfall than the lowest catch of 669.0 mm at gauge OP25. The CV over the whole year is 6.2 percent (Table 4.1). The greater relative variation in gauge catches over the Southwest monsoon may reflect either (i) a greater proportion of the rainfall falling in localised cells of meso-scale convective systems, or (ii) stronger local topographic forcing with the winds arriving from a South-westerly direction.

Table 4.2: Seasonal rainfall totals for DVFC study area from May 1986 to April 1998

Years	South-west	North-east	May - Apr (water year)
86/87	962.5	1124.7	2087.2
87/88	1080.7	1733.3	2814
88/89	1134.3	1685.2	2819.5
89/90	1728.4	1153.6	2882
90/91	1596.55	1088.7	2685.25
91/92	1308.95	931.9	2240.85
92/93	1616	1384	3000
93/94	1113	1609.5	2722.5
94/95	1179.9	1470.1	2650
95/96	1969.9	1821.2	3791.1
96/97	1324.7	1112	2436.7
97/98*	857.5	663.2	1520.7
Mean	1322.7	1314.8	2637.5
σ (mm)	322.7	342.8	527.9
CV (%)	24.4	26.1	20.0
σ_y (mm)	93.1	99.0	152.4

Notes:
* Study period
σ = Std. Deviation
CV = Coefficient of variation
σ_y = Std error of mean

As the sampling period reduces between 2 and 29 days, then the variations in the rainfall catch across the Sapat Kalisun Catchment increase to an average of 27.2% (Table 4.1). Just considering the stochastic nature of the development of individual cumulus clouds in a region, then averaging over progressively larger periods will indeed be expected to remove some of the variability. The large range in the variability of 10 to 70% CV for different 2-29 days periods is in part related to variation in the size of rain event within each period (Figure 4.3). Smaller events tend to be more localised, and hence give a higher spatial variability (Hutchinson, 1969, 1970; Goodrich *et al.*, 1995). Clearly, this has implications for the number of raingauges required to characterise the average rainfall over a catchment to a pre-determined level of accuracy.

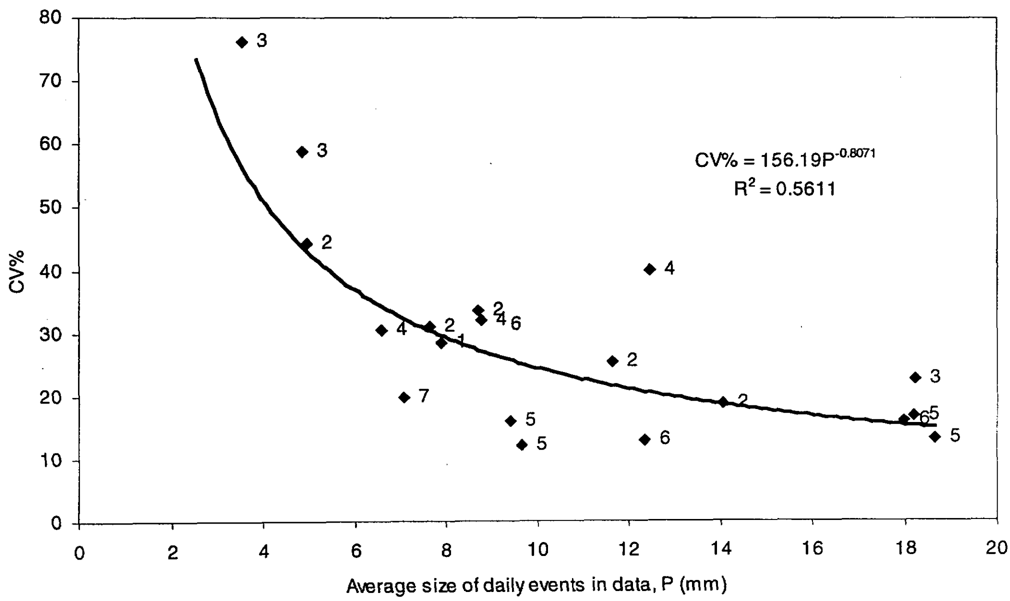
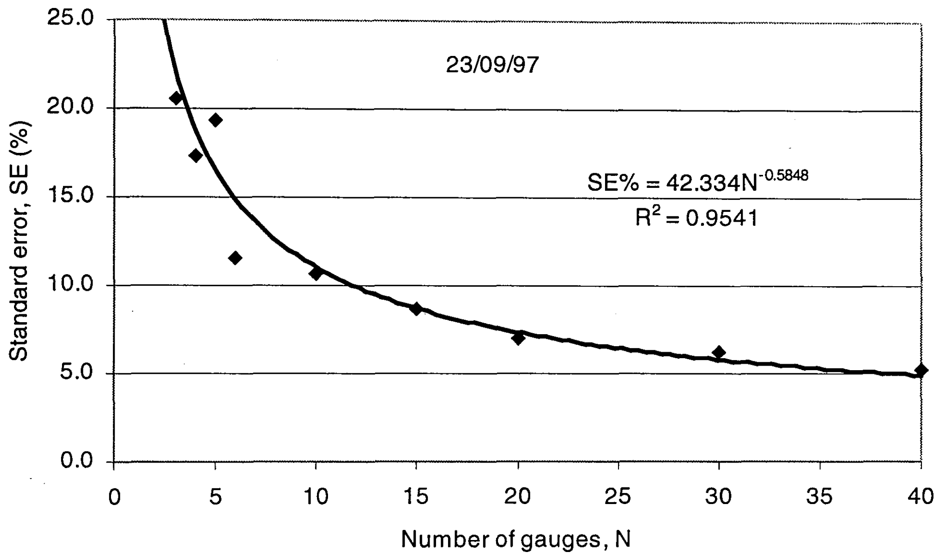
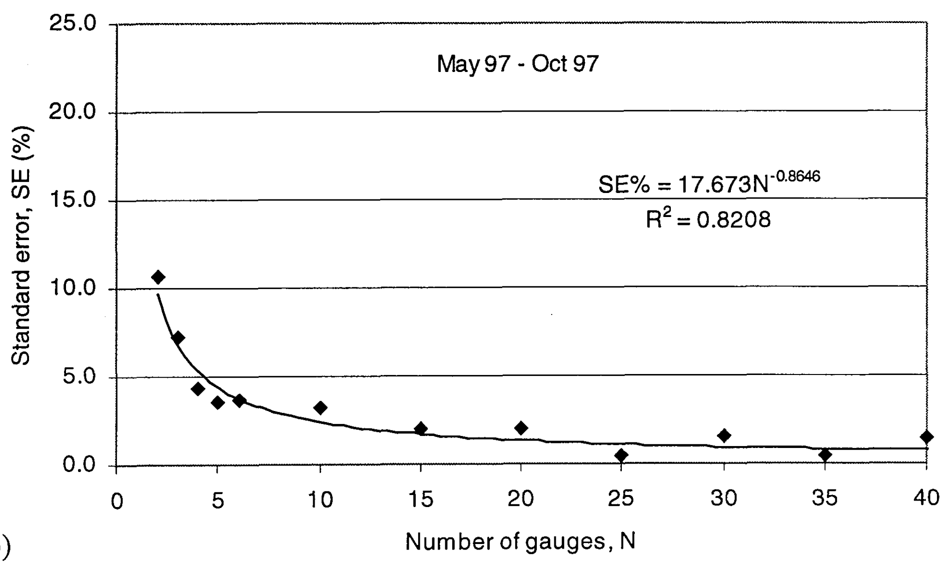


Figure 4.3: The relative measurement error estimates (coefficient of variation, CV%) as a function of event sizes of Sapat Kalisun Experimental Catchment rainfalls. This relationship is comparable to the data of Goodrich *et al.* (1995). Values shown on the individual data points are number of daily events contained in the data respectively.

Figure 4.4 shows that the reduction in the standard error with the addition of raingauges to a network is greater for a 6-month period, than for a single daily event (*e.g.* 23 September 1997). Thus, more raingauges must be added to a network to have the same effect on constraining uncertainty, if event-based or weekly sampling is undertaken.



(a)



(b)

Figure 4.4: Uncertainties in rainfall measurement produced by different number of gauges showing the clear reduction from (a) daily total on 23/09/1997 (two events) to (b) 6-month total from 1 May 1997 to 31 Oct 1997. The gauges selected as a purely random sampling. The standard error decreases as the number of sample increases as suggested by Taylor (1982) apparent for both data periods.

The large variation in the rainfall totals within the small 4-km^2 study area are comparable to those in other recent studies with convective rainfall (*e.g.* Malmer, 1992; Goodrich *et al.*, 1995). For example, Malmer (1992) observed a maximum difference in annual point rainfall of almost 1000 mm amongst 12-gauges within small catchments of 3.4 to 18.2 ha in the Southwestern Sabah. Similarly, Goodrich (1990) reported that two rain gauges approximately 300 m apart often provided significantly different estimates of rainfall depth and intensity in a region characterised by convective thunderstorms. Further, they noted that rainfall-runoff models were very sensitive to this small-scale variability in rainfall. Goodrich *et al.* (1995) and Faures *et al.* (1995) also noted catchment model sensitivity to rainfall variability.

4.5. Location-dependent spatial variability: distance effects

Geostatistical analysis shows that many environmental variables become more dissimilar as distance between sampling point increases (Myers, 1997; Ashraf *et al.*, 1997). The correlation between all combinations of raingauge pairs (C_r) was, therefore, calculated using:

$$Cr = \frac{Sxy}{SxSy} \qquad [4.1]$$

where $$Sxy = \sum_{i=1}^{n} \left[(Xi - \overline{X})(Yi - \overline{Y}) \right] / (n-1) \qquad [4.2]$$

and Sxy is the sample covariance, Sx and Sy are the sample standard deviations for variable X and Y respectively and n is number of samples (McPherson, 1990). This spatial autocorrelation is examined for the rainfall for each raingauge over all events in the 12-month study period, and because the coefficient of variation for the two monsoons are different, for events in these two separate periods also. The results are shown within Figure 4.5. A linear model can be fitted to the inter-gauge correlation for separation distances of between 0.017 and 3.3 km. It can be seen from Figure 4.5 that rainfall totals remain much more similar with increasing gauge separation during the Northeast monsoon, in comparison to the Southwest monsoon. This may mean that rainfall during the Southwest monsoon in Northeast Borneo is more localised or 'patchy' than that in the Northeast monsoon. This greater variability of rainfall during the Southwest monsoon could be caused by (1) a greater proportion of events with smaller rainfall totals or (2) the interaction of the South-westerly wind direction with the local topography with the Sapat Kalisun Catchment.

Against correlation-distance functions for other regions with convective rainfall the Sapat Kalisun data show relatively steep relationships (Figure 4.6). Thus, the rainfall variability across the Sapat Kalisun Catchment is highly localised even for regions of the globe dominated by convective rainfall.

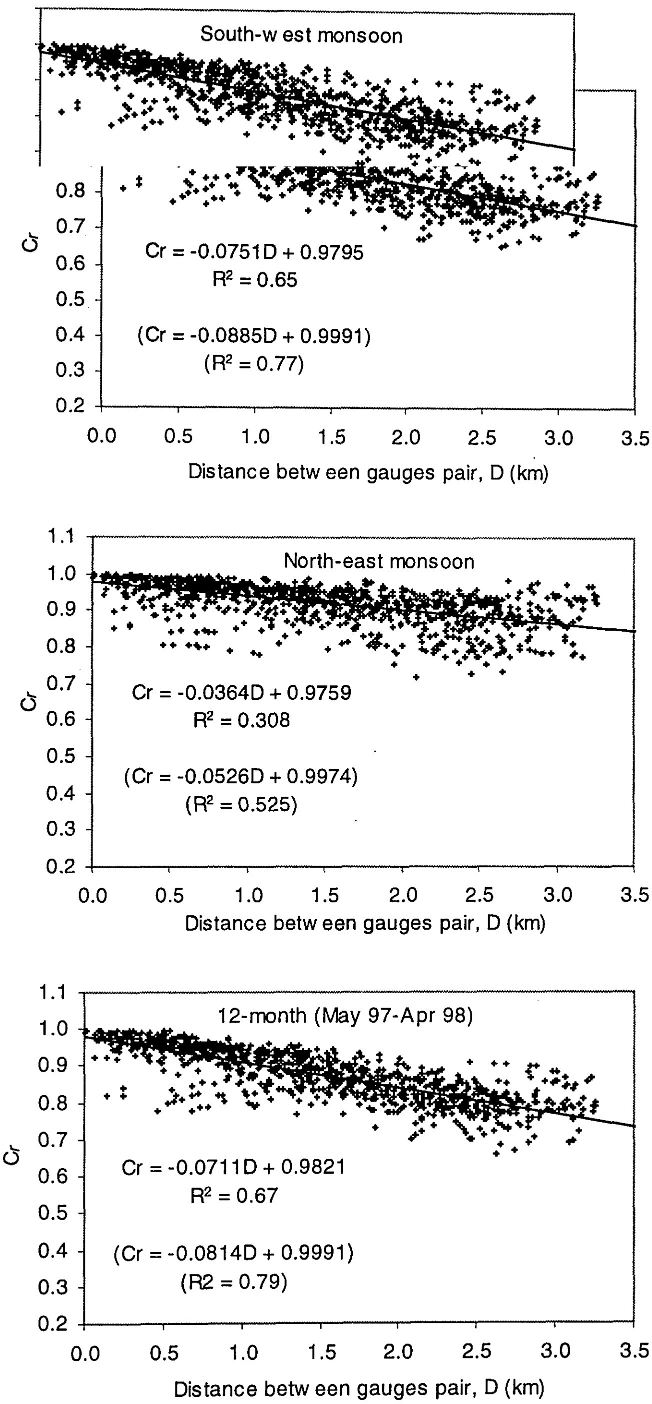


Figure 4.5: Correlation (C_r) amongst point rainfalls as a function of distance between gauges (D) for different periods of monitoring. Equations and r^2 of the relationships in brackets are excluding the data from the Bukit Atur raingauges.

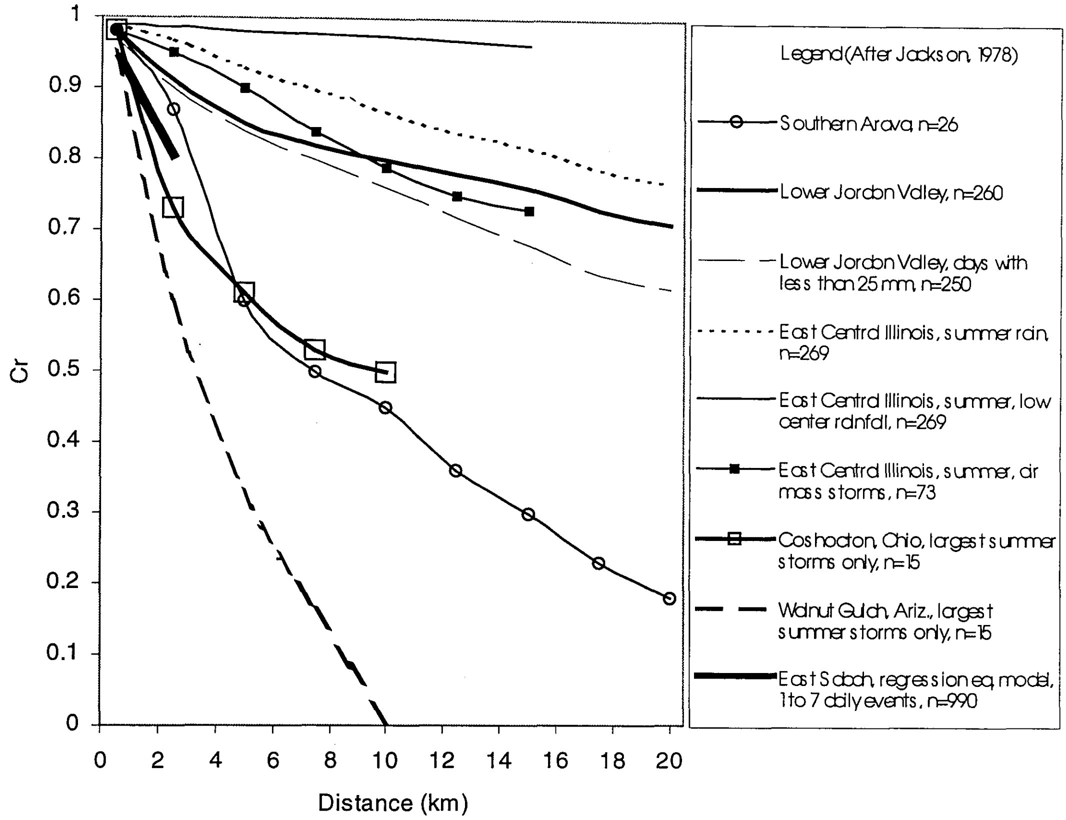


Figure 4.6: Inter-station (gauge) correlation (C_r) against distance between gauges for different regions with convective rainfall (after Sharon, 1972; Jackson, 1978) and comparison with the present study in East Sabah (Sapat Kalisun Experimental Catchment). Number of gauge pairs (n) is given in the legend.

A simple measure of the degree localisation of rainfall is the distance where the inter-gauge correlation $C_r = 0.9$ (Hershfield, 1965; Hendrick and Comer, 1970; Hutchinson, 1972). For the 12-month of 1 May 1997 to 30 April 1998 the separation distance within the Sapat Kalisun where $C_r = 0.9$ is 1.155 km (Table 4.3). This is again indicates a high degree of localisation relative to other areas of convective rainfall (Table 4.4). The lag distance at which $C_r = 0.9$ for the Southwest and Northeast monsoon periods is 1.059 km and 1.119 km respectively. Similar seasonal variations in spatial correlation function have been observed elsewhere (*e.g.* Stol, 1972; Jackson, 1978; Duchon *et al.*, 1995).

Table 4.3: Values of inter-gauge correlation (C_r), percentage of gauge pairs having C_r values ≥ 0.90, and distance between gauges in pair (D) from the regression lines when $C_{r0.9}$ for different period of rainfall measurements across Sapat Kalisun Catchment.

Data periods	1st 6-months (South west monsoon)	2nd 6-months (North-east monsoon)	12-months (May 97 - Apr 98)
Mean C_r	0.865	0.920	0.874
Coeff. of variation C_r (%)	8.90	5.87	8.24
% $C_r \geq 0.90$	42	71	41
Distance (km) at $C_{r0.9}$	1.059	1.119	1.155

Table 4.4: Distance (D) for $C_{r\,0.9}$ and C_r for D = 10 km of for inter-gauge correlation estimates in different climatic regions. All values estimated (re-analysed) from the C_r -distance regression lines or equations reported by the individual authors.

Type of data/event	D at $C_{r0.9}$	C_r at 10 km	Site / Region	Source
Largest summer storm	0.75	0.06	Walnut Gulch, Arizona	Sharon (1972)
Individual events	1.00	0.25	Central Florida	Duchon *et al.* (1995)
Largest summer storm	1.05	0.46	Coshocton, Ohio	Sharon (1972)
Summer, air mass storm	4.95	0.75	East Central Illinois	Sharon (1972)
Daily convective events	5.48	0.83	South-eastern N.England	Sharon (1974)
Monthly totals	3.00	0.62	Ruvu Basin, Tanzania	Jackson (1974)
Totals of one to seven daily events	1.15	0.27	Danum Valley, Malaysia	This study

4.6. Location-dependent spatial variability: relief and aspect.

Where winds drive air over topographic obstacles, where relief maybe as low as 50 m and stratiform conditions exist, the rainfall will be enhanced (Bergeson, 1964; Barry, 1981; Bradley *et al.*, 1997). Monsoonal changes in wind direction may, therefore, result in different sides of topographic obstacles receiving the greater rainfall. Aspect will also effect rainfall, with east facing slopes being heated more, giving greater uplift and hence greater rainfall just downwind (Barry, 1981). The shape or profile of obstacles will also effect the location of the rainfall enhancement. Where air is forced to rise quickly up steep slopes, then rainfall may be enhanced on the windward side. Where only gentle slopes are encountered, then the weak uplift may give rise to rainfall just over the hill (Thielen, 1994). To assess the relief effect on the rainfall across the Sapat Kalisun Catchment rainfall totals are independently correlated with altitude and then with aspect.

By splitting the rainfall totals into averages for each monsoon period, it can be seen that during the Southwest monsoon rainfall is positively correlated with altitude but negatively correlated during the Northeast monsoon (Figure 4.7). Rainfall measurements on the large topographic obstacle of Atur Hill or 'Bukit Atur' (Figure 4.11) appear to show a different distribution. The pattern simplifies if the Bukit Atur (BA) raingauges are excluded from the analysis (Figure 4.7). If single storms are examined, then positive correlations are again seen for most storms within the Southwest monsoon, and negative correlations for most storms within the Northeast monsoon. Figure 4.8 shows the correlation for storm on the 18 June 1997 (Southwest monsoon) and 13 March 1998 (Northeast monsoon). As expected, the strength of the altitude:rainfall correlation increases if a single event is examined.

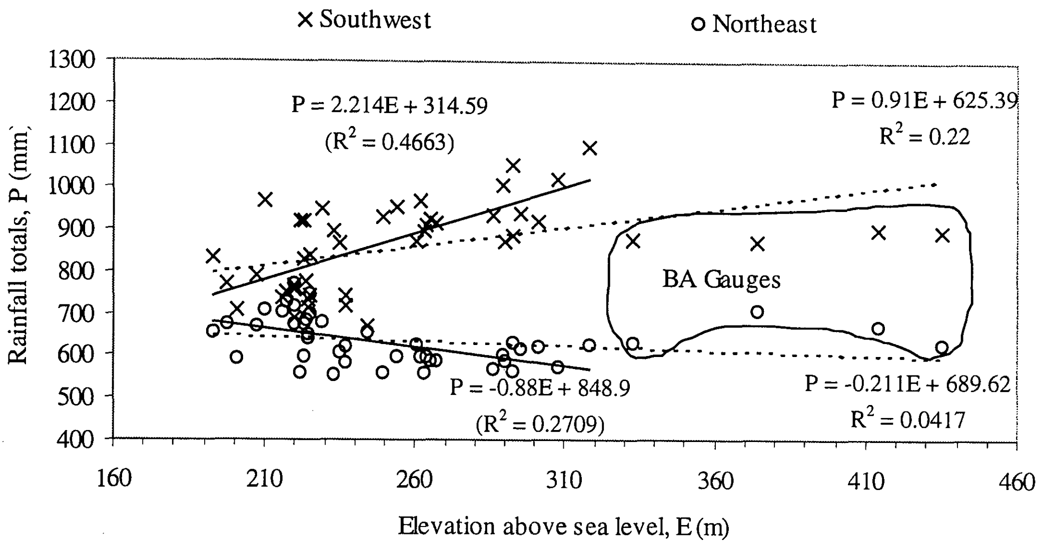


Figure 4.7: Altitudinal effects on spatial rainfall showing also the possible influence of local relief on the distribution of 6-month rainfall totals represented each monsoon. The R^2 in brackets are when gauges in Bukit Atur (BA) excluded in the regression analysis. The dashed regression line is when BA gauges included in the catch-elevation relationship.

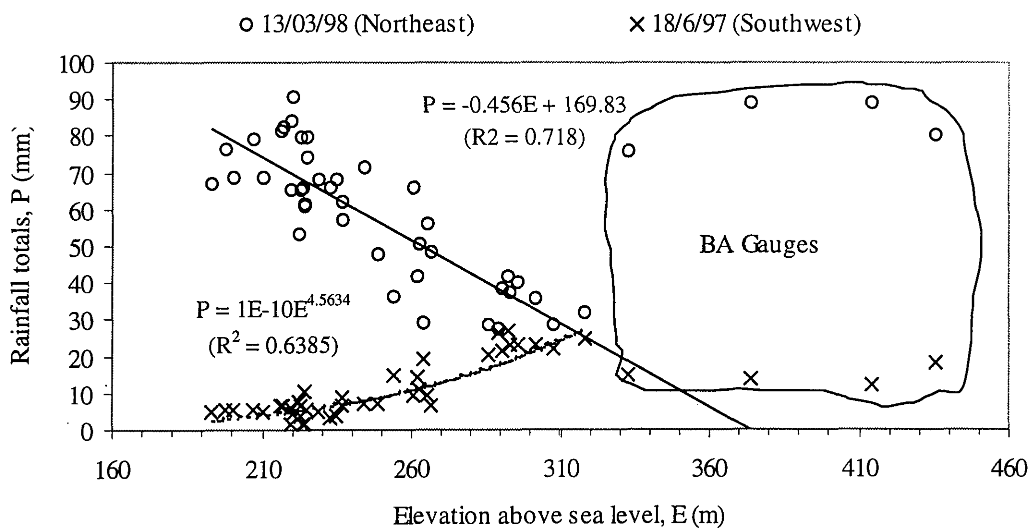


Figure 4.8: Altitudinal effects on spatial rainfall showing also the possible influence of local relief on the rainfall distribution for different periods of measurement. The regression analyses exclude gauges in Bukit Atur (BA).

As there is no direct mechanism whereby decreasing altitude enhances rainfall in the Northeast monsoon, the correlation with altitude are likely to be caused by a more complex topographic effect than simple relief or altitude forcing.

The effect of aspect on rainfall distribution was analysed by correlation with the bearing for each monsoon period (Table 4.5, Figure 4.9 a, b, c, and d). It can be seen that during the Southwest monsoon, rainfall increases in an Easterly and North-easterly direction (Figure 4.9 b & c), while during the Northeast monsoon rainfall increases in northerly and north-westerly directions (Figure 4.9 a & d). Explanation of such phenomena is not achieved with correlation of the independent topographic effects, but requires discussion of the whole regional structure.

Table 4.5: Basic statistics of regression analysis for integration periods of rainfall totals against their relative directions (n=46) showing the mark changes in the rainfall distribution trends between the two monsoon periods.

Directions	South-west monsoon			North-east monsoon		
	P_{level}	Trend	r^2	P_{level}	Trend	r^2
Easting	0.001	+ve	0.51	0.001	-ve	0.23
North-easting	0.001	+ve	0.26	Ns*	-ve	0.13
Northing	Ns	-ve	0.04	0.01	+ve	0.20
North-west	0.001	-ve	0.46	0.001	+ve	0.50

Notes:
Ns – not significant
Ns* - significant at $P < 0.01$ when BA gauges excluded

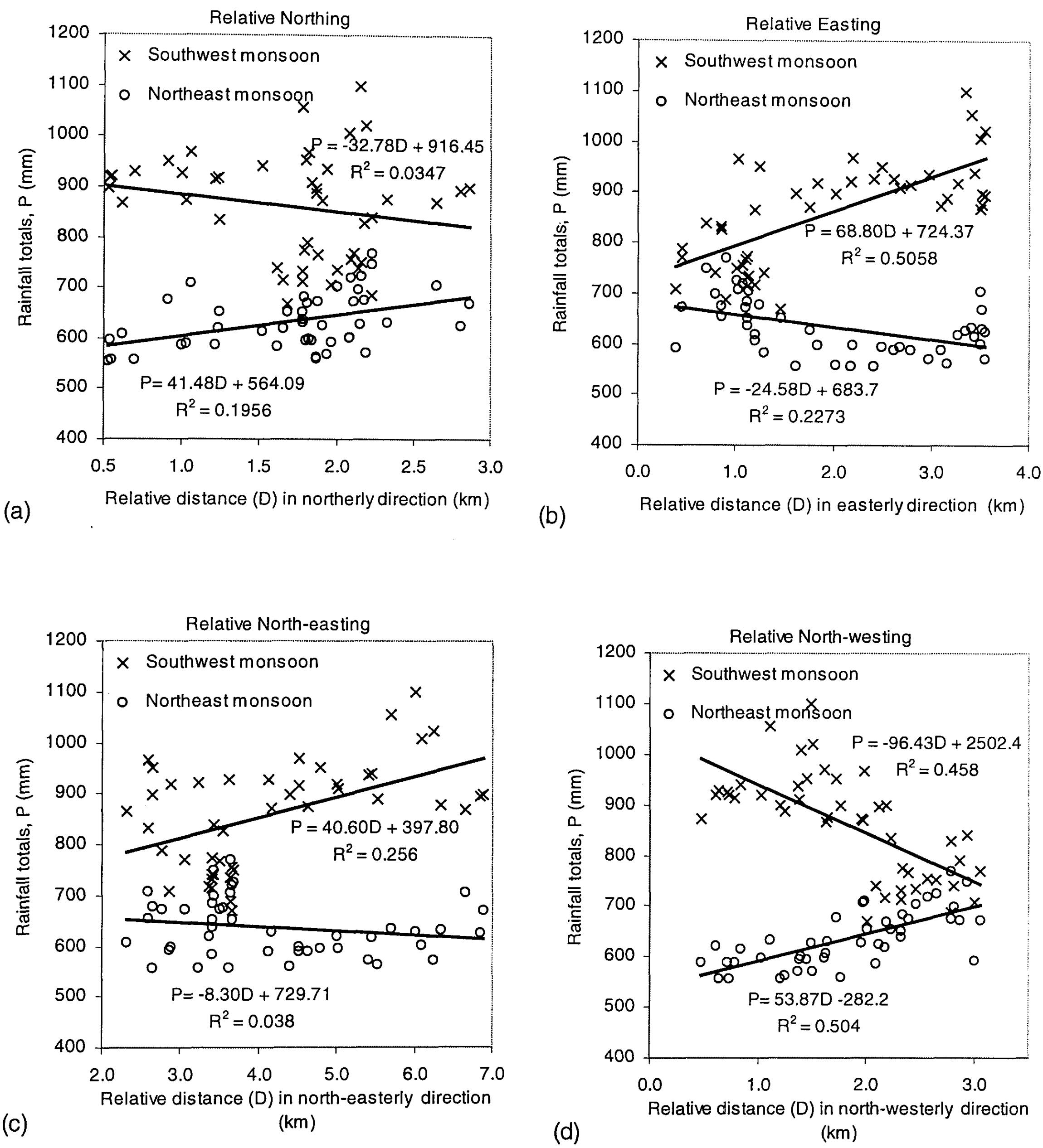


Figure 4.9: Rainfall delivered within the Southwest and Northeast monsoon periods as a function of their relative bearing as shown

4.7. Location-dependent spatial variability: conceptual model of topographic controls

Figures 4.10 and 4.11 show the raingauge location and rainfall catch proportional to symbol diameters for the Southwest and Northeast monsoons respectively. There is clearly some similarity in catch recorded by adjacent gauges. These same data are then plotted over the underlying regional topography (Figures 4.12 and 4.13). During the Southwest monsoon, the winds over the region are predominantly from a Southwest direction. There will be a funnelling of winds northwards along the Segama Valley (to the East of Rhino Ridge in Figure 4.12).

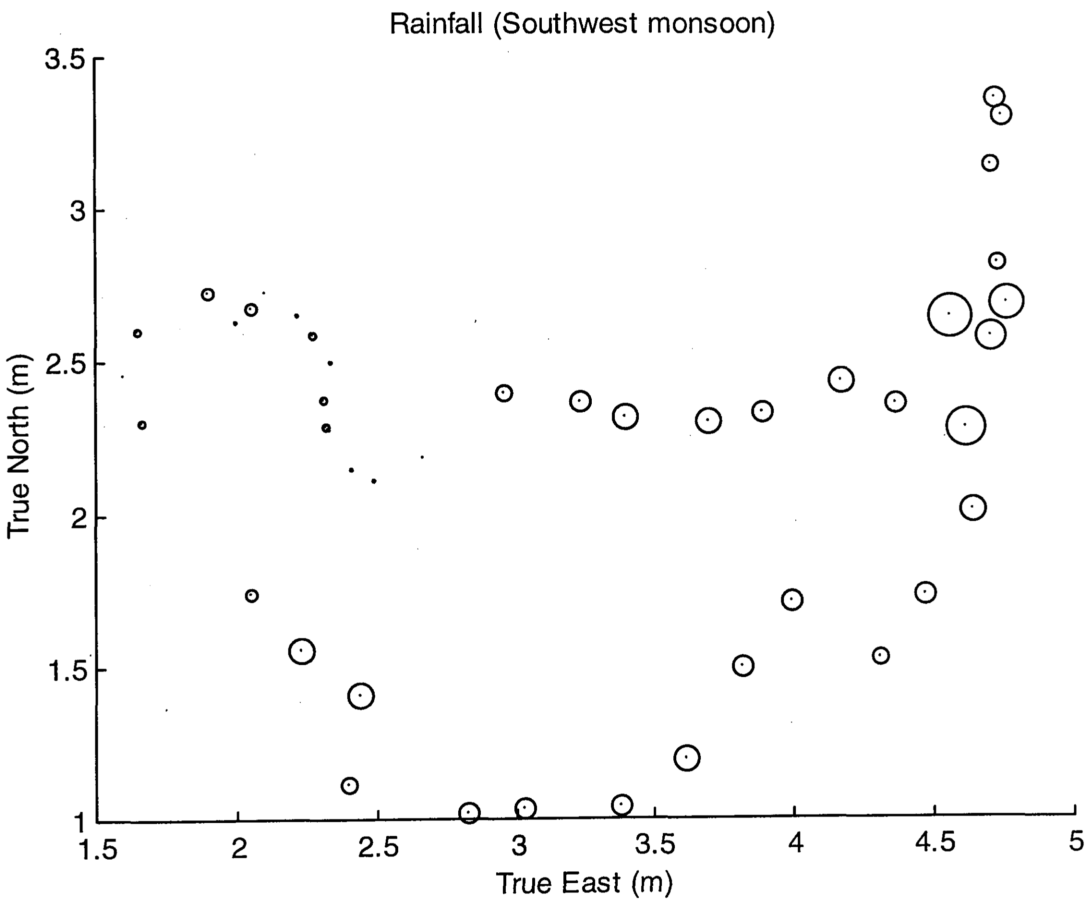


Figure 4.10: Point rainfall totals proportional to symbol diameter during the Southwest monsoon.

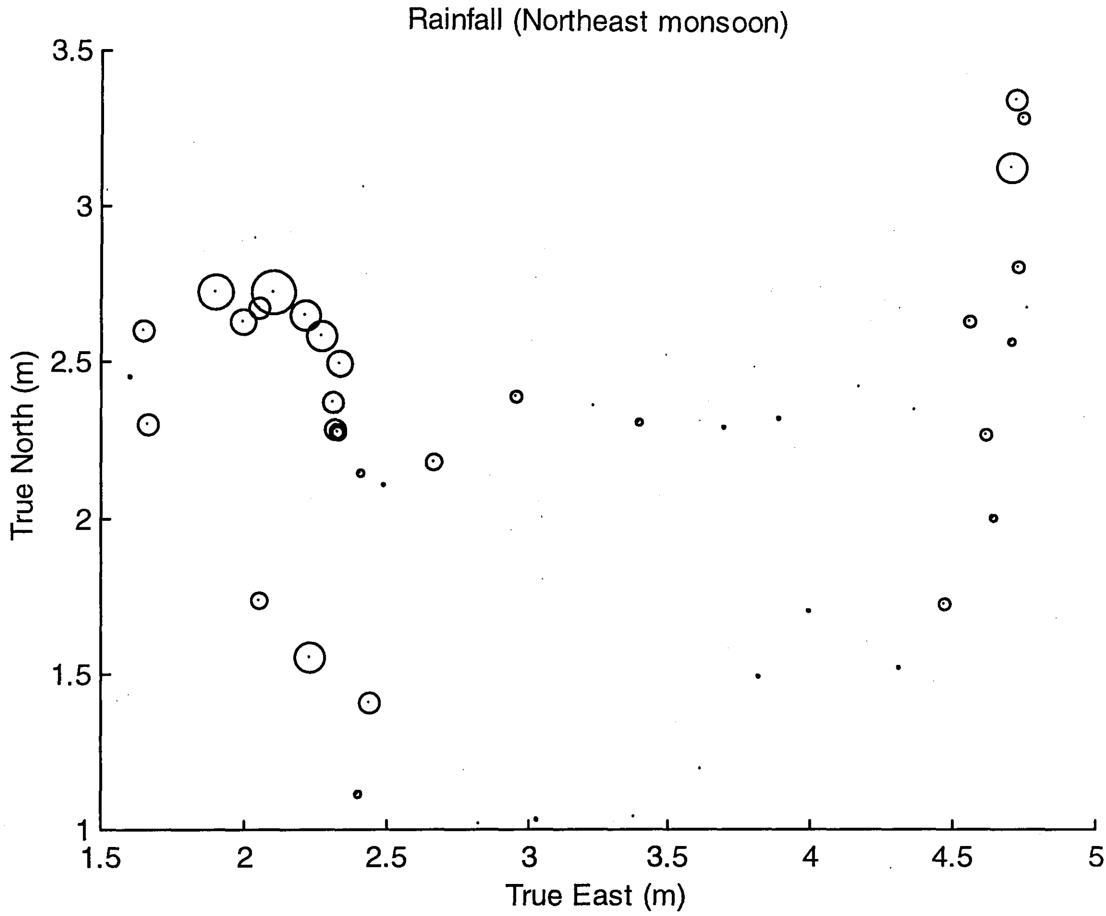


Figure 4.11: Point rainfall totals proportional to symbol diameter during the Northeast monsoon.

These winds are then expected to lift air up the steep Southwest facing slopes of the high point of Bukit Atur (Figure 4.12). This strong uplift, in an area of conditional instability (McIllveen, pers. comm.), may explain the high precipitation recorded on these Southwest facing slopes of Bukit Atur. The small rainfall catch on the Southwest facing slopes of the Baru catchment (Figure 4.12) might be caused by a weak clockwise airflow within the valley to the North of the Sapat Kalisun (Theilen, 1994).

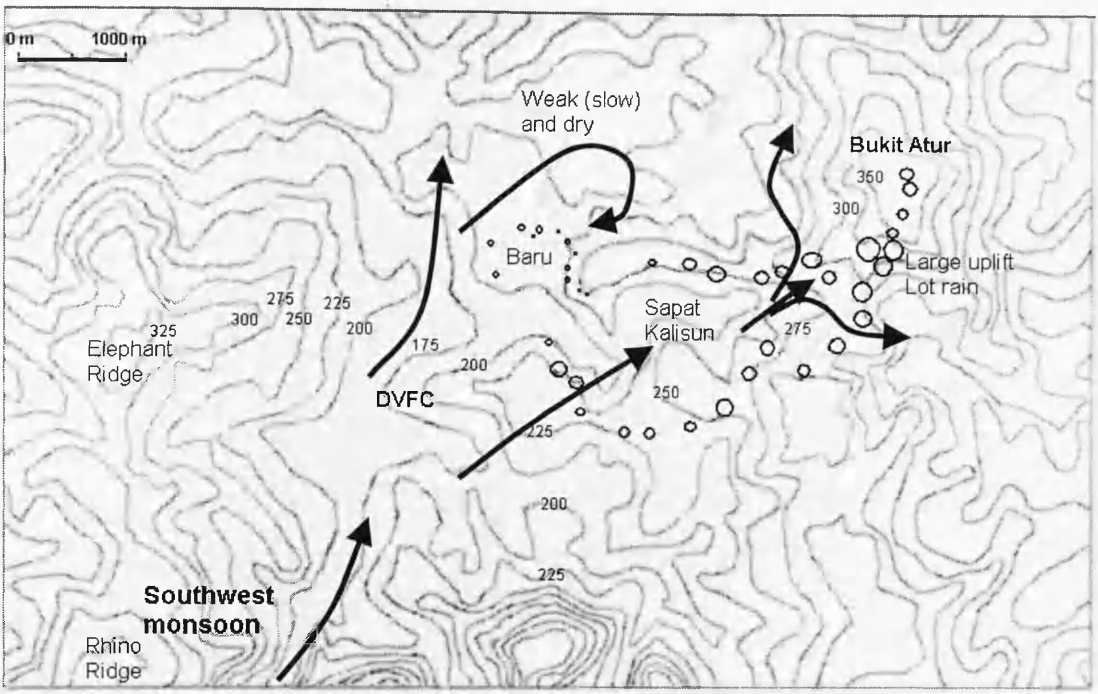


Figure 4.12: The possible wind field during Southwest monsoon over the study region. The circles are proportional to the rainfall totals.

During the Northeast monsoon the strong uplift generated as air is pushed up the Northeast facing slopes of Bukit Atur is likely to generate high rainfall in this area. The resultant drier air that descends over the hill is likely to give less rainfall. Less rainfall is indeed observed on the Southwest facing slopes of Bukit Atur during the Northwest monsoon (Figure 4.13). The reduced wind velocity of a further component of the air being pushed around Bukit Atur would also be expected to give rise to reduced rainfall west of Bukit Atur. It may be that some of the air is forced around the Northern slopes of Bukit Atur is then lifted weakly over the small hill comprising the headwaters of the Baru catchment (Figures 4.1 and 4.13). Weak uplift may explain the elevated rainfall just over the hill of the Baru headwater (Theilen, 1994).

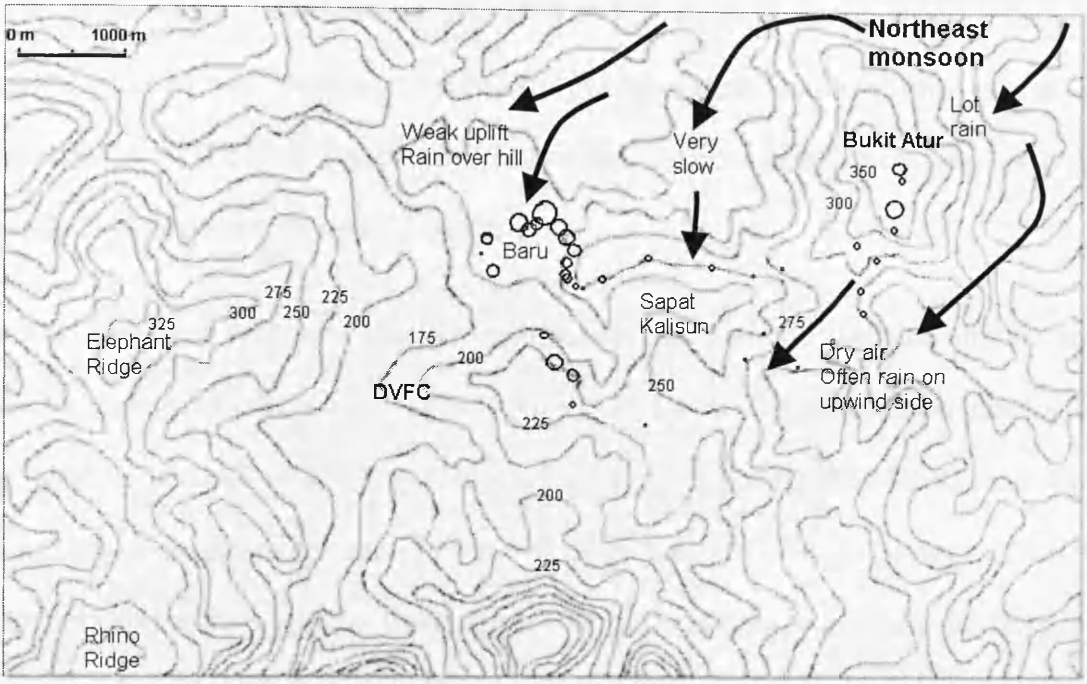


Figure 4.13: The likely wind field during Northeast monsoon over the study region. The circles are proportional to the rainfall totals.

4.8. Conclusions

This study was undertaken within a region experiencing summer and winter monsoons (Southwest and Northeast monsoons, respectively) delivering similar rainfall totals, as seen at other equatorial regions (Shaw, 1988). The 4 km^2 study catchment was within the interior of Borneo, in an area of undulating topography, and that received most of its rainfall in the mid afternoon (*i.e.*, typical of a climatic system dominated by local convective storms). These conditions seem to have given rise to very large spatial variability or 'localisation' in rainfall. This variability is seen within the simple range of rainfall catches and in the large loss of inter-gauge correlation (C_r) with distance. This variability is even high when compared against other areas with convective activity. For example, the distance at which the C_r falls to 0.9 is only 1.155 km within the Sapat

Kalisun Catchment, against 4.95 km within Central Illinois (Sharon, 1972) and 3.00 km in the Ruvu Basin, Tanzania (Jackson, 1994). This rainfall localisation is particularly apparent during the Southwest monsoon, perhaps where more of the rainfall is delivered in local convective systems, rather than the meso-scale 'stratiform' systems that the region also experiences (Chapter 5).

Strong correlations are seen between each season's rainfall and both the altitude and bearing, though the physical explanation requires at least a conceptual understanding of the local wind fields within region incorporating the Sapat Kalisun Catchment. This means that a raingauge spacing of even one gauge per 1.155 km (*i.e.*, where $C_r = 0.9$) may not capture the important topographic controls, that change dramatically from the Southwest to the Northeast monsoon, on rainfall totals.

Further geostatistical analysis, leading to a kriged rainfall map, is currently being undertaken, as this may help explain the patterns of rainfall. This is, however, not trivial given the significant role of the topography in generating 'deterministic drift' within the variogram (Chappell *et al.*, 2001), which must be removed (*i.e.*, modelled) before the true stochastic nature of the variogram can be accurate characterised. The application of a numerical model of the wind fields (*e.g.*, Theilen, 1994) in the 10-30 km^2 region about the Sapat Kalisun Catchment, would aid in this analysis, and would test the conceptual wind fields postulated in this chapter. Assurance in the modelling of wind fields would really need measurements of the vertical profile of the atmosphere about the Danum Valley area.

Chapter 5

Characteristics of rain-events at an inland locality in Northeastern Borneo, Malaysia.

To be submitted as Bidin, K., Chappell, N.A., Douglas, I. and Walsh, R.P.D. Characteristics of rain-events at an inland locality in Northeastern Borneo, Malaysia. *Agricultural and Forest Meteorology*.

Understanding the intensity and duration of tropical rain-events is important to the rate and timing of wet-canopy evaporation, the suppression of transpiration, the generation of infiltration-excess overland flow and hence to erosion, and to the overall catchment responsiveness. Despite this central role, few studies have addressed the characteristics of equatorial rainstorms. This study analyses rainfall data for the region in the vicinity of the 4 km Sapat Kalisun Experimental Catchment in the interior of Northeastern Borneo, collected at sampling frequencies from 1-minute to one day.

The work clearly shows that most rainfall within this inland, forested area is received during regular short duration events (< 15 minutes) that have a low intensity (*i.e.*, < 10 mm hr^{-1} equivalent, sampled at 5-minute interval). The rainfall appears localised, with significant losses in inter-gauge correlations being observable in minutes in the case of the typical mid-afternoon, convective events. This suggests that a dense raingauge network, sampled at a high temporal intensity, is required for accurate rainfall-runoff modelling, and given the lack of rainfalls exceeding soil infiltration rates, the local riverflow flashiness more likely governed by quick subsurface responses.

5.1. Introduction

The characteristics of rain-events regulate shallow water-table fluctuation (Bidin *et al.*, 1993), river responsiveness (Bidin, 1995), the rate and distribution of soil erosion (Douglas *et al.*, 1999), and the rate of wet-canopy evaporation (Lloyd, 1990; Asdak *et al.*, 1998ab; Schellekens *et al.*, 1999; Chappell *et al.*, 2001). Malmer (1990, 1992), Douglas and Bidin (1994), Greer *et al.* (1995), Goodrich *et al.* (1995) and Greer *et al.* (1998) have attributed temporal variation in geomorphic activity to the temporal dynamics of rainfall. Longer-term temporal variations in rainfall, including (i) annual seasonality, (ii) inter-annual cycles, and (iii) 'long-term' drift, have already been shown to affect riverflow and sediment behaviour within the interior of Borneo (Douglas *et al.*, 1999; Chappell *et al.*, 2001). Within this study, the short-term or 'within storm' variations are characterised for the same region.

5.2. Research site and instrumentation

This study was carried out within the vicinity of the Danum Valley Field Centre (DVFC) region in the Ulu Segama Forest Reserve of Sabah, in the interior of Malaysian Borneo (Figure 5.1ab).

The 13-year average annual rainfall recorded at the DVFC meteorological station (1986-1999) is 2,712 mm, with a standard deviation of 435 mm. Using 12 years of the records, the Southwest monsoon (Apr-Oct) produced an average of 1323 mm rainfall per 6-months, while the Northeast monsoon (Nov-Mar) produced an average of 1315 mm rainfall per 6-months. All but one of the raingauges used within the study were located within the 4-km^2 Sapat Kalisun Experimental Catchment (Figure 5.1b). Raingauges were sited at ground-surface altitudes of between 132 and 436 m.

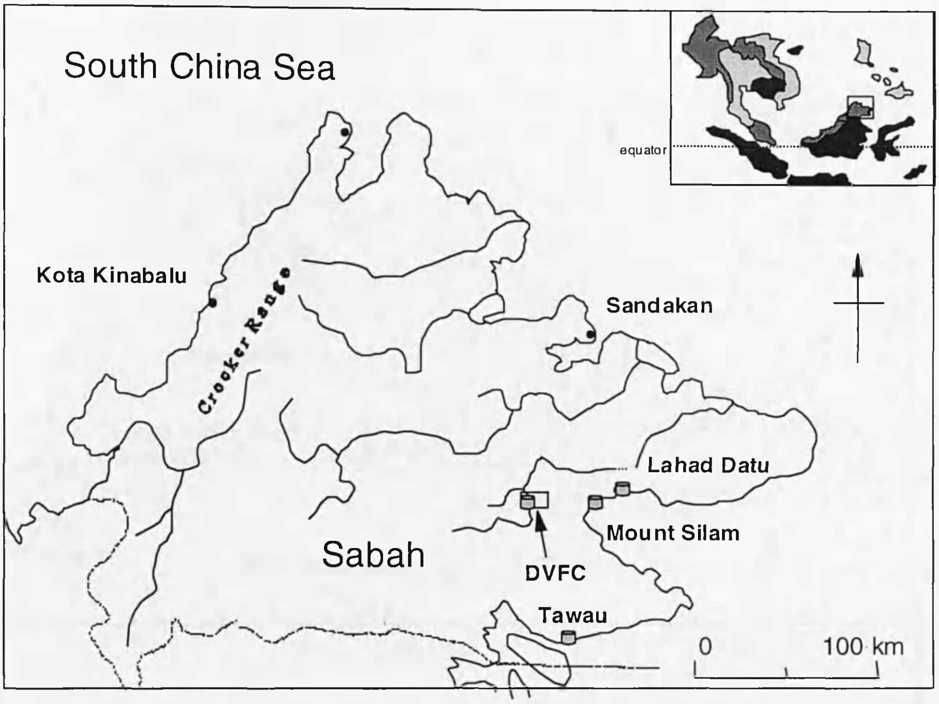


Figure 5.1a. The location of the Danum Valley Field Centre within Northeastern Borneo, Southeast Asia (adapted from Chappell *et al.*, 2001)

The rainfall data were collected by the 8 existing recording raingauges (Casella tipping bucket mechanism, attached to a Technolog data-logger) and a UK Meteorological Office Mark II storage gauge. All gauges were installed in large canopy openings not less than 40 m in diameter. Further, all gauges were geo-referenced by surveying in closed-loop traverses using an electronic theodolite. Tipping buckets were set to tip on receipt of 0.2 mm of rainfall.

5.3. Diurnal distribution of rainfall per season

The diurnal distribution of gross rainfall averaged over a 3-year period (1995-1997) at the 'KM63' raingauge (Figure 5.1b) was presented by Chappell *et al.*, (2001).

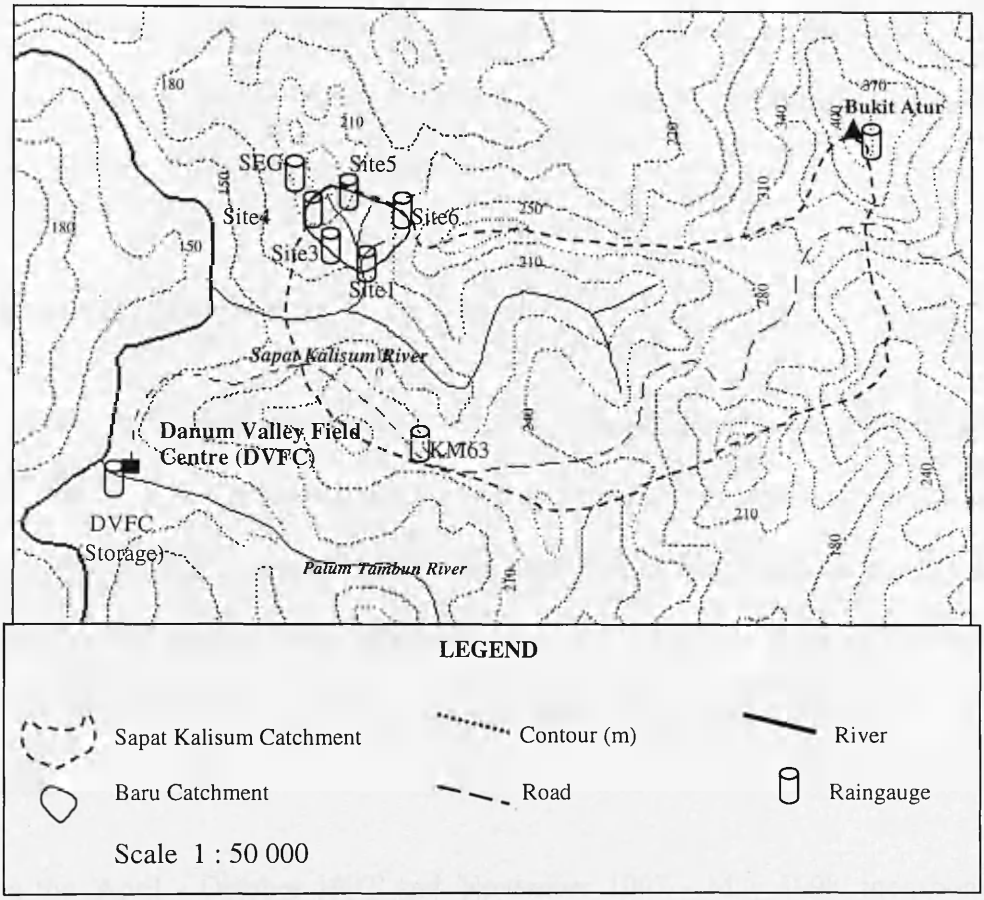


Figure 5.1b: The study area within the Ulu Segama Forest Reserve of Sabah, Malaysia showing the location of recording raingauges installed within the Sapat Kalisun and Baru Experimental Catchments and a MKII storage gauge installed in the DVFC Meteorological Station.

Seasonal changes in this diurnal pattern at this same raingauge are presented here using three water-years from 1 May 1995 to 30 April 1998 (Figure 5.2). The graphical summary of 2-hour rainfall for each monsoon period (Figure 5.2) clearly shows a very strong diurnal cycle. The higher percentage of rainfall generally occurred in the mid afternoon. This is probably as a result of localised convective rainfall events from clouds developed by solar heating through the day (Batan, 1979). Figures 5.2 also shows that there are greater morning rainfalls during the Northeast monsoon in comparison to the Southwest monsoon. This may be the result of greater amounts of rainfall from meso-scale stratiform systems in the Northeast monsoon. The simple unimodal diurnal cycle appears to be disrupted during the November 1997 - March 1998 period (Northeast monsoon) at the trough of the El Nino-Southern Oscillation or 'ENSO' cycle (cf. Chappell *et al.*, 2001).

5.4. Seasonal distribution of rain hours

Five minute sampled rainfall data were used to show those hours with or without rainfall (Figure 5.3). These data summarised in Table 5.1, show that the proportion of hours on record that received rainfall was less than 5 percent, with the Southwest monsoon having slightly fewer rain-hours than the Northwest monsoon. This would again be consistent with a greater presence of stratiform rainfalls during the Northeast monsoon.

During the 'April - October 1997' and 'November 1997 - May 1998' monsoons that occurred during the ENSO drought less than 2 percent of the hour periods had rainfall (Table 5.1) In all periods, intensities < 10 mm hr^{-1} sampled on 5-minute periods dominated the time-series (Table 5.2). Clearly, this contradicts the popular perception that most rainfall within tropical regions has a high intensity.

Table 5.1: Total hours of actual rainfall at KM 63 site near DVFC. The rainy hours are comparable for the south-west (SW) and north-east (NE) monsoons for each annual season.

Period	1995/96		1996/97		1997/98	
	Rainy hours	% wet spell[1]	Rainy hours	% wet spell[1]	Rainy hours	% wet spell[1]
SW	158.7	3.59	142.4	3.23	81.7	1.85
NE	187.3	4.27	152.1	3.50	81.9	1.89
Total	346		294.5		163.6	

Notes:

[1] Percentage duration of wet spells over the monitoring periods respectively

Table 5.2: Rainy hours for different intensity classes over the 1995/96 to 1997/98 monitoring periods. Values in bracket are percentage duration of wet spells over each period.

Five minutes intensity (mmhr^{-1})	1995/96		1996/97		1997/98	
	SW	NE	SW	NE	SW	NE
2.4< I ≥10	119.5 (2.71)	160.8 (3.64)	110.2 (2.49)	127.1 (2.88)	59.8 (1.35)	68.3 (1.55)
10< I ≥20	16.1 (0.36)	12.8 (0.29)	14.3 (0.32)	11.3 (0.26)	8.4 (0.19)	7.0 (0.16)
20< I ≥30	9.2 (0.21)	5.8 (0.13)	6.3 (0.14)	5.8 (0.13)	4.5 (0.1)	2.4 (0.05)
30< I ≥40	4.3 (0.10)	4.1 (0.09)	3.8 (0.08)	2.9 (0.07)	2.2 (0.05)	1.1 (0.02)
40< I ≥50	2.4 (0.05)	1.7 (0.04)	2.4 (0.05)	2.0 (0.05)	1.6 (0.04)	1.5 (0.03)
50< I ≥60	3.0 (0.07)	1.2 (0.03)	2.3 (0.05)	0.9 (0.02)	2.1 (0.05)	0.8 (0.02)
60< I ≥70	1.3 (0.03)	0.3 (0.01)	1.0 (0.02)	0.8 (0.02)	1.5 (0.03)	0.4 (0.01)
70< I ≥80	0.8 (0.02)	0.4 (0.01)	0.4 (0.01)	0.5 (0.01)	1.0 (0.02)	0.1 (0.00)
80< I ≥90	1.1 (0.02)	0.2 (0.00)	0.4 (0.01)	0.4 (0.01)	0.3 (0.01)	0.0 (0.00)
90< I ≥100	0.4 (0.01)	- (0.00)	0.7 (0.02)	0.3 (0.01)	0.0 (0.00)	0.0 (0.00)
100< I ≥110	0.3 (0.01)	- (0.00)	0.3 (0.01)	0.1 (0.00)	0.2 (0.00)	0.1 (0.00)
110< I ≥120	0.2 (0.00)	- (0.00)	0.4 (0.01)	- (0.00)	0.1 (0.00)	0.0 (0.00)
120< I ≥130	- (0.00)	- (0.00)	0.1 (0.00)	- (0.00)	0.0 (0.00)	0.0 (0.00)
130< I ≥140	- (0.00)	- (0.00)	0.1 (0.00)	- (0.00)	0.0 (0.00)	0.1 (0.00)
140< I ≥150	- (0.00)	- (0.00)	- (0.00)	- (0.00)	0.1 (0.00)	0.1 (0.00)
>150	0.1 (0.00)	- (0.00)	- (0.00)	- (0.00)	0.0 (0.00)	0.0 (0.00)
Totals	158.7 (3.6)	187.3 (4.2)	142.4 3.2	152.1 3.5	81.7 1.85	81.9 (1.89)

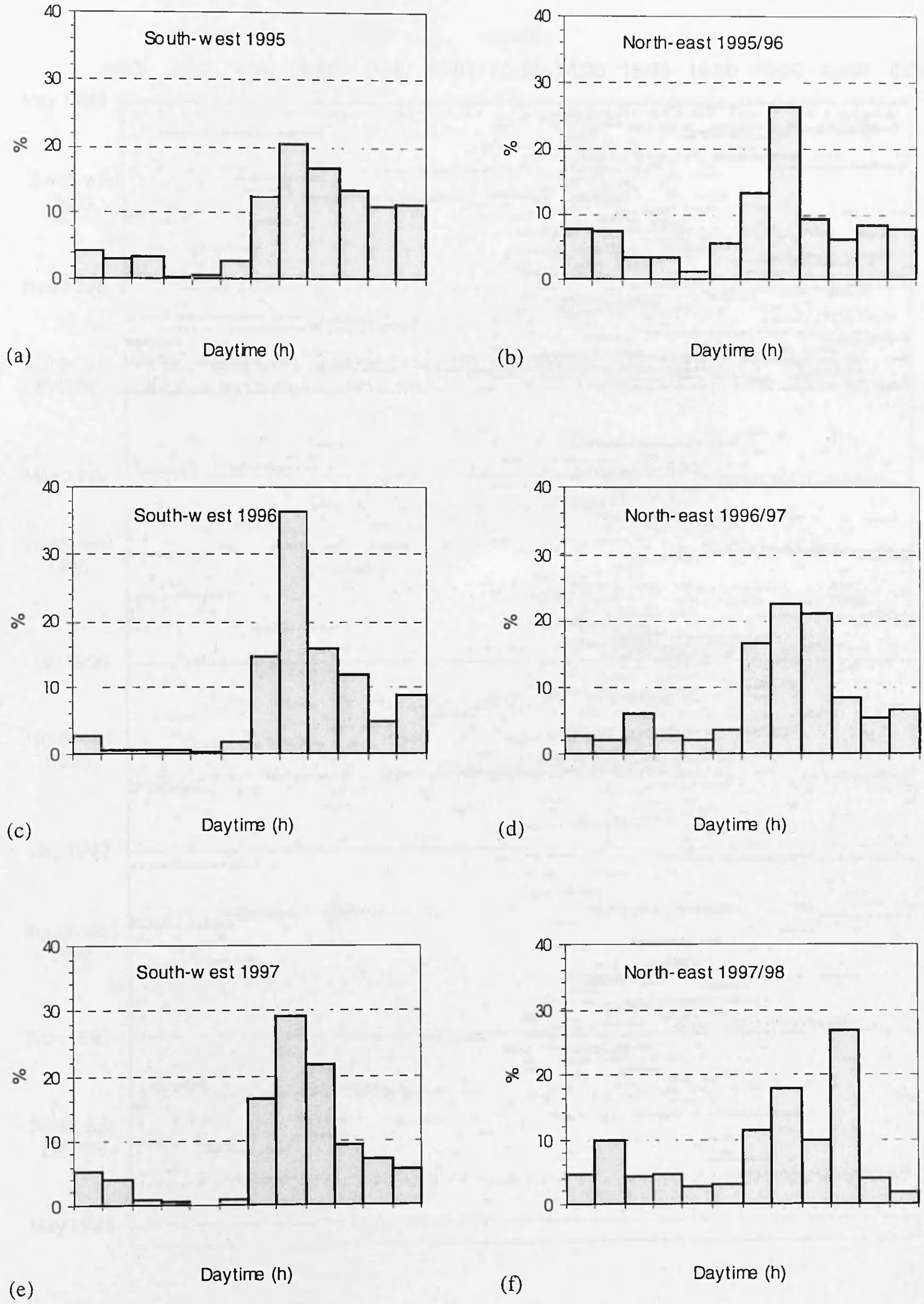


Figure 5.2. Diurnal distribution of rainfall for different monsoon period recorded at KM63 site.

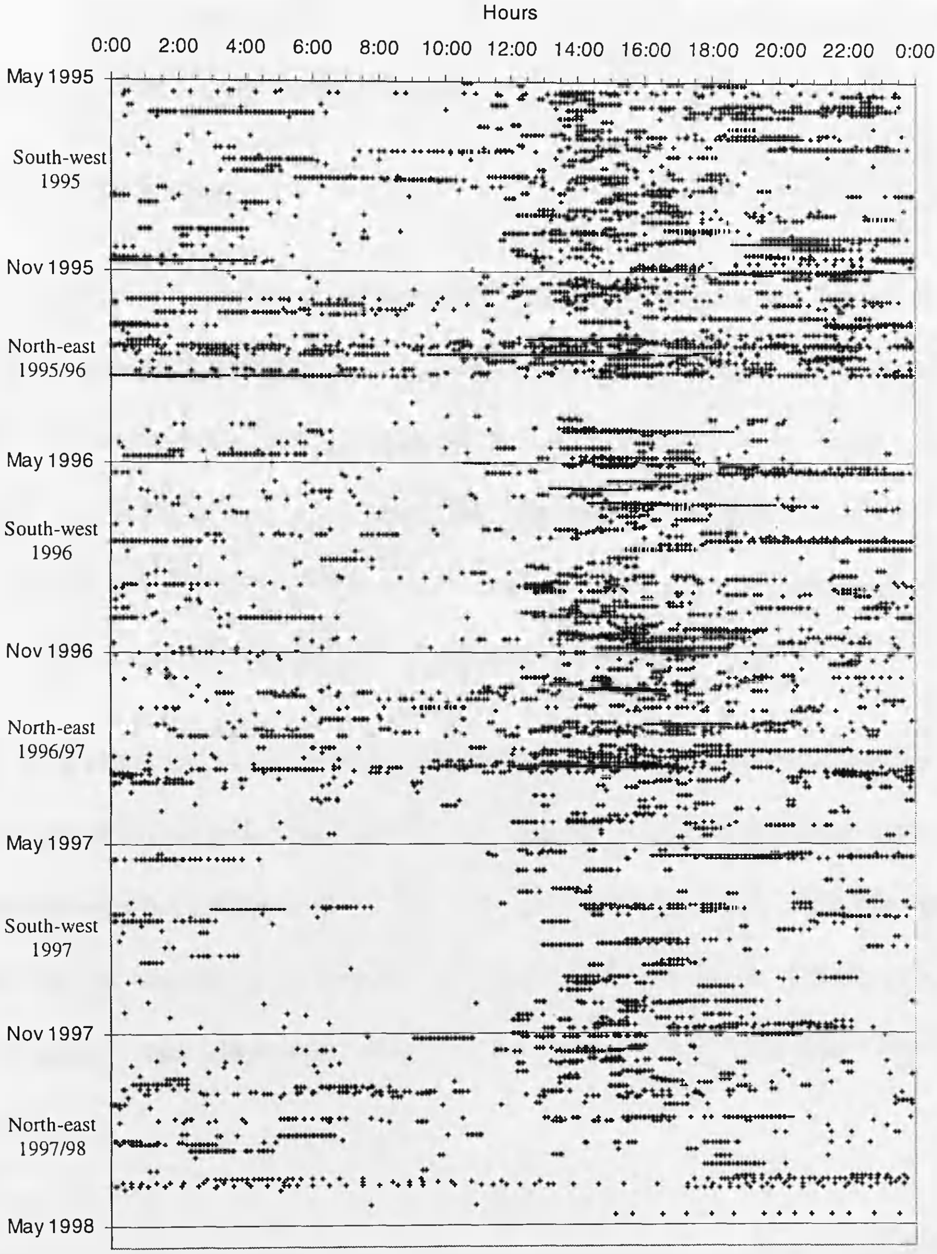


Figure 5.3. Presence and absence of rain events at KM63 near DVFC within the period from 1 May 1995 to April 1998. Each data point represents 5-minute interval with at least 0.2 mm of rain recorded, and each row represents a different day.

5.5. Rainfall intensity and duration

The rainfall intensity and storm duration for all 3-calendar years of rain-events monitored at the 'KM63' gauge were analysed.

5.5.1. Rain-event intensity

Figure 5.4 shows that 5-minute intensities rarely exceeded 100 mm hr^{-1} equivalent and most of the 5-minute intensities were below 10 mm hr^{-1} (Table 5.3). Only on 26-occasions over the three year period (May 95 to April 1998) was a 5-minute intensity equal or above 100 $mmhr^{-1}$ recorded. This observation is consistent with the analysis of Sherlock (1997) for the same study region, which found that the 5-minute rainfall intensities in excess of 100 mm hr^{-1} had a return-period of 139.6 days.

Table 5.4 shows that no events were recorded with an average intensity of greater than 50 mm hr^{-1} sustained for more than 25 minutes. Indeed, over the 3-calendar years only two extreme events occurring on the 24 October 1995 and 16 January 1996 (Douglas *et al.*, 1999) had an average of 50 $mmhr^{-1}$ sustained for 25-minutes. During all other periods, 50 $mmhr^{-1}$ equivalent intensities were not sustained for more than 10-minutes (Table 5.4).

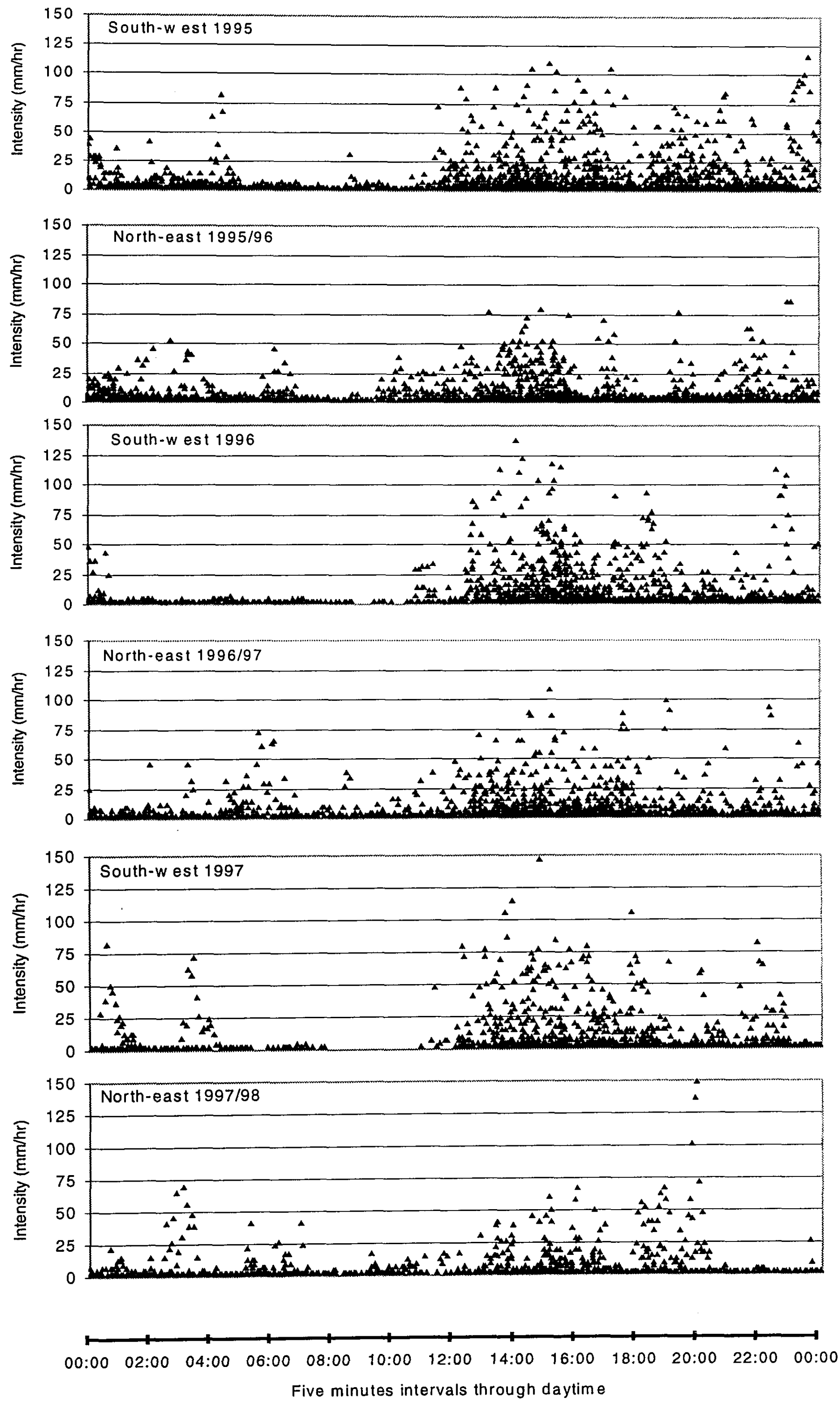


Figure 5.4: Inter-annual and inter-monsoon diurnal distribution of 5-minute 'event-based' rainfall intensity recorded at Site KM63.

Table 5.3: Frequency of 5-minute events occurring at different intensity classes over the 1995/96 to 1997/98 monitoring period. Values in bracket are percentage frequency of occurrence.

Five minutes intensity ($mmhr^{-1}$)	1995/96		1996/97		1997/98	
	SW	NE	SW	NE	SW	NE
2.4< I ≥10	1434 (75.3)	1929 (85.8)	1322 (77.4)	1525 (83.6)	717 (73.2)	820 (83.4)
10< I ≥20	193 (10.1)	153 (6.8)	171 (10.0)	136 (7.5)	101 (10.3)	84 (8.5)
20< I ≥30	110 (5.8)	70 (3.1)	75 (4.4)	70 (3.8)	54 (5.5)	29 (3.0)
30< I ≥40	52 (2.7)	49 (2.2)	45 (2.6)	35 (1.9)	26 (2.7)	13 (1.3)
40< I ≥50	29 (1.5)	21 (0.9)	29 (1.7)	24 (1.3)	19 (1.9)	18 (1.8)
50< I ≥60	36 (1.9)	14 (0.6)	27 (1.6)	11 (0.6)	25 (2.6)	10 (1.0)
60< I ≥70	16 (0.8)	4 (0.2)	12 (0.7)	9 (0.5)	18 (1.8)	5 (0.5)
70< I ≥80	9 (0.5)	5 (0.2)	5 (0.3)	6 (0.3)	12 (1.2)	1 (0.1)
80< I ≥90	13 (0.7)	2 (0.1)	5 (0.3)	5 (0.3)	4 (0.4)	- (0.0)
90< I ≥100	5 (0.3)	- (0.0)	8 (0.5)	3 (0.2)	- (0.0)	- (0.0)
100< I ≥110	4 (0.2)	- (0.0)	3 (0.2)	1 (0.1)	2 (0.2)	1 (0.1)
110< I ≥120	2 (0.1)	- (0.0)	5 (0.3)	- (0.0)	1 (0.1)	- (0.0)
120< I ≥130	- (0.0)	- (0.0)	1 (0.1)	- (0.0)	- (0.0)	- (0.0)
130< I ≥140	- (0.0)	- (0.0)	1 (0.1)	- (0.0)	- (0.0)	1 (0.1)
140< I ≥150	- (0.0)	- (0.0)	- (0.0)	- (0.0)	1 (0.1)	1 (0.1)
>150	1 (0.1)	1 (0.0)	- (0.0)	- (0.0)	- (0.0)	- (0.0)
Totals	1904 (100)	2248 (100)	1709 (100)	1825 (100)	980 (100)	983 (100)

Table 5.4: Occurrence/frequency of a high intensity events (50 $mmhr^{-1}$ and above) sustained for the given duration at Site KM63 for the Southwest (SW) and Northeast (NE) monsoon periods.

Duration (minutes)	10		15		20		25	
Data period	SW	NE	SW	NE	SW	NE	SW	NE
1995/96	7	2	-	-	-	-	1	-
1996/97	3	2	-	-	-	-	1	-
1997/98	1	1	-	-	-	-	-	-

Generally, the more intense rainfalls are seen within the Southwest monsoon (Figure 5.4, Table 5.4). Further, a greater proportion of the total rainfall delivered by high intensity events is seen within the Southwest monsoon (Figure 5.5).

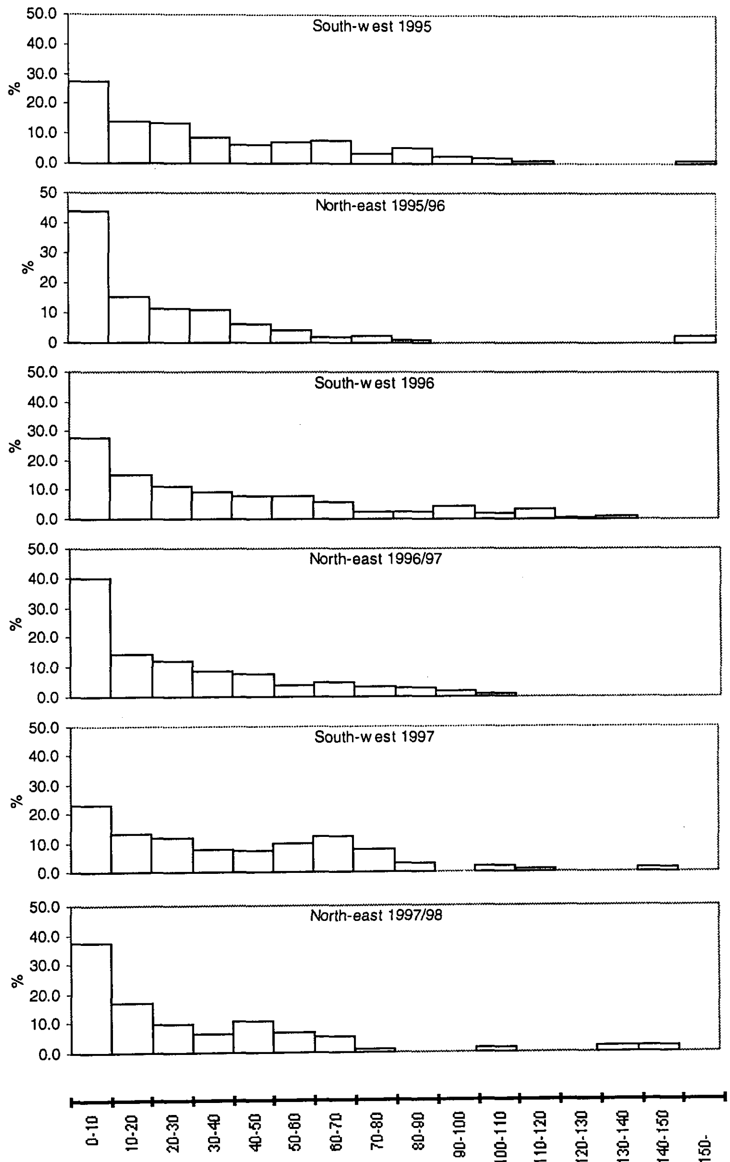


Figure 5.5: Percentages of rainfall delivered at given intensity classes for 5 minutes time steps within each data period (shown in each graph) at Site KM63.

5.5.2. Storm duration

For the analysis of storm duration, storm events were delimited by periods of 20 minutes or more without a raingauge tip (*i.e.*, ≥ 0.2 mm rainfall). The duration of all storm events recorded at the 'KM63' gauge during the 'November 1997 - May 1998' and 'April - October 1998' periods delimited by this criterion was then defined. These data are summarised in Figure 5.6.

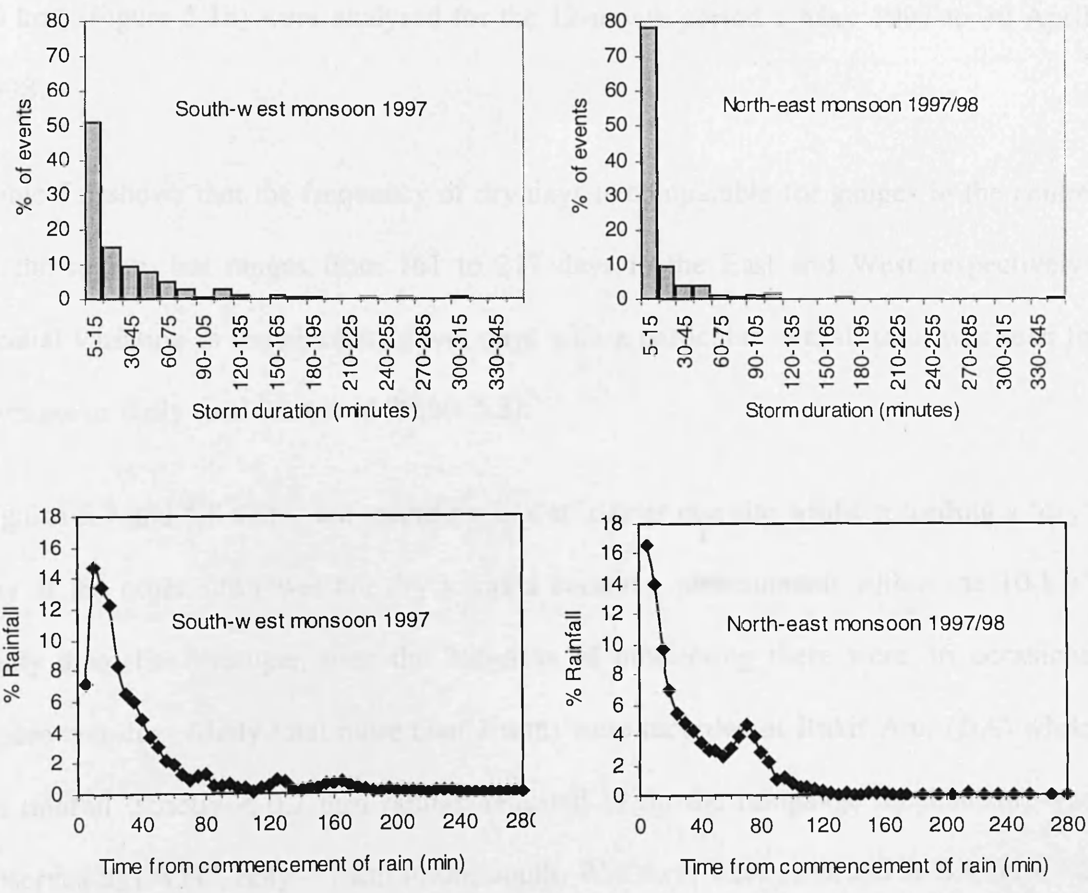


Figure 5.6: Rainfall events storm duration for different monsoon periods as indicated in each graph recorded at Site Km63.

During the 'November 1997 - May 1998' drought period (Northeast monsoon), 78 % of all events lasted for less than 15 minutes, in comparison to 52 % of all events in the 'April-October 1997' period (Southwest monsoon). Almost all rainfall is delivered within the first 80-100 minutes of each event (Figure 5.6).

5.6. Spatial variation of daily rainfall incidence

The spatial variation of raindays recorded by 9 raingauges within a region of less than 10 km^2 (Figure 5.1b) were analysed for the 12-month period 1 May 1997 to 30 April 1998.

Table 5.5 shows that the frequency of dry days is comparable for gauges in the centre of the region, but ranges from 161 to 217 days in the East and West respectively. Spatial variation in the number of wet days with a particular rainfall total was seen to increase as daily total increased (Table 5.5).

Figures 5.7 and 5.8 show that recording a 'wet' day at one site whilst recording a 'dry' day at the other site ('wet but dry') was a common phenomenon within the 10-km^2 study area. For example, over the 365-days of monitoring there were 36 occasions where wet-days (daily total more than 1 mm) were recorded at Bukir Atur (BA) while no rainfall (strictly < 0.2 mm rainfall required to tip the raingauge mechanism) was observed at DVFC, only 4.7-km to the South. Wet days were recorded at BA for 17% of the total number of dry-days at DVFC. Similarly about 22% of the annual rainfall recorded at BA occurred when DVFC was completely dry (Figure 5.7b). On ten occasions when DVFC was dry, BA had daily totals greater than 10 mm (Table 5.6). However, the 'wet and dry' phenomenon seems to be unusual for gauges less than 1-km apart, as within the Baru Catchment (Figures 5.8 and 5.9; Table 5.7). Figure 5.9, while somewhat heteroscedasic (*i.e.*, unequal variance along the trendline), shows how the number of 'wet and dry' days significantly increased as the distance between gauges increased ($r^2 = 0.6649$, $P < 0.001$).

Table 5.5: Frequency (n) of dry and wet days for 9-rainfall monitoring sites within ca. 10-km^2 area (12-month data from 1 may 97 - April 98). Daily totals equal to or more than 0.2 mm considered as a wet day. Rainfall totals over the 12-months monitoring period also shown.

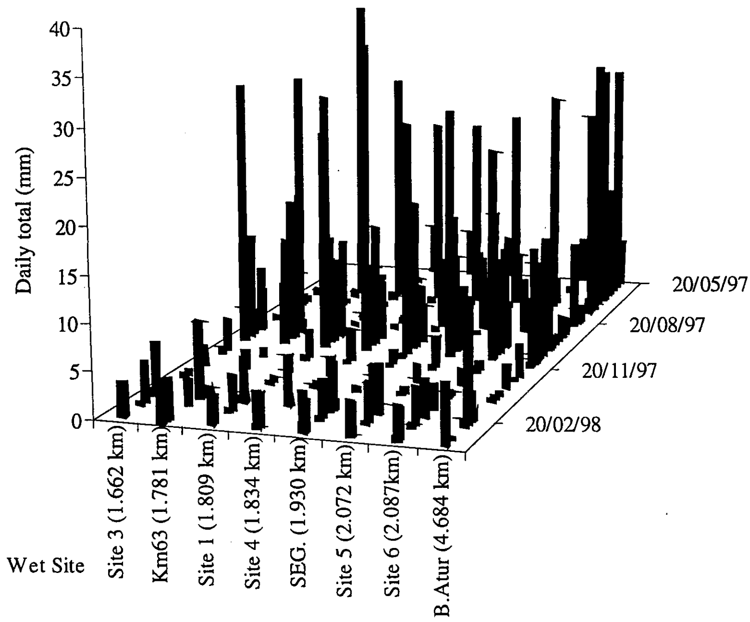
Site	Dry days		Wet days for daily totals sizes					Annual Totals (mm)
	n	%	0.2 ≤≥ 5 mm	> 5 mm	> 10 mm	> 25 mm	> 50 mm	
Site 6	196	53.7	100	69	40	12	2	1317.9
Site 5	196	53.7	100	67	42	12	5	1344.8
Site 4	190	52.1	106	68	43	15	5	1405.4
Site 3	201	55.1	93	71	44	15	5	1445.8
Site 1	194	53.2	112	57	34	14	2	1198.2
SEG.	196	53.7	103	65	44	12	3	1307.8
Km63	190	52.1	100	73	40	20	4	1566.0
B.Atur	161	44.1	129	74	46	10	3	1342.2
DVFC	217	59.5	73	72	47	19	3	1524.5
Average	193.4	53.0	101.8	68.4	42.2	14.3	3.6	1383.6
Stdev	14.6		14.9	5.2	3.9	3.4	1.2	114.6
CV%	7.6		14.7	7.6	9.2	23.4	34.8	8.3

Table 5.6: Frequency of rain-days recorded at particular sites (daily totals > 1 mm) compared to DVFC site when reported completely dry (daily totals < 0.2 mm). Percentages of rain-days (>1mm) over number of dry-days at DVFC are also given.

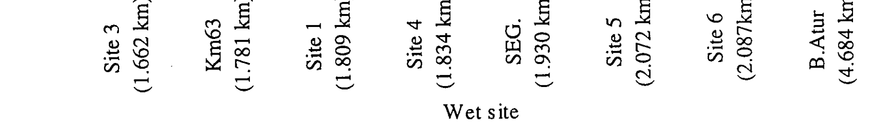
Wet Site	Distance (km) from DVFC	Number of rain-days			%1mm
		>10mm	>5mm	>1mm	
Site 6	2.087	4	8	19	9.26
Site 5	2.072	4	8	18	9.26
Site 4	1.834	3	6	18	8.33
Site 3	1.663	4	9	20	8.33
Site 1	1.809	3	6	18	9.26
SEG.	1.93	4	8	20	8.33
Km63	1.781	3	9	20	8.8
B. Atur	4.684	10	16	36	16.67

Table 5.7: Frequency of rain-days recorded at particular sites (daily totals > 1 mm) compared to Site 5 when reported completely dry (daily totals < 0.2 mm). Percentages of rain-days (>1mm) over number of dry-days at Site 5 are also given.

Wet Site	Distance (km) from Site 5	Number of rain-days			%1mm
		>10mm	>5mm	>1mm	
Site 4	0.342	0	0	0	0
Site 3	0.459	0	0	0	0
Site 6	0.491	0	0	1	0.51
SEG.	0.516	0	0	0	0
Site 1	0.545	0	0	0	0
Km63	1.571	0	0	3	1.53
DVFC	2.072	3	6	14	7.14
B. Atur	2.833	5	8	15	7.65

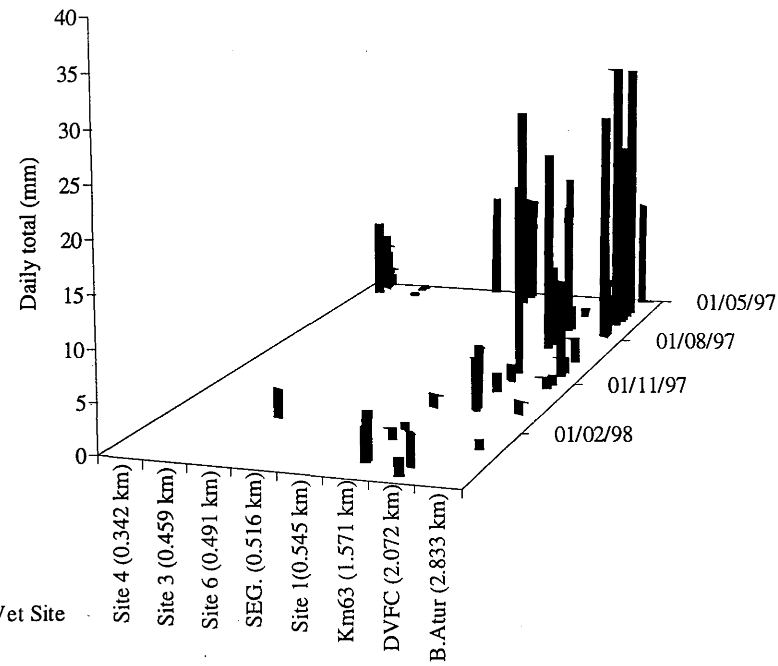


(a)

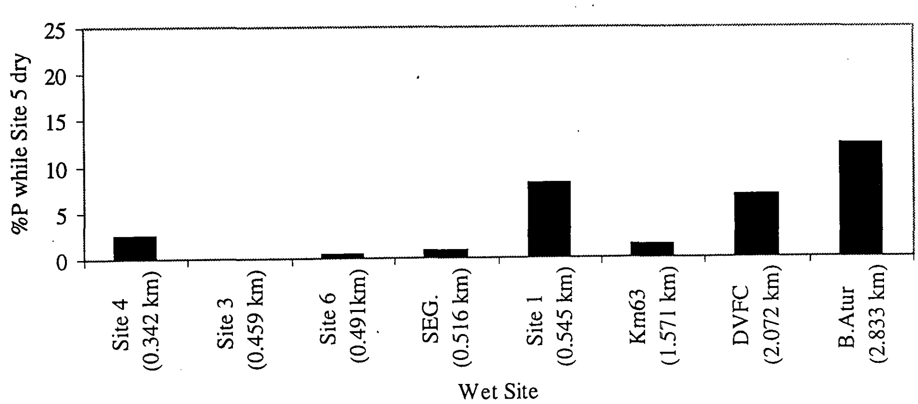


(b)

Figure 5.7: Wet spells for given location when dry at DVFC (1 May 1997 to 30 April 1998) (a) frequency of daily totals where at least 1 mm was recorded (b) annual percentage of rainfall total delivered at individual sites while dry at DVFC. Values in brackets are the distances of wet site from DVFC site.



(a)



(b)

Figure 5.8: Wet spells for given location when dry at Site 5 (1 May 1997 to 30 April 1998) (a) frequency of daily totals where at least 1 mm was recorded (b) annual percentage of rainfall total delivered at individual sites while dry at Site 5. Values in brackets are the distances of wet site from Site 5.

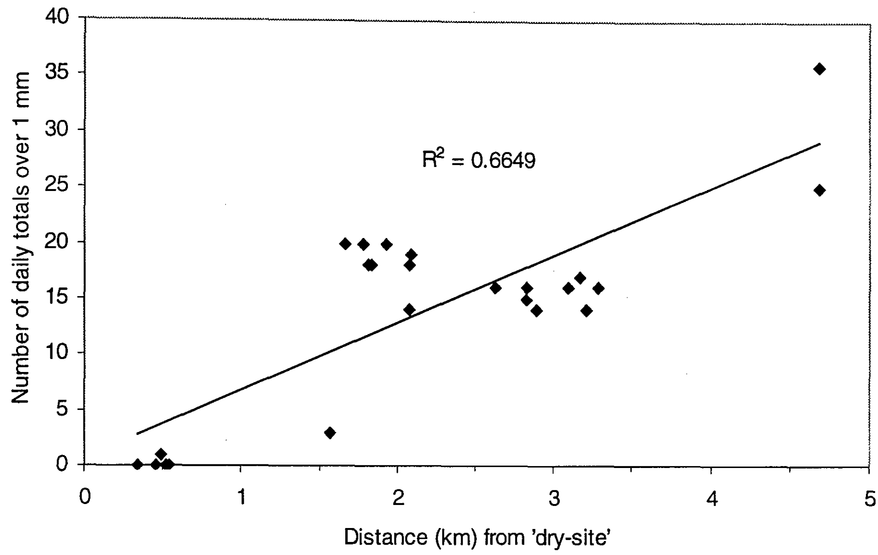


Figure 5.9: Relationship between number of recorded wet days (daily totals >1 mm) at particular sites when neighbouring sites were completely dry (daily total < 0.2 mm) and the distance between sites. The data presented is for all sites given in Table 5.2 and 5.3 for the wet sites when either DVFC, Bukit Atur, or Site 5 was dry (1 May 1997 to 30 April 1998)

5.7. Modelling inter-gauge correlation within the Sapat Kalisun Catchment

Cross-correlation (May and Julien, 1990) between four raingauges within the Sapat Kalisun catchment (*i.e.*, raingauges 'KM63', 'B.Atur', 'Site 6', and 'Site 5') was undertaken for two example storms. The objective of this analysis was to identify the correlation between pairs of rainfall time-series. The rainfall rate *r* at raingauge location G_i, is a function of space and time ($r(G_i,t)$), thus the cross-correlation is given by:

$$\rho_r(G_1,G_2) = \frac{1}{n-\gamma}\sum_{k=1}^{n}\frac{[r(G_1,t_k)\delta_k - r(G_1)][r(G_2,t_{k+\gamma})\delta_k - r(G_2)]}{S(G_1)S(G_2)} \qquad [5.1]$$

where ρ_γ is the correlation coefficient at lag γ, t_k is the kth time step, δ_k is a rainfall indicator, n is the record length at zero lag, r is the mean of the time series and S is the biased estimate of the standard deviation. The rainfall indicator (δ_k) is designed to suppress long periods with no rainfall. It is equal to 0 when both rates are 0, and 1 in other cases (Messaoud and Pointin, 1989; Goodrich *et al.*, 1995).

Each time-series was compared to the other three time-series giving nine pairs (NB. only 6 pairs are shown in Figures 5.10 and 5.11). The distance between each gauge was between 0.5 and 3.2 km. Two example events selected, included one relatively high intensity, convective event observed on the 11 July 1997, and one low intensity, long duration event, classified as a 'stratiform event' (Messaoud and Pointin, 1989) observed on 18 May 1997. The convective event selected lasted from as short as 72-minutes recorded at B.Atur to 200-minutes at KM63. The rainfall total for this event ranged from 65 mm at KM63 raingauge to 41 mm at Site 6 and only 6 mm at B.Atur. The selected stratiform event lasted 269 to 278-minutes. Rainfall depths of this single event ranged from 46 mm at KM63 gauge to 52 mm at B.Atur gauge. This storm was the longest single event recorded during 1 May 1997 to 30 April 1998 period.

Correlograms of cross-correlation coefficient and lag time were computed and plotted for each gauge pair for rainfall integrated over time-steps of 1, 5, and 15 minutes. This transformation effectively produces a new time series with a different temporal resolution (May and Julien, 1990).

It was found that the time distribution pattern analysis for the convective rain event is best described by a 1-minute event data series. A longer time resolution produced unreliable correlogram model due to the short duration of these events (McCuen and Snyder, 1986). McCuen and Snyder (1986) recommend that the magnitude of lag (γ)

should be limited to about 10% of the record length (n) at ρ_o. Once γ exceeds this empirical limit, the correlograms may begin to oscillate. For the present analysis, a maximum lag time of 30 time-steps (*i.e.*, 30-minutes or 2 hours 30-minutes) was chosen, and the correlograms are presented in Figure 5.10 and 5.10

Excluding pairs with B.Atur, the 1-minute correlograms for the convective event have sharp peaks (Figure 5.10) in comparison to those of the stratiform event (Figure 5.11). This indicates that the convective events are of shorter duration and smaller spatial extent. A longer sampling interval (*i.e.*, lag time) of 5-minutes is required to identify the loss of correlation between gauge pairs during the stratiform event (Figure 5.11). Therefore, accurate assessment of the spatial pattern of rainfall during convective events requires a greater temporal sampling frequency in comparison to stratiform events.

The shift in the peak of the convective event correlograms that include the B.Atur raingauge indicates either (i) rainfall over Bukit Atur is produced by a different cloud to that over KM63, Sites 5 and 6 within the centre of the catchment, and that this cloud releases rainfall 20-30 minutes after that in the centre of the catchment, or (ii) a local cumulus cloud over centre of the Sapat Kalisun Catchment is moved towards Bukit Atur with an airflow from the Southwest at a rate of approximately 3 km per 25 minutes.

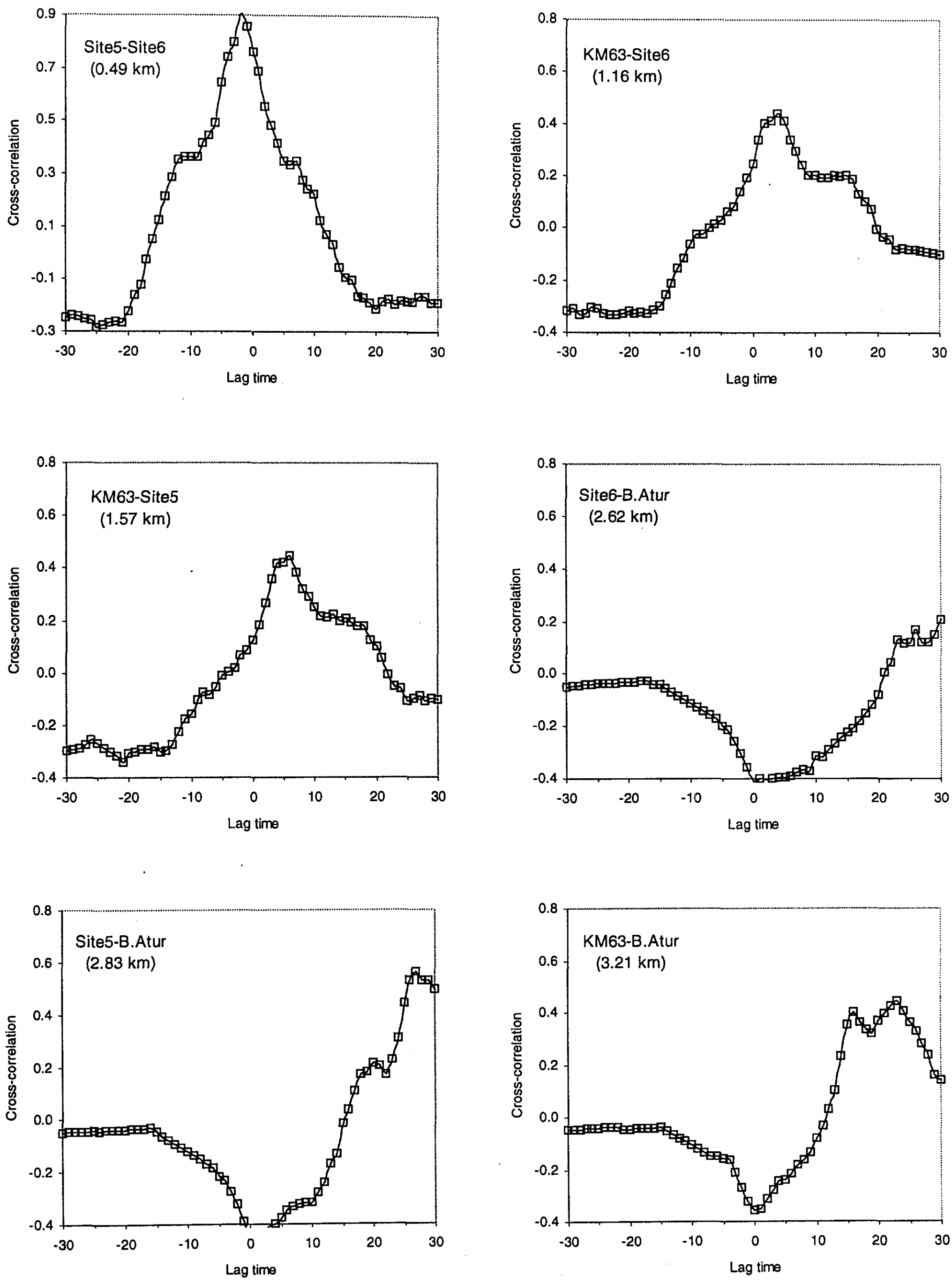


Figure 5.10: Correlograms for the site pairs for the 1-minute interval convective event on 8 July 1997 (in the Southwest monsoon). Site locations are shown in top left of each graph.

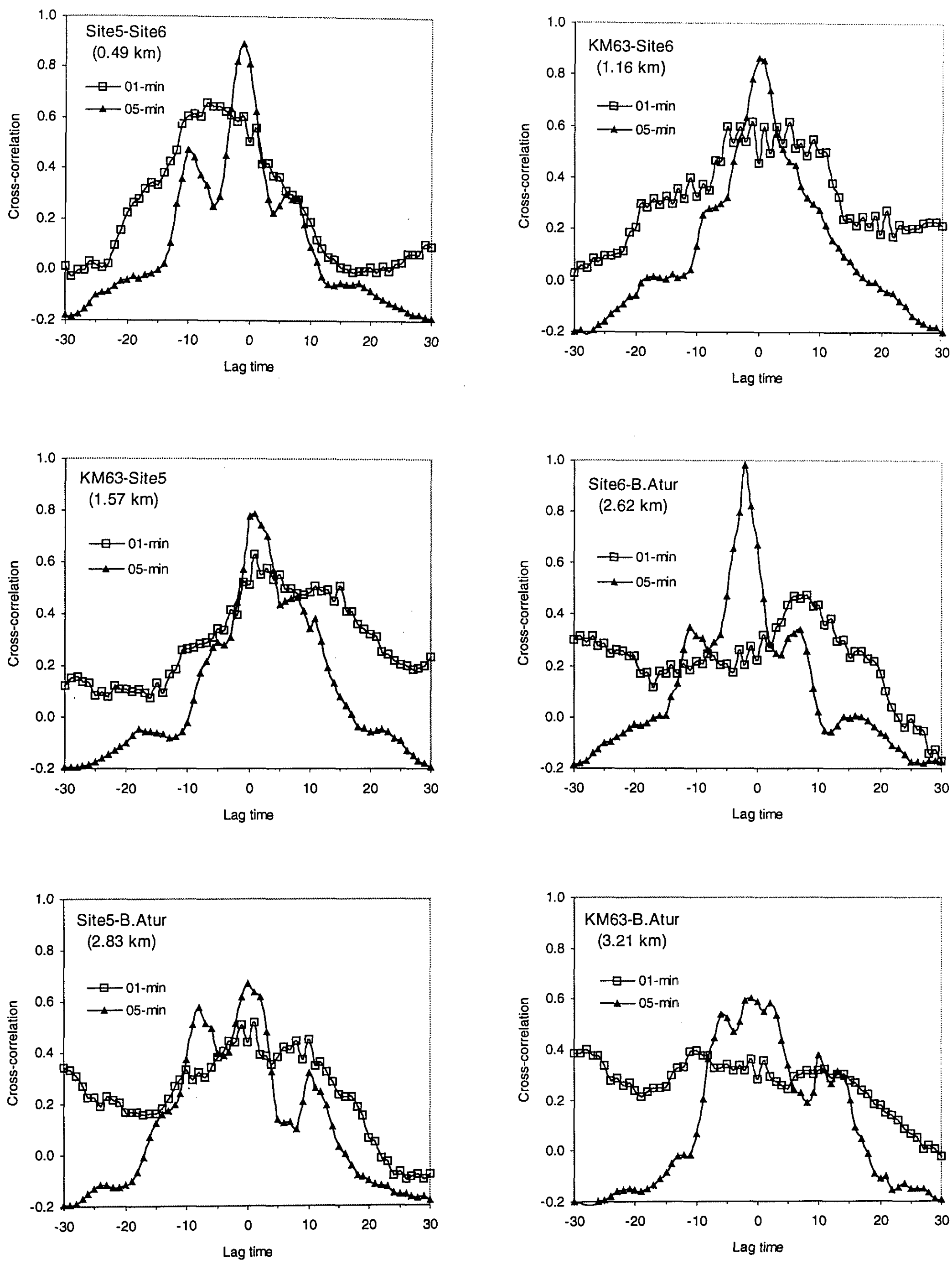


Figure 5.11: Correlograms for the site pairs for the 'stratiform' event on 18 May 1997 showing both 1-minute and 5-minute recording intervals. Site locations are shown in top left of each graph.

5.8. Conclusions

This inland, equatorial location appears to receive most of its rainfall in low intensity (*i.e.*, < 10 mm hr^{-1} equivalent, sampled at 5-minute interval) events. Even the two extreme events sampled during the 3-year analysis period, only maintained 50 mm hr^{-1} intensities (from 5-minute sampled data) for 25 minutes. Such a rainfall regime is clearly very different that that seen within regions experiencing tropical cyclones (*i.e.*, Philippines - East Asia - South Asia, S.W. Pacific - N.E. Australia, Central America - Caribbean, see Bonell and Balek, 1993). Given that near-surface permeabilities have a geometric mean of about 500 mm hr^{-1} over most of the Sapat Kalisun Catchment and surrounding region (Chappell *et al.*, 1998a), large quantities of infiltration-excess overland flow are not expected, with most rainfall entering the soil as Chappell *et al.* (1999) concluded.

Storm durations (where storms are separated by > 20 minutes without 0.2 mm of rainfall) are typically short, particularly during the 1997/8 Northeast monsoon, where 78 % of all rainfall was delivered within events of less than 15 minutes duration. Such a situation would be consistent with that most rainfall is delivered in localised (Chapter 4) mid-afternoon events that have developed through the morning. The typical short duration of the events is may explain the flashiness of the river hydrographs monitored within the Baru catchment tributary of the Sapat Kalisun (Bidin, 1995; Chappell *et al.*, 1999).

The localised nature of the rain-events within the Sapat Kalisun Catchment (Chapter 4) can be seen in the temporal pattern of the rainfall incidence. Raingauges that are less than 1 km apart, tend to experience rainfall on the same days. As gauge spacing increases to 2 - 4 km apart, then rainfall is not received on the same days for some 15-

30 days in the year. Loss of inter-gauge correlation is most strongly seen during the mid-afternoon convective events, where temporal inter-gauge correlation falls off in minutes even for gauges a few hundred metres apart. In contrast, stratiform events maintain their temporal inter-gauge correlation perhaps by a factor 5 more slowly. The short duration and localised nature of the convective events within the Sapat Kalisun Catchment, therefore, demand not only a dense raingauge network, but also a high temporal sampling intensity. Indeed, Chappell *et al.* (1999) found that they needed a 5-minute sampling intensity to model the rainfall-runoff characteristics within a tributary of the Sapat Kalisun.

Chapter 6

Sub-canopy rainfall and wet-canopy evaporation in a selectively-logged rainforest, Sabah, Malaysia

To be submitted as Bidin, K., Chappell, N.A., Douglas, I. and Walsh, R.P.D. Sub-canopy rainfall and wet-copy evaporation in a selectively-logged rainforest, Sabah, Malaysia. *Journal of Hydrology.*

Understanding the impact of the selective removal of trees from a tropical rainforest on the rate of wet-canopy evaporation and transpiration is critical to the assessment of the impact of so called 'sustainable forestry' on local climate, and the water resources potential of rivers. Accurate quantification of the changes in the wet-canopy evaporation component is, however, difficult given the extreme heterogeneity of the vegetation patchwork produced by commercial, selective logging (Chapter 2).

In order to address this issue for an area of lowland dipterocarp forest, selectively-logged some eight years prior to the study, a network of 450 throughfall gauges, plus 22 gross rainfall and 40 stemflow gauges, was installed within the 44 hectare Baru Experimental Catchment (Sabah, Malaysian Borneo). Most of these gauges were located randomly within plots, themselves stratified according to the six canopy classes identified in Chapter 2.

The results showed that more rainfall reached the forest floor beneath the undisturbed remnants of rainforest (*i.e.*, the protected areas), than those patches of canopy subject to light or heavy impact. This may have been because the disturbed forest patches had a higher rate of wet-canopy evaporation (*i.e.*, 12 - 18 % of gross rainfall) in comparison to the undisturbed remnants (*i.e.*, 7 % of gross rainfall). Alternatively, the difference may, at least in part, have been caused by the lower disturbed patches of vegetation being sheltered by the undisturbed forest remnants, leading to the receipt of less rainfall on their canopy surfaces.

6.1. Introduction

Wet-canopy evaporation (E_{wc}) is the vapourisation of rainfall from wetted vegetation surfaces, and is an important component of the water budget of tropical catchments (Bruijnzeel, 1990; Black, 1996). Despite this, there is a dearth of studies on the impact of selective commercial forestry on rates and patterns of wet-canopy evaporation from tropical forests (Asdak *et al.* 1998b). This study, therefore, aims to quantify the rates of wet-canopy evaporation and the remaining component of rainfall that reaches the ground as throughfall and stemflow (also called 'sub-canopy rainfall') within a lowland diperterocarp rainforest recovering from selective forestry.

6.2. Research site

The study area is 44 ha Baru Experimental Catchment, situated near the Danum Valley Field Centre (DVFC) in the Malaysian state of Sabah, Northeast Borneo (Figure 6.1). The catchment has an undulating terrain with an altitudinal range of 70 m.

The area was selectively logged in early 1989 using bulldozers and high-lead yarding, leaving the complex structure of regenerating forest patches, areas of protection forest and areas of highly damaged forest. The 'forest mosaic' within the Baru Catchment has been classified into six categories depending on the level of forest disturbance and recovery rate (Chapter 2).

The study period 1 May 1997 to 30 April 1998 coincided with the 1997/98 El Niño-Southern Oscillation (ENSO) drought. Not suprisingly the recorded 1520 mm of rainfall during this period was the smallest on record at the DVFC meteorological station from 1986-1999 (Figure 6.1). The longer-term average annual rainfall being 2638 mm.

6.3. Sampling / instrumentation network

The sampling network for this study includes a distribution of raingauges within canopy openings (min diameter of openings was 40 m), and throughfall and stemflow gauges to measure the rainfall penetrating the forest canopy.

6.3.1. Rainfall measurement

The raingauges installed within the 44 ha Baru Experimental Catchment are a subset of the larger network of raingauges within the 4-km^2 Sapat Kalisun Experimental Catchment (Chapter 4). There are 22 raingauges within openings in the Baru Catchment, comprising the 16 simple storage raingauges (Chapter 3), and six tipping-bucket raingauges (Figure 6.1).

6.3.2. Throughfall measurement

Sub-canopy rainfall or net rainfall refers to the volume of rainfall that reaches the forest floor and comprises 'direct throughfall' (*i.e.*, rainfall that falls through canopy gaps), 'leaf drip throughfall' and 'stemflow'. In this study the direct throughfall and leaf drip throughfall was measured together using 450 simple storage raingauges (Chapter 3; Figure 6.1).

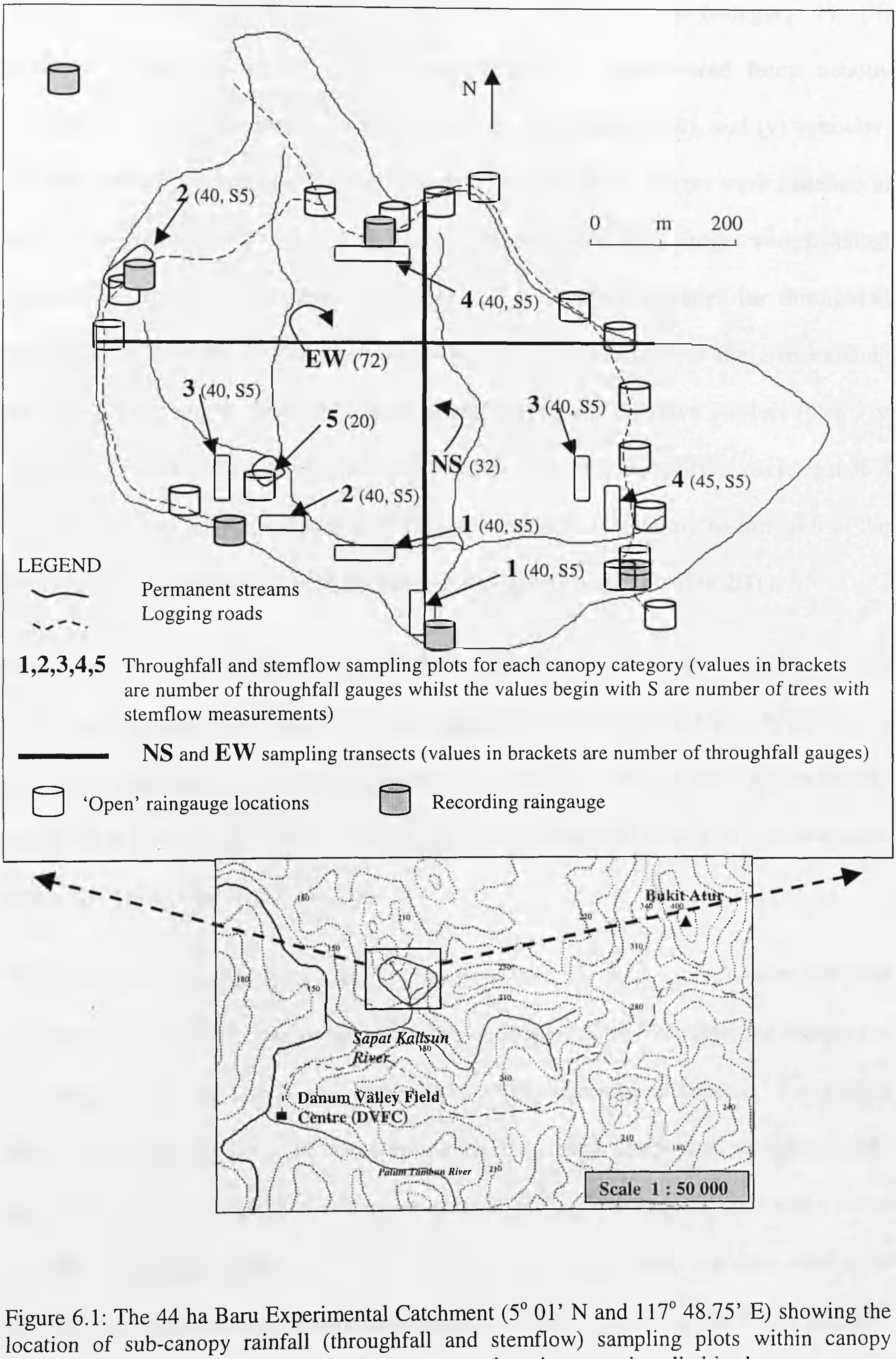


Figure 6.1: The 44 ha Baru Experimental Catchment (5° 01' N and 117° 48.75' E) showing the location of sub-canopy rainfall (throughfall and stemflow) sampling plots within canopy categories 1, 2, 3, 4, and 5. The cylinders represent the raingauges installed in the open canopy to measure gross rainfall (canopy category 6). See Section 2.3 for canopy classification.

Most of the throughfall gauges were located within plots beneath clearly defined 'canopy categories'. These are (i) undisturbed forest canopy (category 1), (ii) moderately impacted forest canopy (category 2), (iii) vine-covered forest canopy (category 3), (iv) *Macaranga* spp pioneer tree canopy (category 4), and (v) sprawler-covered canopy gap (category 5; see Chapter 2). Eighty to 85 gauges were installed in each of the canopy categories 1, 2, 3, and 4 (Chapter 3). Only 20 gauges were installed beneath the 'sprawlers' of canopy category 5. The locations of sites for throughfall measurement beneath all canopy categories were located close to the five existing recording rain gauges within the Baru Catchment (Figure 6.1). Two clusters (plots) of gauges (*i.e.*, 40 to 45 gauges in each plot, except in canopy category 5) were installed for each canopy category (Figure 6.1). Plots were selected randomly within each of the stratified canopy categories, with the plot sizes ranging from 100 m^2 to 200 m^2.

Additional throughfall measurements were made with 105 gauges installed within mixed canopy categories found along two transects (North-South and East-West) across the Baru Experimental Catchment (Figure 6.1). Collectors were located approximately every 20 m along the 650 m 'North-South transect' and every 10 metres approximately along the 720 m 'East-West transect'.

The clusters of gauges within canopy categories 1, 2, 3, 4, and 5 were installed randomly at a fixed position beneath the forest canopies. Once installed, the location of all gauges within the region was surveyed using an electronic theodolite. The gauges were secured firmly in a 10-cm deep pit to keep them fixed and upright. Gauge relocation was not applied for three reasons. Firstly, the research involved a large number of gauges (typically 80 per canopy type), therefore, provided sufficient replication of experimental conditions (Hurlbert, 1984). Secondly, the forest canopies were recovering from selective logging, so throughfall characteristics may have changed with time (cf. Wong, 1991). Thirdly, geostatistical analysis of the long-term throughfall data was to be attempted, which requires a fixed location.

6.3.3. Stemflow measurement

Exactly 40 trees and lianas were measured for stemflow. For canopy categories 1, 2, 3, and 4, eight trees and two lianas were measured for stemflow (Figure 6.1). The trees and lianas were selected randomly within each plot. Stemflow 'collars' were used to measure the stemflow. These collars were shaped out of aluminium plate, supported by 1-cm nails and sealed with a marine adhesive ('Mastik'). Silicon sealant was used to repair any leakage of the collars throughout the study period. Most stemflows were then collected volumetrically, though one gauge was continuously monitored with a datalogged 3-litre tipping-bucket device.

The total stemflow for the trees sampled is scaled to the whole plot using a survey of the basal area of all trees within each plot, *i.e.*:

$$\text{Total stemflow(mm)} = \frac{TA}{PA} \times \frac{SV}{SA} \qquad [6.1]$$

where TA = Total tree basal area in plot (m^2)

PA = Area of the plot (m^2)

SV = Total stemflow volume collected from all sampling trees (mm^3)

SA = Total basal area of sampling trees (mm^2)

(After Wong, 1991).

6.4. Spatial variability of throughfall

The spatial variability of the throughfall within each canopy category and between different canopy categories was examined.

6.4.1. Cumulative throughfall at each gauge

Figure 6.2 shows the cumulative catch in throughfall measured at each of 20 collectors located along the East-West transect (Figure 6.1). Some sub-canopy gauges collect considerably more than the average gross rainfall for the catchment, due to some gauges being located beneath 'drip points' where branches and leaves have focused the intercepted rainfall (*e.g.* Rutter, 1963; Anderson *et al.*, 1969; Lloyd *et al.*, 1988; Black, 1991; Herwitz and Slye, 1992). Additionally, some of the cumulative curves cross, which indicates that the canopy characteristics change with time, due to perhaps movement by wind, growth of vines, branch fall etc.

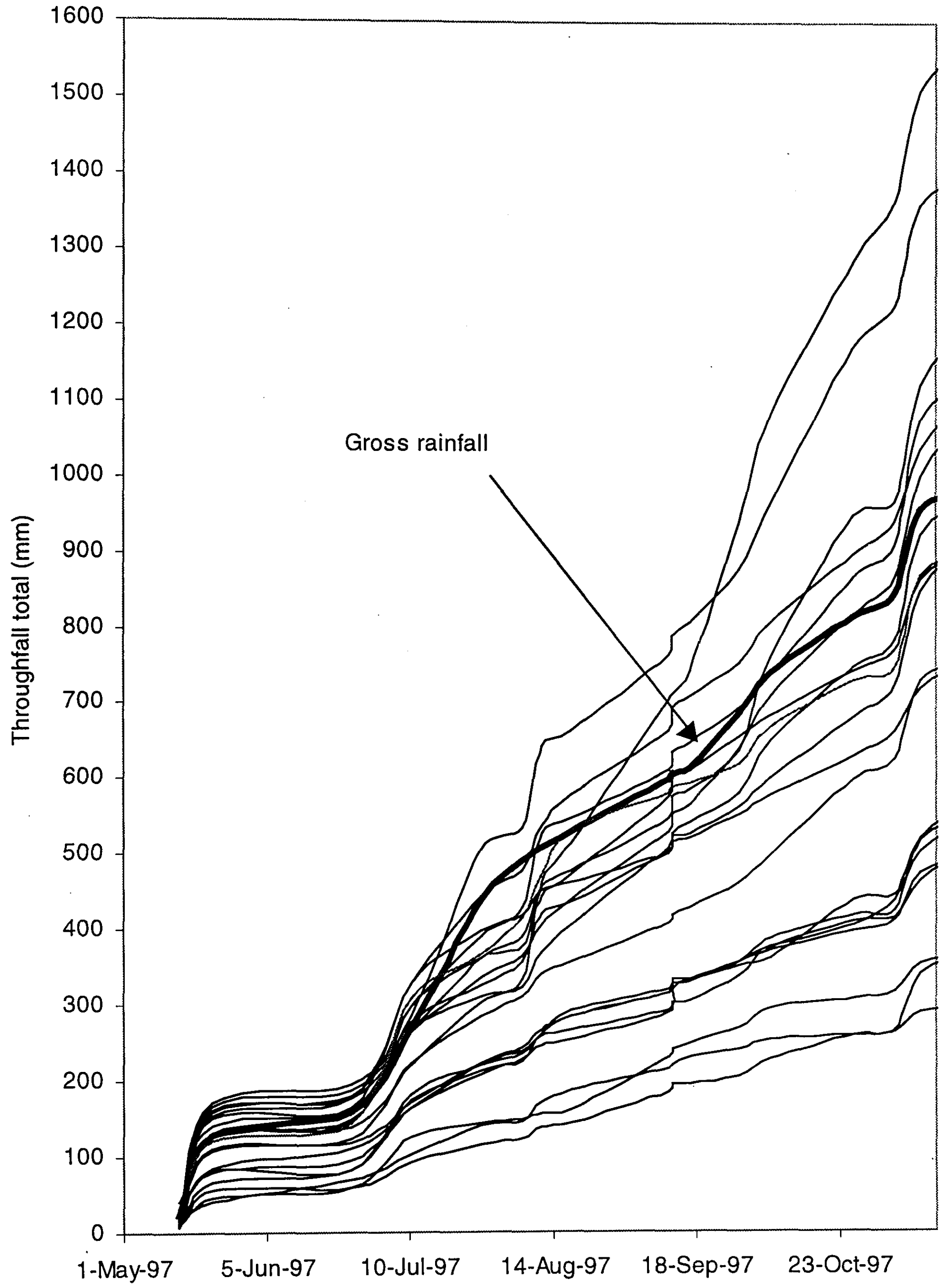


Figure 6.2: Throughfall mass curves for 20 gauges in the East-West transect, Baru Experimental Catchment.

6.4.2. Throughfall variability within each canopy classes

Within each canopy category, the coefficient of variation (CV) in annual throughfall catch ranged from 16.2% for canopy category 1 to 30% in canopy category 5 (Table 6.1). The standard error in the catch was, however, small due to the large number of gauges used. The standard error can be seen to reduce exponentially as the number of randomly sampled gauges increases (Figure 6.3), comparable with that observed by Lloyd and Marques (1988). There were significant variations between the different canopy categories. For example, category 1, the undisturbed forest, only required 10 gauges to constrain the uncertainty (*i.e.*, standard error) to 5 %, compared with 20, 30, 16, and 35 gauges for canopy categories 2, 3, 4, and 5 respectively (Figure 6.3). The highly heterogeneous transects required 40 gauges for 5 % sampling uncertainty. The pattern of throughfall along the East-West Transect across Baru Catchment is shown in Figure 6.4. The different number of gauges required to constrain uncertainty to 5 % for different canopy covers suggests that throughfall in logged-over forest was much more variable than in remnants of undisturbed forest. Canopy category 5 was the most variable, followed by categories 3, 2, and 4 respectively. The lowest uncertainty for the disturbed forest blocks was for canopy 4, due to the fact that almost 80 % of the trees within the plot were *Macaranga* spp. pioneer trees.

Over the year, the standard errors in throughfall catches were only 1.8 %, 2.6 %, 3.3 %, 2.0 %, 7.1 %, and 2.7 % for canopy categories 1, 2, 3, 4, 5, and the transects respectively (Table 6.1).

Table 6.1: Sub-canopy and gross rainfall (Can. 6) of the five canopy categories and transects in Baru Catchment during 12-months period of monitoring 1 May 1997 to 30 April 1998. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference.

	Canopy Category					Transects
	1	**2**	**3**	**4**	**5**	
Gross rainfall (Pg) – canopy 6						
N	3	3	6	8	2	22
Total (mm)	1398.0	1431.0	1417.7	1417.9	1453.3	1413.0
σ (mm)	138.6	22.7	58.4	94.5	19.2	100.1
CV%	9.9	1.6	4.1	6.7	1.3	7.1
σ_x (mm)	80.0	13.1	23.9	33.4	13.6	21.3
Diff. in mean[1]	-	ns	ns	ns	ns	ns
Net rainfall (Pnet)						
Throughfall						
N	80	80	80	85	20	105
Total (mm)	1285.9	1150.2	1157.1	1241.9	1205.6	1201.3
σ (mm)	208.0	262.5	340.0	234.2	383.3	335.0
CV%	16.2	22.8	29.4	18.9	30.0	27.9
σ_x (mm)	23.3	29.4	38.0	25.4	85.7	32.9
Diff. in mean[2]	P < 0.001					
Diff. in mean[3]	P < 0.001	ns				
Diff. in mean[4]	P < 0.1	P < 0.1	P<0.05			
Diff. in mean[5]	ns	ns	ns	ns		
Diff. in mean[6]	ns	ns	ns	ns	ns	
%Tfall (%)	92.0	80.4	81.6	87.6	83.0	85.0
Stemflow						
N	10	10	10	10	-	-
Total (mm)	15.0	27.0	14.0	5.9	14.0*	15.5**
σ_x (mm)	2.4	6.2	4.6	1.9	3.8*	3.8**
%Sflow (mm)	1.1	1.9	1.0	0.4	1.0	1.1
Pnet total (mm)	1300.9	1177.2	1171.1	1247.8	1219.6	1216.8
σ_x total (mm)	25.6	35.6	42.6	27.3	89.5	36.6
Comparison of gross and net rainfall						
Diff. mean (Pg vs Pnet)	P < 0.1	P<0.05	P<0.005	P<0.05	ns	P<0.05
Pg - Pnet (mm)	97.1	253.8	246.6	170.1	233.7	196.2
$\sigma_{compound}$ (mm)	249.9	263.5	344.9	252.5	383.8	349.6
Diff. Pg – Pnet[2]	P < 0.05					
Diff. Pg – Pnet[3]	P<0.001	ns				
Diff. Pg – Pnet[4]	ns	ns	P<0.05			
Diff. Pg – Pnet[5]	ns	ns	ns	ns		
Diff. Pg – Pnet[6]	ns	ns	ns	ns	ns	
%Pnet (%)	93.1±7.5	82.3±3.1	82.6±4.4	88.0±4.2	83.9±6.9	86.1±3.9
Tfallgauges > Pg (%)[7]	28.8	13.8	20.6	23.1	20	34.7

Cont.'d...

Notes:
[1] level of significance difference against canopy category 1
[2] level of significance difference against canopy category 2
[3] level of significance difference against canopy category 3
[4] level of significance difference against canopy category 4
[5] level of significance difference against canopy category 5
[6] level of significance difference against transect canopy
[7] throughfall gauges recorded rainfall totals more than gross rainfalls
[ns] not significant at $P < 0.1$
* estimated value – assumed as that of canopy category 3 (corresponding error mean of canopy 1 – 4)
** estimated value – assumed as an average of canopy category 1 to 4 (also corresponding error)

The percentage of throughfall catches that exceeded the gross rainfall were 28 %, 14 %, 20.6 %, 23 %, 20 %, and 35 % for canopy categories 1, 2, 3, 4, 5, and the transects, respectively (Table 6.1). This was consistent with the 29 % for undisturbed Amazon rainforest (Lloyd and Marques, 1988), but larger than the 13 % observed by Wong (1991) during the wet period 1989/90 at Danum Valley.

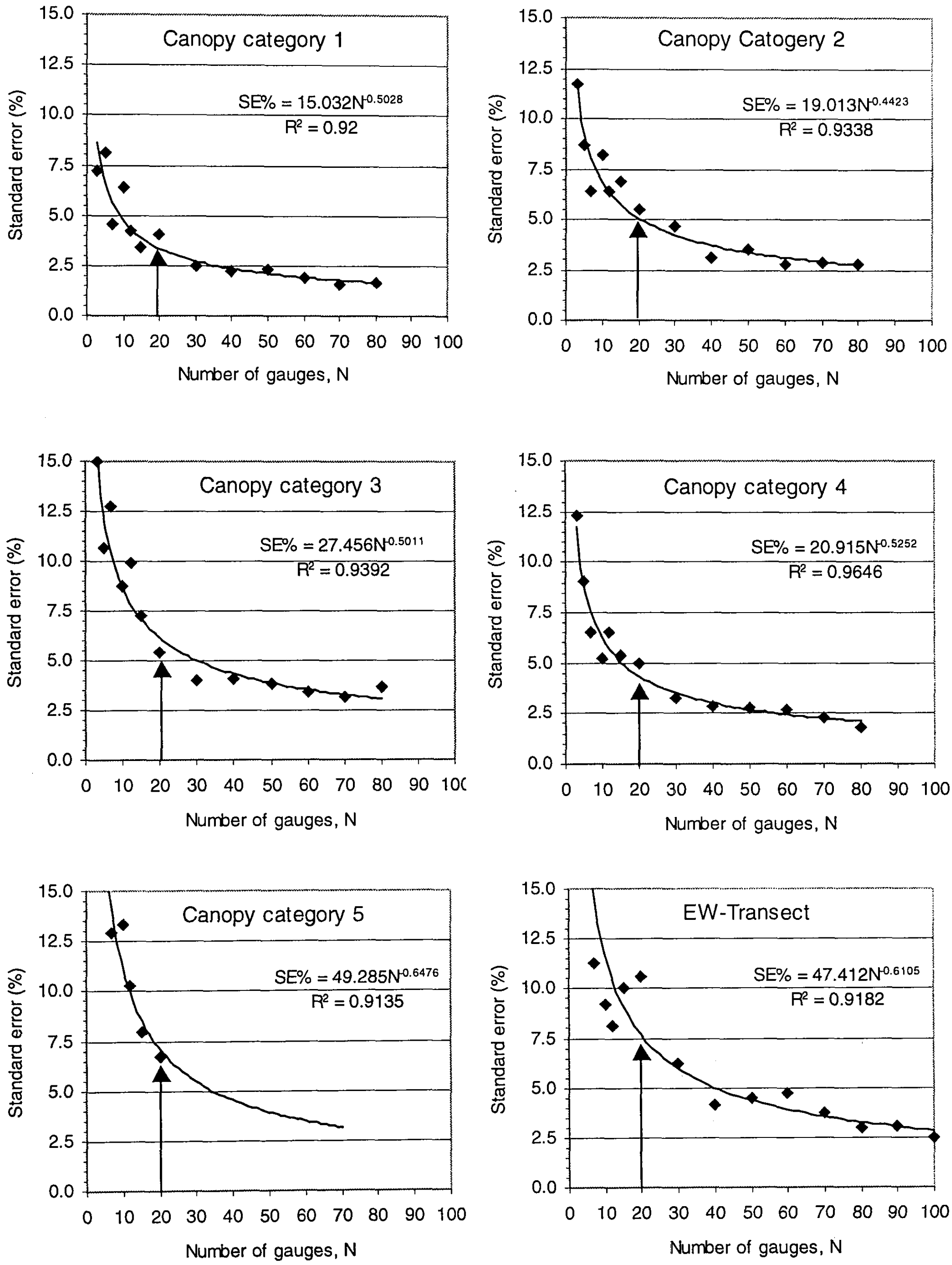


Figure 6.3: Uncertainty in throughfall measurement produced by different number of gauges under different canopy categories. An arrow on each plot shown the standard error in catch where 20 raingauges to be used under that particular canopy category.

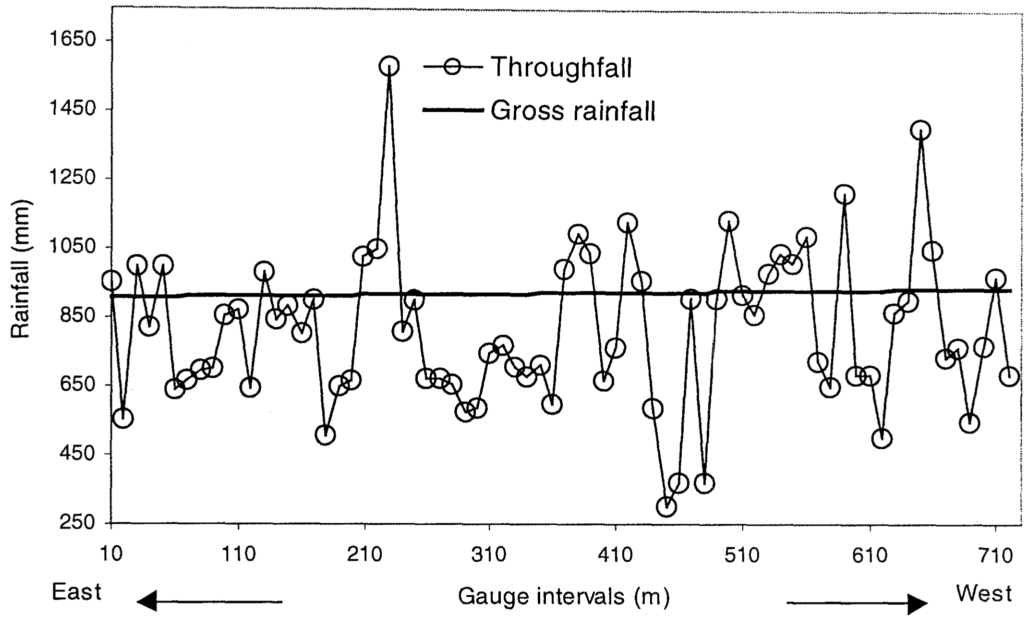


Figure 6.4: Throughfall totals for the period 1 May 1997 to 30 April 1998 along the East-West Transect of collectors in the Baru Catchment. Gross rainfall was measured by single gauges at each end of the transect.

6.4.3. Difference in annual throughfall between the canopy types

No statistically significant differences were observed between plots of the same canopy category (Table 6.1). In contrast, the differences in mean catch of canopy category 1, the undisturbed forest, and both canopy 2 (moderately impacted forest) and canopy 3 (vine-covered, highly disturbed forest) were highly significant ($P < 0.001$). Canopy category 3 was also significantly different to canopy 4 (*Macaranga* spp trees) ($P < 0.05$). On average, canopy 1 allowed 1286 mm of rainfall to reach the forest floor compared with 1150 mm, 1157 mm, 1242 mm, 1206 mm, and 1201 mm for canopies 2, 3, 4, 5, and the transects, respectively. These figures suggest that disturbed canopies allowed less rainfall penetration than undisturbed canopies. There are several possible reasons why less rainfall reaches the forest beneath disturbed canopies of selectively logged lowland forest. These relate to possible differences in: (i) gross rainfall intercepted by the canopy, and (ii) canopy surface characteristics.

(i) ***Gross rainfall intercepted by canopy*:** The higher canopies of virgin forest patches of forest within selectively logged forest may shelter the lower disturbed canopies, and hence lead to reduced rainfalls received in the lower disturbed forest patches (Hayes and Kittredge, 1949; Aldridge, 1975; Ford and Deans, 1978; Barry and Chorley, 1982 p300; Herwitz and Slye, 1992). Herwitz and Slye (1992) termed the process 'the differential interception of inclined rainfall' and produced a model to illustrate the process within their tropical rainforest in Queensland. Ford and Deans (1978) explained that when rain falls at an angle, the leading shoots at the top of a canopy tree present a greater intercepting area than its vertically projected crown area. Thus if patches of undisturbed forest canopy receive more gross rainfall, then greater throughfall volumes would be expected if wet-canopy evaporation rates with the same or smaller then those of the disturbed forest patches.

(ii) ***Canopy-surface characteristics:*** There are two aspects of canopy surface that may have attributed to lower throughfall in disturbed canopy. Firstly, qualitative field observation shows that there is an increased density of leaves on the outer surfaces of the disturbed upper canopy, as a result of the expansion of the woody climbers. This outer surface experiences the highest temperatures and rates of net radiation, thus may be subject to higher rates of potential E_{wc}. Additionally, some of the disturbed canopy appeared to contain more dead leaf and woody matter, turning parts of the canopy a darker colour and hence reducing the albedo. The increased leaf density and reduced albedo in this part of the canopy may, therefore, have had a disproportionate effect on the whole canopy E_{wc}. Secondly, selective removed of the upper canopy trees during the logging operations increases the roughness of the forest surface. This could increase the 'atmospheric conductance' and lead to a net increase in evaporation rate (Dingman, 1994; John Gash, pers. Comm.). Indeed, Klaassen *et al.* (1996) found that windspeed tended to increase around forest gaps, generating more turbulence, thus promoting E_{wc}.

Amongst the canopies in disturbed forest, canopy category 4 (*Macaranga* spp trees) recorded significantly higher throughfall (*i.e.*, $P < 0.1$ and $P < 0.05$ relative to canopies 2 and 3, respectively). This is probably because the *Macaranga* spp trees at Danum have a very open canopy structure and low leaf area index (LAI, cf. Pitman, 1989) allowing much rainfall to penetrate. Additionally, the smooth bark of the *Macaranga* spp trees will not promote storage and subsequent evaporation from the tree trunk (cf. Herwitz, 1985).

6.5. Variations in stemflow between different canopy types

Uncertainties in sampling and calculation of stemflow are usually very high (Lloyd and Marques, 1988), though it normally constitutes only a very small proportion of sub-canopy rainfall. These small, but highly focused inputs can, however, becomes significant, for local erosion and mineral leaching (Herwitz, 1993) and in the moderation of local water stress (Navar, 1993).

The annual totals of stemflow for each of the canopy categories 1, 2, 3, and 4 were 15 mm, 27 mm, 14 mm, and 6 mm respectively (Table 6.1). The very low stemflow beneath canopy 4 was expected, due to the branching architecture of the *Macaranga* spp. and the sparsity of vines within these forest blocks. The highest stemflow rates observed were beneath canopy 2 where there was a higher proportion of *Aporusa & Mallotus* spp. trees which have small branching angles (Chapter 2).

The stemflow expressed as a proportion of gross rainfall was 1.1 %, 1.9 %, 1.0 %, and 0.4 % for canopy categories 1, 2, 3, and 4 respectively (Table 6.1). The 1.1 % stemflow within the undisturbed forest remnants (canopy category 1) was slightly smaller than the 1.8 % reported by Lloyd and Marques (1988), 1.9 % by Sinun *et al.* (1992), and 1.4 % by Asdak *et al.* (1998b). This may be due to the fact that this study was undertaken during an ENSO drought.

6.6. Estimation of wet-canopy evaporation

Subtracting the combined throughfall and stemflow totals from local measurements of gross rainfall gave annual wet-canopy evaporation (E_{wc}) percentages of 7 %, 18 %, 17 %, 12 %, 16 %, and 14 % from the canopy categories 1, 2, 3, 4, 5, and the transects, respectively (Table 6.1).

An estimate of the catchment-average E_{wc} was calculated by weighting the canopy-specific rates by the estimated proportions of the catchment covered by that canopy type (cf. Chapter 2). This gave an average E_{wc} for the Baru Catchment of 13.6 % (Table 6.2). Encouragingly, this rate is comparable with that from the mixed canopies along the two transects within the Baru catchment (Table 6.3).

Table 6.2: Upscaling wet-canopy evaporation (E_{wc}) from proportional contributions of each canopy category (Chapter 2) during different periods of monitoring in Baru catchment. See Table 6.1 for statistical details in the estimates.

	Canopy category						Baru total
	1	2	3	4	5	6 (Open)	$\%E_{wc}$ [d]
Area prop[b]	0.182±0.04	0.248±0.03	0.300±0.03	0.102±0.03	0.098±0.03	0.07±0.03	1±0.18
SW-monsoon							
E_{wc} (%)[a]	8.4	16.1	21.6	12.2	17.0	-	
Area weighted[c]	1.5	4.0	6.5	1.2	1.7	-	14.9
NE-monsoon							
E_{wc} (%)[a]	5.2	19.6	12.6	11.8	14.9	-	
Area weighted[c]	0.9	4.9	3.8	1.2	1.5	-	12.3
12-months							
E_{wc} (%)[a]	7	18	17	12	16	-	
Area weighted[c]	1.3	4.5	5.1	1.2	1.6	-	13.6

Notes:

[a] E_{wc} as a proportion of gross rainfall for individual canopy categories

[b] area occupied by individual canopy categories as a proportion of Baru catchment area

[c] E_{wc} of each canopy multiplied by the proportional area occupied by that category, including area only uncertainty

[d] upscaled value from contributions of each canopy category.

Table 6.3: Mixes of disturbed and undisturbed forest mosaics E_{wc} rates representing Baru Catchment measured by different combinations of throughfall gauges, showing no significant different in the values. However the upscaled value of E_{wc} is slightly lower, as this approach considered the area covered by roads and gaps, producing 0% E_{wc}.

Measurement of throughfall and calculation approach	No. gauges	Annual		
		Rainfall (mm)	Sub-canopy rainfall (mm)	E_{wc} (%)
1- Arithmetic mean of gauges in transects across catchment	105 (s)	1413	1217	13.9
2- Arithmetic mean of gauges in plots of different canopy categories regardless of the area covered by each canopy	345 (s)	1424	1225	14.0
3- E_{wc} values from plots of different canopy categories considering of proportional areas covered by each canopy	345 (s)	1424	1230	13.6
4- Arithmetic mean of gauges in 1 & 2 regardless of the area covered by each canopy	450 (s)	1422	1223	14.0

6.6.1. Rate of wet-canopy evaporation within undisturbed lowland rainforest

The E_{wc} value of 7 % for undisturbed forest blocks in this study is amongst the lowest rates for tropical rainforests (Table 6.4) but within range of reliable values defined Bruijnzeel (1990). If one considers the errors with some other studies (Lloyd *et al.* 1988), then the rate is comparable to the 9 % for undisturbed Amazonian terra firma rainforest reported by Lloyd and Marques (1988) and the 11 % reported for Kalimantan rainforest by Asdak *et al.* (1998b). These uncertainties include (a) the ±1 % reported standard errors, (b) admissions of gauge overflows during extreme events (cf. Asdak *et al.*, 1998b), and (c) the distance between throughfall collectors and the rainguages measuring gross rainfall (cf Lloyd, 1990). Given that this study was undertaken during an ENSO drought year, differences may have resulted from this longer-term temporal cyclicity (Chappell *et al.*, 2001). The smaller annual rainfall is probably associated with less rainfall being delivered as wind-driven, inclined rainfalls (Herwitz, 1985; Herwitz and Slye, 1992, 1995) giving reduced potential for wet-canopy evaporation. Tsukamoto and Ishigaki (1989) have also reported increased E_{wc} with increased gross rainfall. Indeed, Table 6.2 shows that the slightly smaller rates of E_{wc} were observed during the Northeast monsoon, in comparison to the Southwest monsoon, and Chapter 5 shows that the Northeast monsoon had typically lower rainfall intensities.

Table 6.4: Pertinent studies presenting annual rates of E_{wc} measured in undisturbed secondary rainforest.

Reference	**Location**	**No. gauges**	**.......annual........** **Rainfall (mm)**	**E_{wc} (%)**
Calder *et al.*, 1986	West Java	2[b] (s)	2850	21
Walsh, 1987	Dominica	nk[d]	5204	27
Lloyd *et al.*, 1988	Amazon	36 (m)	2805	9
Kasran, 1989	West Malaysia (central)	4[a] (s)	3786	27
Sinun *et al.*, 1992	East Sabah	40 (m)	2824	17
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	2199	11
Current study	East Sabah	80 (s)	1398	7[+]

Notes:

a 0.7 m^2 trough
b plastic sheet
d not known
s stationary
m moved
\+ undisturbed patches with logged-over forest

6.6.2. Effect of selective forestry on wet-canopy evaporation

Depending on the integration procedure, the catchment-average E_{wc} for the Baru catchment ranges from 13.6-14.0 % of the incident rainfall (Table 6.5). This rate is comparable with those observed by Asdak *et al.* (1998b) for the 'closed canopy' logged forest at their Kalimantan site, and for the disturbed lowland forest at Bukit Tarek in Peninsular Malaysia (Yusop, 1996). There is, however, considerable variability in the rates reported for disturbed tropical forests.

Table 6.5: Pertinent studies presenting annual rates of E_{wc} measured in disturbed secondary rainforest.

Reference	**Location**	**No. gauges**	**.......annual.........** **Rainfall (mm)**	**E_{wc} (%)**
Nik *et al.*, 1979	West Malaysia (central)	11[a] (s)	nk[d]	27
Scatena, 1990	Puerto Rico	22 (m)	5745	39
Yusop, 1996	West Malaysia (central)	nk[d]	2723	13
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	3563	15**
Current study	East Sabah	265 (s)	1427	13.6-14.0

Notes:
[a] 0.7 m^2 trough
[d] not known
s stationary
m moved
** Arithmetic mean of 3 different disturbed canopy types (excluding open canopy) provided by the authors.

6.7. Conclusions

The 1997/8 water-year studied, turned out to be a severe ENSO drought. During this period, the remnants of undisturbed lowland dipterocarp forest studied allowed 93.1 ± 7.5 % of the rainfall through the canopy to the ground, giving wet-canopy evaporation rate of approximately 7 % of gross rainfall. This figure is towards the lower end of the range of wet-canopy evaporation rates observed for undisturbed tropical forests. The low rate may relate to the expected lack of storminess during the 1997/8 drought (Chapter 5).

Selective harvesting of the forest generated patches of moderately-impacted forest (canopy category 2) and more heavily damaged areas, now with the remnant climax trees covered by vines (canopy category 3). Much smaller volumes of sub-canopy rainfall were observed below these forest patches (*i.e.*, 82.3 ± 3.1 % and 82.6 ± 4.4 % respectively). This result could be explained by (1) these (on average) lower forest canopies receiving less incoming rainfall due to sheltering by the undisturbed remnants, or (2) the changed canopy surface characteristics. The surfaces of the disturbed canopies often have a greater surface density of leaves, which may have a disproportionate effect on rates of wet-canopy evaporation. Further, the more uneven surface of the disturbed canopy patches may increase atmospheric turbulence and thus increase the rate of evaporation. These two phenomena may also account for the unexpectedly high estimates of wet-canopy evaporation from the areas of sprawlers and shrubs (canopy category 5).

Taking into account the area covered by the six canopy categories (Chapter 2), the catchment-wide estimate for wet-canopy evaporation from the selectively-managed forest (following eight years of recovery) was 13.6 % of the gross rainfall. This figure was almost identical to the 14.0 % wet-canopy evaporation rate calculated from the two transects of mixed canopy types. The study, therefore, suggests that the rate of wet-canopy evaporation may significantly increase as a result of selective logging. It is then becomes important to know whether these extra losses are offset by reductions in the rate of transpiration, and also to know what is the resultant impact on the water yield of the river (Chapter 7).

Chapter 7

Water-yield and riverflow responsiveness of a 44 ha catchment recovering from selective tropical forestry

Preliminary analysis of an 8-year water-balance record is presented as only one other such record associated with the effects of the first episode of selective tropical forestry (see Abdul Rahim Nik and Yusop, 1994) is available in the literature. A new research project to complete the quality assurance of these data (QAA) is, however, required before substantial conclusions based upon these data could be published within a journal article.

The impact of commercial, selective forestry on the water balance is a key concern for those trying to assess anthropogenically-induced changes to the tropical climate or the water resources of rivers. Despite this fundamental importance, there are very few water balance studies undertaken within tropical catchments following a single selective harvesting period. The problem is confounded further in the Southeast Asian tropics by the recent acknowledgement of the impact of natural cycles in the climate associated with the El Niño Southern Oscillation (ENSO). Such natural cycles may have a significant effect on the purely natural dynamics of the evaporative losses, as reflected in the rainfall minus riverflow (P-Q) data.

Within this study, we use a new and very robust method of separating the effects of natural cycles from those long-term drifts in the P-Q data that may be caused by forestry impacts on the canopy processes. This method utilises the Dynamic Harmonic Regression (DHR) model of Young *et al.* (1999). The data were collected for a 44 ha catchment in Borneo during the year of forest disturbance to over eight years post forestry activities. As a further measure of the potential impact of the recovering vegetation of the riverflow, through for example, the growth of vegetation on logging trails and its impact on overland-flow generation (Douglas *et al.*, 1995), an index of the flashiness of the catchment response was examined.

The results indicate that while (a) catchment responsiveness changes with forest / terrain recovery, and that (b) P-Q changes in response to seasonal and inter-annual cycles in the rainfall, the P-Q and hence total evaporation, has not changed significantly in the eight years following selective logging. It is imperative that this study continues to see if and when vegetation recovery significantly impacts on the total evaporation and water yield.

7.1. Introduction

There are very few rainfall-runoff records for tropical catchments recovering from catchment-wide, selective timber harvesting (Bruijnzeel, 1990; Yusop, 1996). This means that the impact of sustainable (*i.e.*, non-clearfell) forms of forestry on river flashiness and water yield are still debated (Bruijnzeel, 1990; Chappell *et al.*, 2000).

This study presents an analysis of (a) monthly rainfall and riverflow data for a small tropical catchment for an 8-year period following selective-logging activities in 1988/9, and (b) four separate years of daily riverflow data for the same catchment. River flashiness is characterised by the Hewlett and Hibbert (1967) 'quickflow' index, estimated from the stream hydrograph using a method developed by Bidin and Greer (1997). A wet year (1990) and a dry year (1992) shortly after logging are compared with the response of another wet year (1995) and a dry year (1997/8) latter in the succession of forest recovery. The Dynamic Harmonic Regression (DHR) model (Young *et al.*, 2000) is used to separate the annual seasonality and inter-annual cycles from the longer-term drift in evapo-transpiration, strictly rainfall minus discharge (P-Q), that may result from the recovery in the selectively logged forest.

7.2. Catchment characteristics

The 44 ha Baru Experimental Catchment is in the Danum Valley area of the Ulu Segama Forest Reserve, Sabah, Malaysian Borneo (4°58' N and 117° 48'E). The average annual rainfall (1986-1999) received at the nearby Danum Valley Field Centre (DVFC) meteorological station is 2,712 mm, but varies with the impact of the El Niño Southern Oscillation (ENSO) from, for example, 1,520.7 mm in the 1997/8 drought year (where the water-year is from the 1 May - 30 April) to 3,791 mm in 1995/6 (Chapter 4 and 5).

The catchment is within a melange geological unit which comprises of siltstones, sandstones, cherts, spilites, and tuffs (Leong, 1974; Gasim *et al.*, 1988). Soils are dominated by Haplic Alisols (Chappell *et al.*, 1999). The catchment, like the region, has an undulating topography with altitude ranging from 120 to 250 m. The slopes around the catchment divide are approximately 18-25°, declining generally to 10° near the main stream, but with short slopes of up to 45° where outcrops of sandstone and tuff occur. Indeed, there is a high density of ephemeral channels in the region, which when incorporated with the perennial stream channels, give a very high drainage density of 20 km km^{-2} (Walsh and Bidin, 1995). This density is even higher if the skidder trails and gullies created during logging are considered.

The Baru Catchment was selectively logged in 1988/9 and the encompassing logging coupe experienced a timber extraction rate of 79.9 m^3ha^{-1} (Moura Costa and Karolus, 1992). A highly heterogeneous mosaic of remnant forest and forest disturbed to different degrees was left in the area (Chapter 5). Some recovery in the forest (Tangki, In prep.) and erosional processes (Douglas *et al.*, 1995, 1999) has been observed in the years following the timber harvesting.

7.3. Rainfall and riverflow monitoring

Rainfall was measured by a siphoning-tank raingauge (1988-1992) and a data-logged, tipping bucket raingauge (1992-) installed in a large roadside clearing. The site is known as 'KM 63' (Chapters 4 and 5). This gauge, located at an approximately 1 km from the Baru gauging structure, was used to measure the rainfall for this study for the water years 1988/89 to 1996/97.

The gauging station known as 'Baru' was established in June 1988 just before the commercial selective logging took place (Douglas *et al.*, 1992; Greer *et al.*, 1995). During the period 1988-1992, a horizontal float gauge (Ott) was used to record a continuous trace of water level with weekly charts (scale 1:10). The charts were digitized on a Summagraphics digitizing tablet and Sigma Scan digitizer. From early 1992, a digital shaft encoder and Newlog datalogger (Technolog) was used to measure the water-levels. During the period 1988 to early 1996, a natural rock section was used to provide the hydraulic drop. This section was regularly rated with current metering and dilution gauging (Chappell *et al.*, 1999). A 120^{o} thin-plate V-notch weir, pinned into the solid bedrock and built to a height of 2 m with zinc plate and concrete retaining was used for 1996 onwards. The author was involved in monitoring flows at this river station from 1989.

For this preliminary analysis mean daily rainfall was calculated only from a single raingauge, and the mean daily riverflows were calculated by applying the rating equation to mean daily water-level data. A further project could undertake a much more accurate assessment of the water-balance data by using a combination of (a) the new understanding of the spatial variability of the rainfall over the local region (Chapter 4), and (b) by a detailed Quality Assurance Analysis (QAA) of the chart and datalogged water-level records plus application of the rating equation to the sub-hourly digital data.

7.4. Long-term P-Q dynamics

Over the water-years 1988/9 to 1996/7, the annual percentage of rainfall that does not appear as riverflow within the Baru ranges from 30 to 73 percent (Table 7.1). If the catchment is assumed to be watertight (see Bruijnzeel, 1990) and the storage tends to zero after one year (Gregory and Walling, 1973), this 'P-Q' value would equate to the annual evapotranspiration.

The range in annual evapotranspiration (as estimated by 'P-Q') of 865 mm (1995/6) to 1904 mm (1992/3). For all but the water-year 1995/6, the range of 1,371 - 1,904 mm is comparable to that recorded by other studies in the tropics (Table 7.2; see also Bruijnzeel, 1990). The low 'P-Q' percentage for 1995/6 may relate to the high proportion of extreme rainstorms that occurred in this water-year, which has given rise to a larger effect of error due to the approximate rating of the high flows within this preliminary analysis.

Table 7.1: Water-year (1st May - 30th April) variations in rainfall (P), streamflow (Q), and evapotranspiration (P-Q) totals for the Baru Catchment.

Period	P (mm)	Q (mm)	P-Q (mm)	P-Q/P%
1989/90	2802.80	1316.65	1486.15	53
1990/91	2548.90	875.74	1673.16	66
1991/92	2127.90	756.57	1371.33	64
1992/93	2763.10	858.71	1904.39	69
1993/94	2575.20	846.35	1728.85	67
1994/95	2446.90	988.94	1457.96	60
1995/96	2915.00	2050.31	864.69	30
1996/97	2434.30	663.64	1770.66	73

Table 7.2: Estimated annual evapotranspiration (ET) estimates from some tropical forest areas.

Catchment region	Catchment area (ha)	ET (mm)	Source
Java, Indonesia	Microclimate study	1,481	Calder *et al.* (1986)
West Sabah, Malaysia	3.4 –18.2	1,540	Malmer (1992)
Central Amazon	23.4	1,120	Lesack (1993)
Central Amazon	130	1,493	Leopoldo *et al.* (1995)
East Sabah, Malaysia	44	1,510	This study

To examine whether the inter-annual dynamics in P-Q are attributable to changes in the re-growth of the selectively logged forest (even within such a preliminary study), the effects of the climatic dynamics must be identified. Such climatic cycles may have a significant impact on the short and long term behaviour of the water balance (Chappell *et al.*, 2000, 2001).

Within this study, the strength of seasonal climatic cycles and the possibility that longer-term cycles related to phenomena such as ENSO could be affecting the P-Q data-series was assessed by applying the recently developed Dynamic Harmonic Regression (DHR) model of Young *et al.* (1999). This model was applied to the monthly, rainfall (P), riverflow (Q) as well as the P-Q data to allow greater explanation. Data for the eight-year and seven-month period from August 1988 to February 1997 inclusive are used for this analysis.

Changes in the longer-term P-Q (called the 'drift'), perhaps related to changes in the evaporative losses from the forest, will be identifiable once inter-annual cycles (associated with physical phenomena) are removed.

The model was then used to identify (separately) within-year or 'seasonal' cycles (S_t). Additionally, by combining these seasonal cycles, with the inter-annual cycles and the drift, a model of the rainfall, the riverflow and the P-Q data is produced and the level of explanation ('efficiency') quantified.

The Dynamic Harmonic Regression (DHR) model is a recursive interpolation, extrapolation and smoothing algorithm for non-stationary time-series (Young 1998; Young *et al.*, 1999). The DHR model identifies three components in the time-series, *i.e.*,

$$U_{(t)} = T_t + S_t + e_t \qquad [7.1]$$

where $U_{(t)}$ is the observed rainfall, riverflow or P-Q time-series, T_t is the trend which includes (a) the 'drift' in long-term average data and (b) the inter-annual cycles, S_t is the periodic component related to annual and intra-annual seasonality, and e_t is the white noise. The S_t term is further defined as:

$$S_t = \sum_{i=1}^{R} \{a_{it} \cos(\omega_i t) + b_{it} \sin(\omega_i t)\} \qquad [7.2]$$

where $a_{i,t}$ and $b_{i,t}$ are the Time-Variable-Parameters (*TVP*s) of the model, R is the number of seasonal components, and ω_i are the set of frequencies chosen by reference to the spectral properties of the time-series. Optimisation of the *TVP*s was achieved by first estimating the Noise-Variance-Ratio (*NVR*) of the *TVP*s. This is achieved in the frequency domain by fitting the logarithmic pseudo-spectrum of the DHR model to the estimated logarithmic AutoRegressive (*AR*) spectrum of the observed rainfall series. Once *NVR* parameters are optimised, a single run of two recursive algorithms, the Kalman Filter and Fixed-Interval-Smoothing equations provide estimates of the various components (Young, 1998; Young *et al.,* 1999). This approach results in relatively high

NVRs (about 1×10^{-2}) that ensures a good model optimisation to the main seasonal components (i.e., those with longest periodicity) observed within the spectra plot (Figure 7.1)

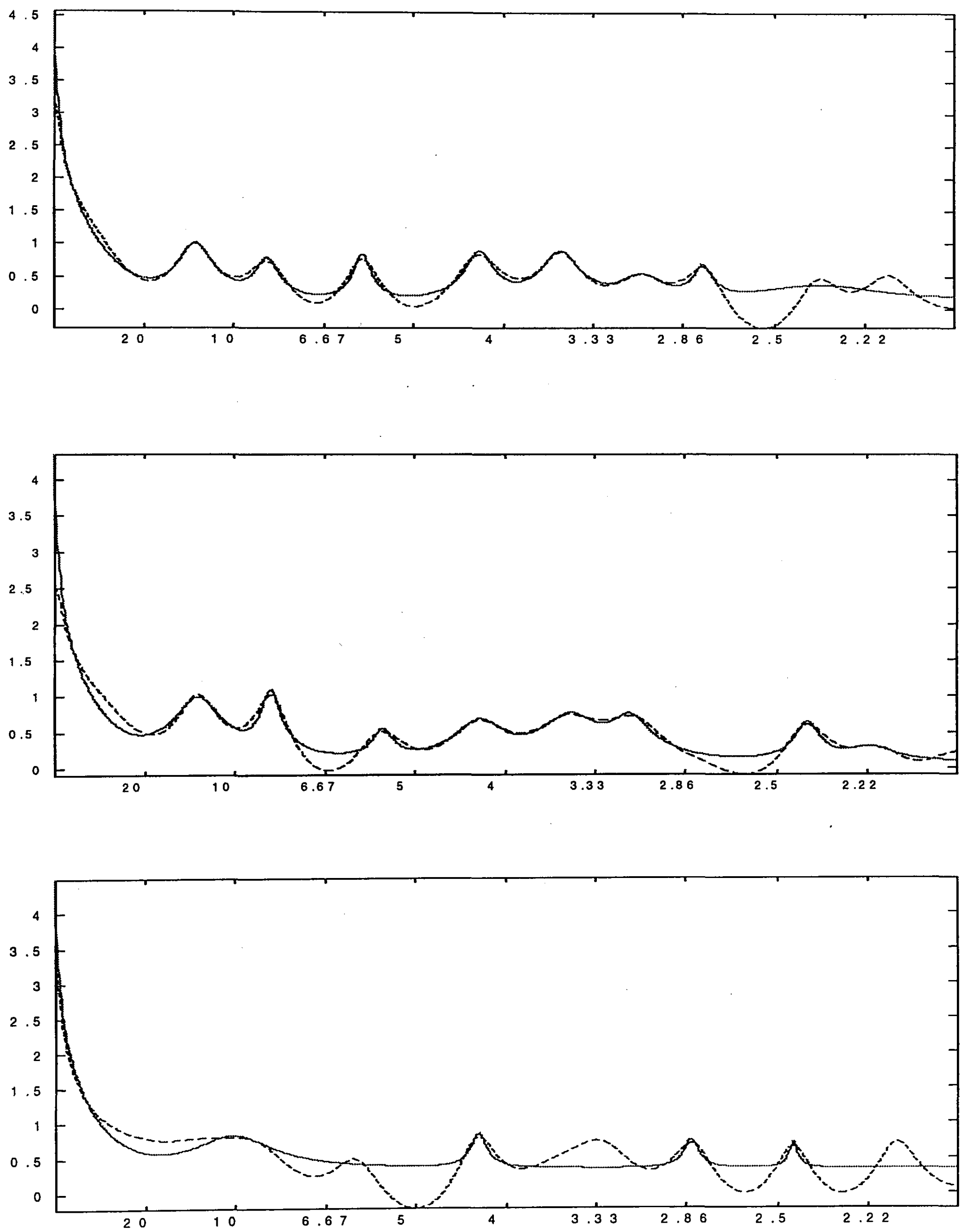


Figure 7.1. Spectral plots of the within-year or 'seasonal' components (broken line) and the DHR model results (solid line) for (a) rainfall, (b) riverflow and (c) P-Q of the Baru Experimental Catchment. The x-ordinate is in months and the y-ordinate is $\log_{10}$ power.

The efficiency of model in predicting all of the components of the rainfall, riverflow and P-Q time-series (using the high *NVRs*) is 83 %, 86 % and 79 % respectively (Figures 7.2, 7.3 and 7.4).

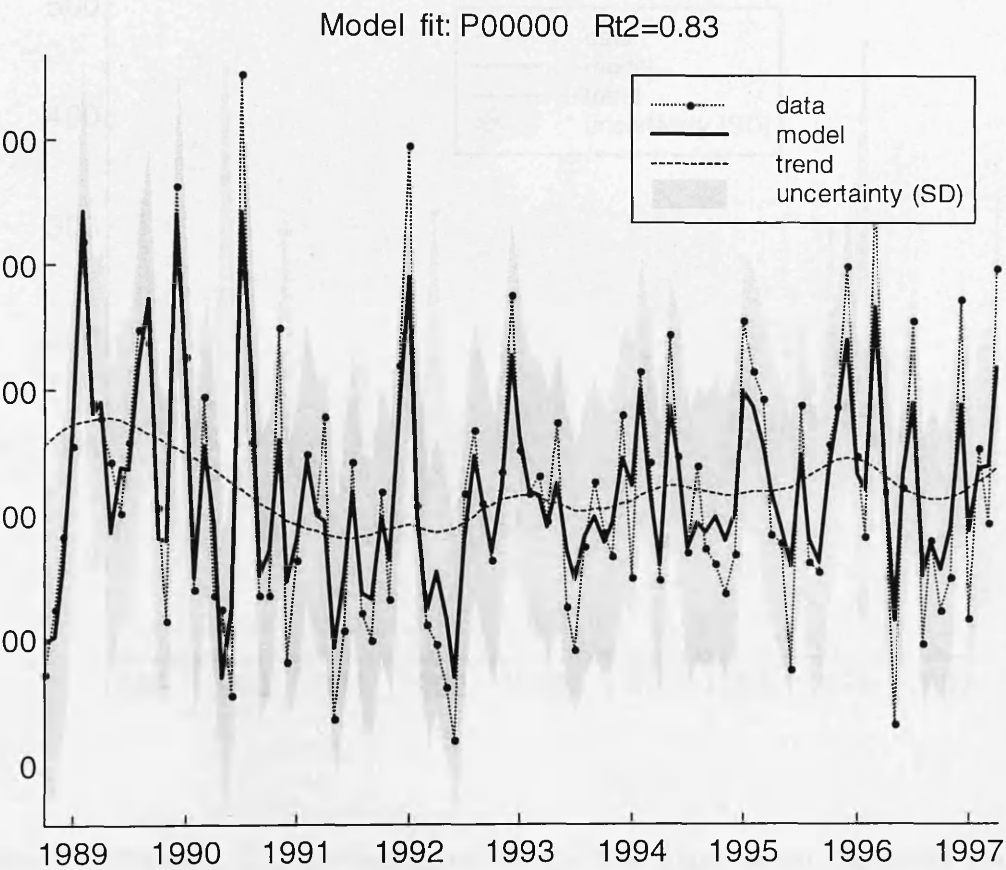


Figure 7.2. Observed rainfall time-series for the Baru Experimental Catchment (..•..) and DHR-modelled rainfall time-series (-) together with the uncertainty band (± one standard deviation in grey shading). The trend comprising the inter-annual cycles and drift is also shown (---). The x-ordinate is the year, and the y-ordinate is the monthly rainfall (mm).

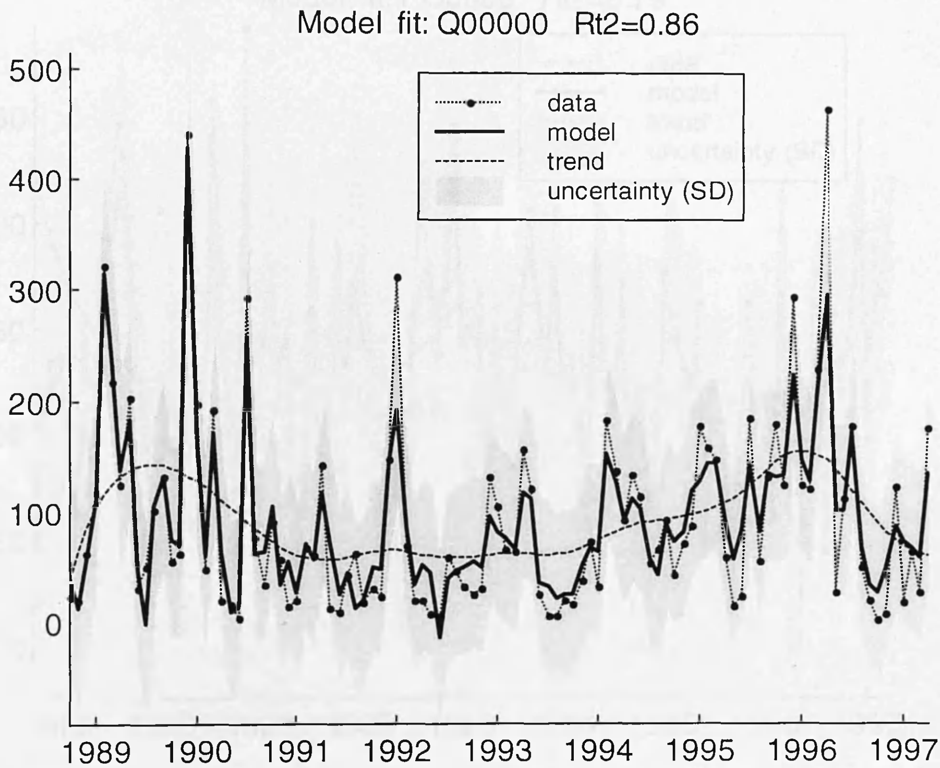


Figure 7.3. Observed riverflow time-series for the Baru Experimental Catchment (..•..) and DHR-modelled rainfall time-series (-) together with the uncertainty band (± one standard deviation in grey shading). The trend comprising the inter-annual cycles and drift is also shown (---).The x-ordinate is the year, and the y-ordinate is the monthly rainfall (mm).

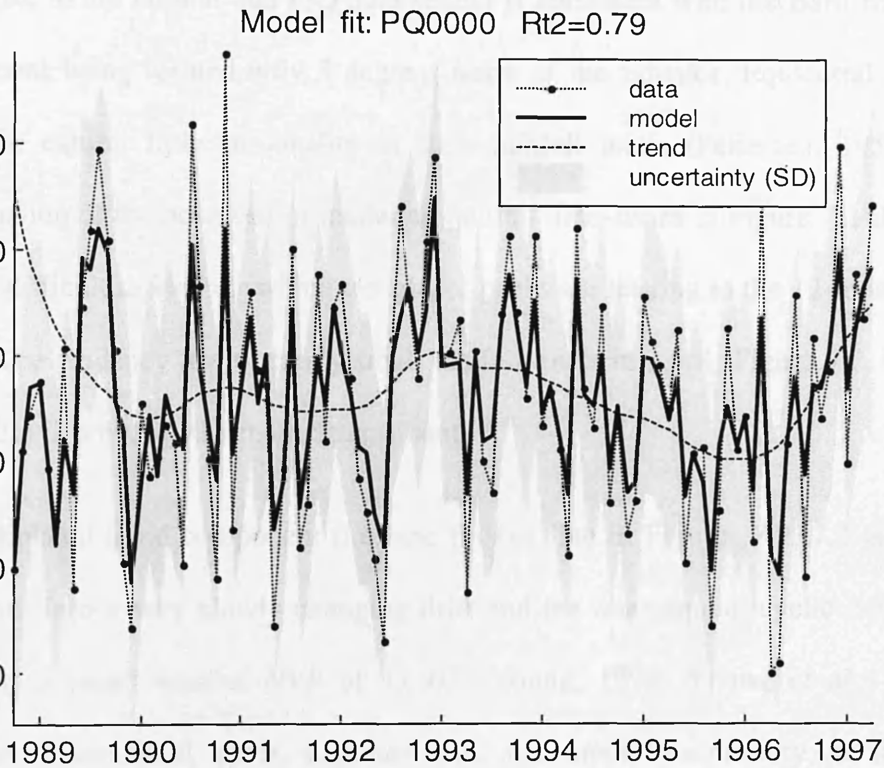


Figure 7.4. Observed rainfall-riverflow (P-Q) time-series for the Baru Experimental Catchment (..•..) and DHR-modelled rainfall time-series (-) together with the uncertainty band (± one standard deviation in grey shading). The trend comprising the inter-annual cycles and drift is also shown (---).The x-ordinate is the year, and the y-ordinate is the monthly rainfall (mm).

It can be seen from Figures 7.2, 7.3 and 7.4, that the model efficiency is good (i.e., the modelled time-series (solid line) closely matches the observed time-series (dotted line), but also that the uncertainty (shaded area) is high relative to the dominant cyclicity. This is not surprising given that the dominant seasonal cyclicity (i.e., 12 months) is not that pronounced (relative to the other within-year cycles) within the spectral plots (Figure 7.1). The lack of a strong seasonal cycle within the rainfall (which would propagate to the rainfall and P-Q data-series) is consistent with the Baru Experimental Catchment being located only 5 degrees north of the Equator. Equatorial regions are know to exhibit little seasonality in their rainfall totals (Pettersen, 1958). Indeed, examination of the observed or modelled rainfall time-series in Figure 7.2 shows that it is very difficult to identify which troughs or peaks are leading to the 12-month seasonal cycle. The tendency for relatively small rainfall totals in April (Figure 7.2, Chappell *et al.*, 2001) is probably the main determinant.

The estimated trend component (i.e., the broken line in Figures 7.2, 7.3 and 7.4) was then split into a very slowly changing drift and the inter-annual cyclic component by selecting a much smaller *NVR* of 1×10^{-5} (Young, 1998; Young *et al.,* 1999). The resultant inter-annual cycle, together with the model uncertainty in the rainfall, riverflow and P-Q is shown in Figure 7.5. Relative to the uncertainty bands, the riverflow time-series (Figure 7.5b) shows a very clear peak in 1989 and at the end of 1995. These peaks coincide with the so-called 'La Nina' peak on the ENSO cycle observed in Insular South East Asia (Wolter and Timlin, 1998). The ENSO cycles are not as clear in the rainfall (Figure 7.5a) and P-Q data (Figure 7.5c), partly as a result of the shortness of the data-series giving large uncertainties over the initial few months of the simulation.

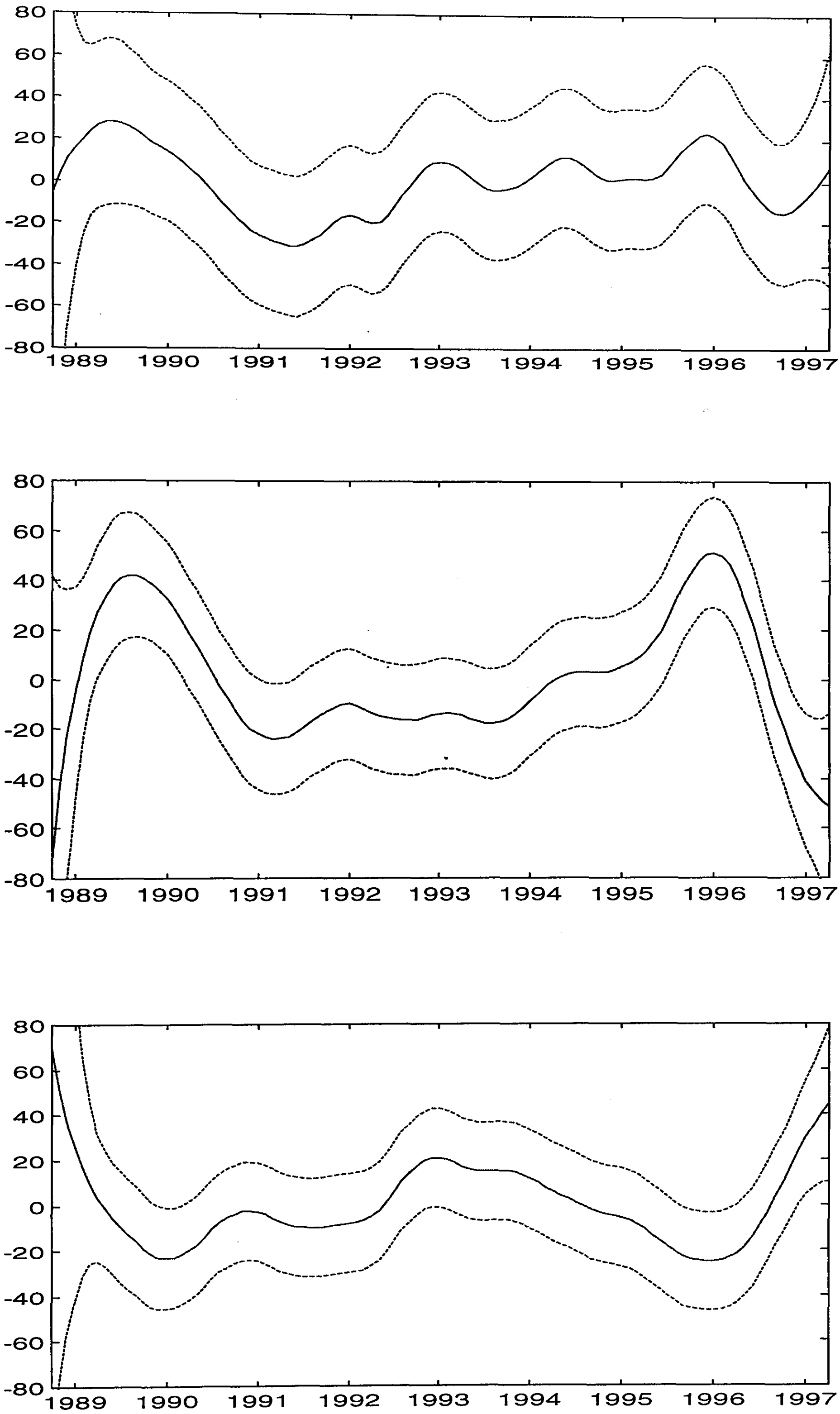


Figure 7.5. Inter-annual cyclicity observable within the time-series of (a) rainfall, (b) riverflow and (c) P-Q when the trend is modelled with a low *NVR* of 1×10^{-5}. The uncertainty (± one standard deviation) is shown with a broken line.The x-ordinate is in years, and the y-ordinate is the monthly totals normalised by the mean (mm).

The increase in the P-Q from 1996 to 1997 (figure 7.5c) probably results from the differences in the observed flows during the water-year 1995/6, which probably results from the approximation of the calibration of the river-levels to riverflows noted earlier.

The drift component of the rainfall, riverflow and P-Q, that was separated from the trend, is presented in Figure 7.6, 7.7 and 7.8, respectively.

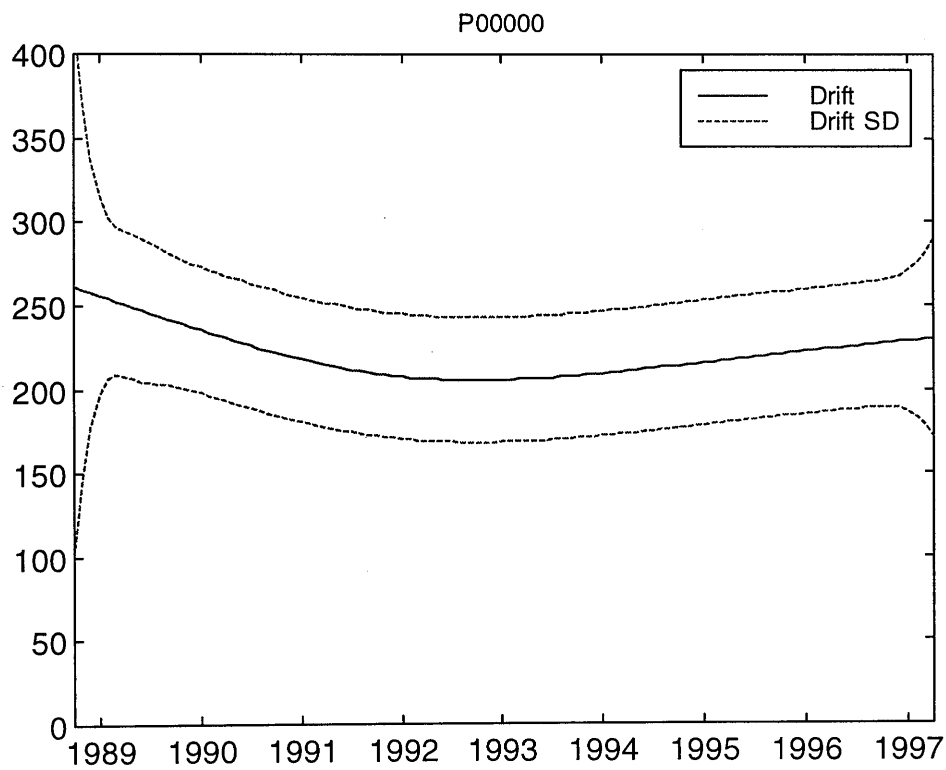


Figure 7.6. Longer-term drift in the DHR model of the Baru catchment rainfall time-series when the trend is modelled with a low *NVR* of $1x10^{-5}$. The uncertainty (± one standard deviation) is shown with a broken line. The x-ordinate is in years, and the y-ordinate is the monthly totals (mm).

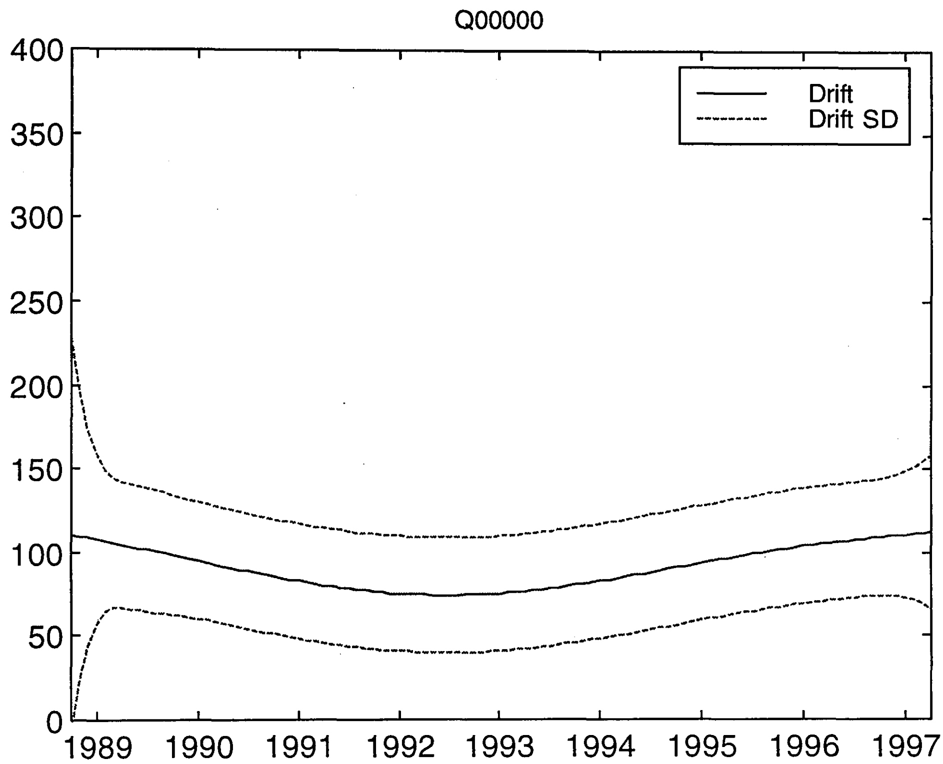


Figure 7.7. Longer-term drift in the DHR model of the Baru catchment riverflow time-series when the trend is modelled with a low *NVR* of 1×10^{-5}. The uncertainty (± one standard deviation) is shown with a broken line. The x-ordinate is in years, and the y-ordinate is the monthly totals (mm).

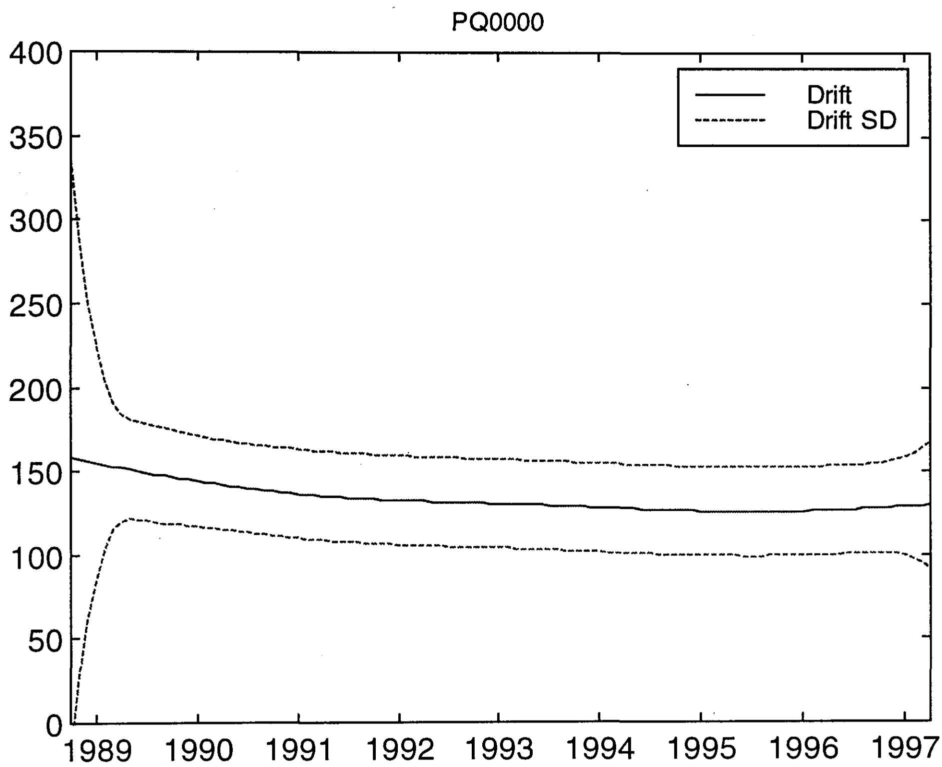


Figure 7.8. Longer-term drift in the DHR model of the Baru catchment P-Q time-series when the trend is modelled with a low *NVR* of $1x10^{-5}$. The uncertainty (± one standard deviation) is shown with a broken line. The x-ordinate is in years, and the y-ordinate is the monthly totals (mm).

Taking into account the uncertainties in the data and the modelling, it is clear that no marked drift is apparent within the rainfall, riverflow and P-Q time-series. This is partly because of the short period of data available for the modelling (i.e., 8-years), which means that it is difficult to set an appropriate *NVR* to separate out meaningful inter-annual cycles. Thus it is possible, that some of the drift may have been 'removed' to form part of the inter-annual cycle. It is clearly important to continue the water-balance measurements to allow a stronger basis for the separation of the drift and inter-annual components. Clearly, more reliable modelling and hence more robust conclusions might be able to me made, if future research could undertake a more detailed quality assurance of the water-balance data.

If the lack of a consistent drift in the P-Q is, however, real then it might indicate that changes in the evapotranspirational losses does not change significantly with only 8-years of forest recovery from the first episode of selective logging. Such a conclusion would be consistent with the results of the only other study undertaken over several years following the first episode of selective tropical logging. The authors of this study (Abdul Rahim Nik and Zulkifli, 1994) concluded that many years of forest regrowth following the harvesting year was required to significantly alter the forest structure and hence evapotranspiration.

While it remains unclear as to whether the monthly water-balance has been affected by a possible terrain and/or vegetation recovery following selective harvesting, there remains the possibility that the riverflow hydrograph shows signs of change with such recovery.

7.5. Catchment responsiveness

To understand the temporal dynamics of river hydrograph in relation to (i) natural climatic variations and (ii) terrain/vegetation recovery from selective logging, the riverflow record was separated into 'stormflow' (Q_{SF}) and 'baseflow' (Q_{BF}) components. The inclined line method of Hewlett and Hibbert (1967) within a spreadsheet-based solution (Bidin and Greer, 1997) was used. Flashy catchments have a high stormflow proportion (*e.g.*, $Q_{SF}/Q\% = 50\ \%$) or a low baseflow proportion, while damped river responses are characterised with small stormflow proportion (*e.g.*, $Q_{SF}/Q\% = 5\ \%$) or a high baseflow proportion. Hydrograph separation is used as it provides an objective way of comparing the 'flashiness' of different catchments or different time periods using a single number. Within this study, no physical interpretation of the pathways giving rise to the area under the hydrograph described as 'stormflow' is implied.

The construction and use of 'skidder trails' within rainforests (*i.e.*, the tracks used to drag timber towards the haulage lorries) may increase the proportion of water that reaches the rivers by the infiltration-excess overland flow pathway. The flashy nature of this pathway may then increase the flashiness of the rivers. Douglas *et al.* (1995) have shown that in the years following rainforest logging, the growth of grasses on skidder trails leads to a reduction in the proportion of rainfall that generates infiltration-excess overland flows locally on these tracks. If indeed the local impacts of track construction and use can be seen within the riverflow records, then these impacts may reduce in the years following the activity. To assess this question, two pairs of years '1990 plus 1992' and '1995 plus 1997/8' were selected for study, as they were one plus three years and six plus eight years, respectively, post track construction. Pairs of years were chosen to account for the differences in the climate. The years 1992 and 1997/8 relate to El Niño

Southern Oscillation (ENSO) drought years (Chappell *et al.*, 2001), while 1990 and 1995 were 'wet years' (Table 7.1).

Table 7.3: Comparison of some water balance components representing 'wet' water years of 1990 (just after logging period) and 1995 showing the relative increased baseflow runoff (Q_{BF}) as the forest regenerated. The 1992 and 1997/98 ENSO drought years components are also shown, but cannot be directly compared because of the difference in annual rainfall. Significant differences in the mean values were identified using the non-parametric, Mann-Whitney U-test based.

	1990 wet year		1992 dry year		1995 wet year		1997/8 dry year	
	(mm)	%P	(mm)	%P	(mm)	%P	(mm)	%P
Rainfall (P)	2534.8		2222.3		2709.1		1562.8	
Stream runoff (Q)	901.0	35.5	542.3	24.4	1458.5	55.1	259.6	16.6
Stormflow (Q_{SF})	539.2	21.3	270.9	12.2	469.3	17.3	108.9	7.0
Baseflow (Q_{BF})	361.8	14.3	271.4	12.2	989.2	36.5	150.7	9.6
Q_{SF}/Q%	59.8		50.0		31.5		41.9	
Q_{BF}/Q%	40.2		50.0		68.5		58.1	
σ^2 monthly P	19577.2		9983.0		7473.0		5242.9	
CV% in P	5.5		4.5		3.2		4.6	
σ^2 monthly Q	7538.5		1523.9		6143.7		437.3	
σ^2 monthly Q_{SF}	2738.7		523.6		1292.5		133.4	
σ^2 monthly Q_{BF}	1449.9		293.5		2507.3		268.3	
[1] Diff. in mean 1990 vs 1995 P					Ns			
[2] Diff. in mean 1990 vs 1995 Q					P < 0.1			
[3] Diff. in mean 1990 vs 1995 Q_{SF}					Ns			
[4] Diff. in mean 1990 vs 1995 Q_{BF}					P < 0.01			
[1] Diff. in mean 1992 vs 1997/8 P							P < 0.1	
[2] Diff. in mean 1992 vs 1997/8 Q							P < 0.1	
[3] Diff. in mean 1992 vs 1997/8 Q_{SF}							P < 0.1	
[4] Diff. in mean 1992 vs 1997/8 Q_{BF}							P < 0.05	

Notes:

[1] Level of significance of difference between rainfall (P) monthly means
[2] Level of significance of difference between total stream runoff (Q) monthly means
[3] Level of significance of difference between stormflow runoff (Q_{SF}) monthly means
[4] Level of significance of difference between baseflow runoff (Q_{BF}) monthly means
[ns] Not significant at P < 0.1

The results of the hydrograph separation analysis (Table 7.3) show that the baseflow component of the hydrograph increases over time from one wet-year to later wet-year (1990 to 1995), and from a dry-year to a latter dry-year (1992 to 1997/8). These changes were seen to be statistically significant when tested with a Mann-Whitney U-test (Table 7.3). This change may be physically important, given that the Baru has a flashy regime ($Q_{BF}/Q\%$ = 40-68 %), similar or larger than that of some other small catchments in the tropics (Table 7.4).

Table 7.4: Comparison of stormflow and baseflow proportions of some small tropical rainforest catchments.

Tropical location	Catchment area (ha)	Q_{SF} /Q%	Q_{BF} /Q%	Source
Baru 1990 (Malaysia)	44	60	40	This study
Baru 1992 "	44	50	50	"
Baru 1995 "	44	31	69	"
Baru 1997/8 "	44	42	58	"
W8S5 1991/2 "	170	51	49	Bidin & Greer (1997)
Queensland (Australia)	26	47	53	Bonell & Gilmour (1978)
Dominica (W. Indies)	122	10-20	80-90	Walsh (1980)
Amazon (S America)	130	9	91	Leopoldo *et al.* (1995)

These limited analyses (only four years) may suggest that the flashiness of the catchment is reducing slightly, perhaps a result of reducing infiltration-excess flow components concomitant with the re-vegetation of the skidder trails and haulage roads. As with the preliminary water-balance analyses, the results are tentative and await a more robust QAA of the riverflow data.

7.6. Conclusions

The hydrograph separation analysis clearly shows that the Baru Experimental Catchment has a very flashy rainfall-runoff regime (*i.e.*, stormflow percent ranges from 32 % to 60 %), in part as a result of the short-duration of the storm-events (Chapter 5). Moreover, it shows that the index may be changing over the period of forest regeneration, and that the changes may as much associated with the stage of regeneration as the inter-annual changes in the climate.

In some contrast, though the conclusions are tentative awaiting more robust QAA of the riverflow data in particular, P-Q data does not appear to show a systematic change with years following the harvesting activities. This result is, however, consistent with the results of the only other study undertaken over several years following the first episode of selective tropical logging (Abdul Rahim Nik and Zulkifli, 1994). The experimental catchment used by Abdul Rahim Nik and Yusop (1994) was inundated following reservoir construction shortly after their study. It is, therefore, very important that the rainfall and riverflow monitoring within the Baru Experimental Catchment continue for many more years to see if changes in the vegetation eventually have a significant impact on the evapotranspiration. Clearly, it would be helpful to re-establish the wet-canopy evaporation studies within the same catchment (Chapter 6) at a latter date, and to establish long-term transpiration studies, as this may allow future P-Q to be interpreted. Without doubt, long-term water balance studies are urgently required in managed forests, both natural forests and plantations, elsewhere within the tropics.

Lastly, the reliability of both the hydrograph separation and water-balance analyses relies on the use high quality data-series. There is therefore the need for further research explicitly addressing the QAA of the existing Baru riverflow data, but also the rainfall data in light of the conclusions of Chapter 4.

Chapter 8

Conclusions and recommendations

The success of the study in meeting the aims identified in Chapter 1 are first addressed. The recommendations for further study are then identified.

8.1. First aim

The first aim of the study asked How is gross rainfall spatially distributed across a small equatorial catchment, do the patterns change with time, and what are the possible causes?

Before addressing this aim specifically, it was important to examine the constituent aim 'what are the errors associated with the rainfall measurement?'

The spatial variability in gross rainfall and net rainfall within this study was monitored using a dense network of simple storage raingauges that utilised two inexpensive plastic bottles. Analysis presented in Chapter 3 showed that this design did not give large catch errors when tested for evaporation losses (*i.e.*, only -0.54 % error per month), inner-surface wetting errors (*i.e.*, only -0.198 % error with weekly sampling) or volumetric recording (*i.e.*, ± 0.025 % error with sampling). Catch differences between these gauges and standard raingauges (*e.g.*, UK Meteorological Office Mark II gauge) were similarly small, at -0.110 % additional error, over a month's sampling. While more extensive testing needs to be undertaken with this simple raingauge design, the evidence so far suggests that weekly or storm-based catches from these gauges do not have significantly larger errors than the < 5 % error expected of commercially-built storage raingauges. As a result we felt justified in their use for the rainfall and wet-canopy evaporation studies.

The rainfall study was undertaken within a region experiencing summer and winter monsoons (Southwest and Northeast monsoons, respectively) delivering similar rainfall totals, as seen at other equatorial regions (Shaw, 1988). The 4 km^2 study catchment was within the interior of Borneo, in an area of undulating topography, and that received most of its rainfall in the mid afternoon (*i.e.*, typical of a climatic system dominated by local convective storms). These conditions seem to have given rise to very large spatial variability or 'localisation' in rainfall. This variability was seen within the simple range of rainfall catches and in the large loss of inter-gauge correlation (C_r) with distance. This variability was even high when compared against other areas with convective activity. For example, the distance at which the C_r falls to 0.9 was only 1.155 km within the Sapat Kalisun Catchment, against 4.95 km within Central Illinois (Sharon, 1972) and 3.00 km in the Ruvu Basin, Tanzania (Jackson, 1994). This rainfall localisation was particularly apparent during the Southwest monsoon, perhaps where more of the rainfall is delivered in local convective systems, rather than the meso-scale 'stratiform' systems that the region also experiences (Chapter 5).

Strong correlations were seen between each season's rainfall and both the altitude and bearing, though the physical explanation required at least a conceptual understanding of the local wind fields within region incorporating the Sapat Kalisun Catchment. This means that a raingauge spacing of even one gauge per 1.155 km (*i.e.*, where $C_r = 0.9$) may not capture the important topographic controls, that change dramatically from the Southwest to the Northeast monsoon, on rainfall totals.

8.2. Second aim

The second aim of the study asked What are the characteristics of the rainstorms within a small equatorial catchment within the interior of Borneo Island, and do these change with season?

The inland location of equatorial Borneo that was under investigation appeared to receive most of its rainfall in low intensity (*i.e.*, < 10 mm hr^{-1} equivalent, sampled at 5-minute interval) events. Even the two extreme events sampled during the 3-year analysis period, only maintained 50 mm hr^{-1} intensities (from 5-minute sampled data) for 25 minutes. Such a rainfall regime is clearly very different that that seen within regions experiencing tropical cyclones (*i.e.*, Philippines - East Asia - South Asia, S.W. Pacific - N.E. Australia, Central America - Caribbean, see Bonell and Balek, 1993). Given that near-surface permeabilities have a geometric mean of about 500 mm hr^{-1} over most of the Sapat Kalisun Catchment and surrounding region (Chappell *et al.*, 1998a), large quantities of infiltration-excess overland flow are not expected, with most rainfall entering the soil as Chappell *et al.* (1999) concluded.

Storm durations (where storms are separated by > 20 minutes without 0.2 mm of rainfall) were typically short, particularly during the 1997/8 Northeast monsoon, where 78 % of all rainfall was delivered within events of less than 15 minutes duration. Such as situation would be consistent with that where most rainfall is delivered in localised (see Chapter 4) mid-afternoon events that have developed through the morning. The typical short duration of the events may explain the flashiness of the river hydrographs monitored within the Baru catchment tributary of the Sapat Kalisun (Bidin, 1995; Chappell *et al.*, 1999).

The localised nature of the rain-events within the Sapat Kalisun Catchment (Chapter 4) was seen in the temporal pattern of the rainfall incidence. Raingauges that were less than 1 km apart tended to experience rainfall on the same days. As gauge spacing increased to 2 - 4 km apart, then rainfall was not received on the same days for some 15-30 days in the year. Loss of inter-gauge correlation was most strongly seen during the mid-afternoon convective events, where temporal inter-gauge correlation fell off in minutes even for gauges a few hundred metres apart. In contrast, stratiform events loose their temporal inter-gauge correlation perhaps by a factor 5 more slowly. The short duration and localised nature of the convective events within the Sapat Kalisun Catchment, therefore, demand not only a dense raingauge network, but also a high temporal sampling intensity. Indeed, Chappell *et al.* (1999) found that they needed a 5-minute sampling intensity to model the rainfall-runoff characteristics within a tributary of the Sapat Kalisun.

8.3. Third aim

The third aim of the study asked Do the different patches of vegetation seen within a region recovering from the first episode of selective forestry have different rates of net rainfall (*i.e.*, sub-canopy rainfall) and wet-canopy evaporation?

Before addressing this aim specifically, it was important to examine the constituent aim 'can the complex patchwork of selectively-managed forest be classified to allow representative plots to be established for wet-canopy evaporation studies?'

The 44 hectare area of selectively-managed forest that comprises the Baru Experimental Catchment was first qualitatively classified into the six categories of: (1) undisturbed forest canopy, (2) moderately impacted forest canopy, (3) vine-covered forest canopy, (4) *Macaranga* forest canopy, (5) sprawler-covered canopy gap, and (6) canopy gap. Statistical analysis then indicated that these categories, easily distinguishable from visual characteristics of their respective canopies, could be objectively identified using biophysical data.

The remnants of undisturbed forest canopy (canopy 1), which occupy 18 ± 3 % of the catchment, could be separated on the basis of their much higher tree basal area (*i.e.*, >> 30 m^2 ha^{-1}) and estimated biomass (*i.e.*, >> 300 t ha^{-1}). The density of vines could perhaps have been used to separate 'moderately impacted forest canopy' (canopy category 2) from the 'vine-covered forest canopy' (canopy category 3). Within the areas categorised as 'vine-covered forest canopy' the basal area of vines was >> 1.0 m^2 ha^{-1}. The patches of forest dominated by *Macaranga* spp. (*i.e.*, 79 % of all tree genera), that occupy 10 ± 4 % of the catchment, had a characteristically low canopy complexity (*i.e.*, Shannon diversity index of << 2.0) and tree density (*i.e.*, << 300 t ha^{-1}). After some eight years following the first (and only) harvesting activity, 17 ± 4 % of the catchment remained without pioneer or climax trees (larger than saplings). As a result, these areas (canopy category 5 and 6) were easily distinguishable from the categories 1, 2, 3, and 4.

Given that the visual differences in the six canopy categories defined are supported by measurable differences in the biophysical properties, each canopy was expected to intercept, store and release different quantities rainfall, and thereby result in different rates of wet-canopy evaporation (Chapter 6).

The 1997/8 water-year studied, turned out to be a severe ENSO drought. During this period, the remnants of undisturbed lowland dipterocarp forest studied allowed 93.1 ± 7.5 % of the rainfall through the canopy to the ground, giving a wet-canopy evaporation rate of approximately 7 % of gross rainfall. This figure was towards the lower end of the range of wet-canopy evaporation rates observed for undisturbed tropical forests. The low rate may relate to the expected lack of 'storminess' during the 1997/8 drought (Chapter 5).

Selective harvesting of the forest generated patches of moderately-impacted forest (canopy category 2) and more heavily damaged areas, now with the remnant climax trees covered by vines (canopy category 3). Much smaller volumes of sub-canopy rainfall were observed below these forest patches (*i.e.*, 82.3 ± 3.1 % and 82.6 ± 4.4 % respectively). This result could be explained by (1) these (on average) lower forest canopies receiving less incoming rainfall due to sheltering by the undisturbed remnants, or (2) the changed canopy surface characteristics. The surface of the disturbed canopies often has a greater surface density of leaves, which may have a disproportionate effect on rates of wet-canopy evaporation. Further, the more uneven surface of the disturbed canopy patches may increase atmospheric turbulence and thus increase the rate of evaporation. These two phenomena may also account for the unexpectedly high estimates of wet-canopy evaporation from the areas of sprawlers and shrubs (canopy category 5).

Taking into account the area covered by the six canopy categories (Chapter 2), the catchment-wide estimate for wet-canopy evaporation from the selectively-managed forest (following eight years of recovery) was 13.6 % of the gross rainfall. This figure was almost identical to the 14.0 % wet-canopy evaporation rate calculated from the two transects of mixed canopy types. The study, therefore, suggests that the rate of wet-canopy evaporation may significantly increase as a result of selective logging.

8.4. Fourth aim

The fourth aim of the study asked Does the natural recovery of the forest and terrain since selective harvesting have a significant impact on the water yield, when set against the impacts of natural climatic fluctuations?

The hydrograph separation analysis showed that the Baru Experimental Catchment has a very flashy rainfall-runoff regime (*i.e.*, stormflow percent ranges from 32 % to 60 %), in part as a result of the short-duration of the storm-events (Chapter 5). Moreover, it showed that the index may be changing over the period of forest regeneration, and that the changes may as much associated with the stage of regeneration as the inter-annual changes in the climate.

In some contrast, though the conclusions are tentative awaiting more robust QAA of the riverflow data in particular, P-Q data does not appear to show a systematic change with years following the harvesting activities. This result is, however, consistent with the results of the only other study undertaken over several years following the first episode of selective tropical logging (Abdul Rahim Nik and Zulkifli, 1994). The experimental catchment used by Abdul Rahim Nik and Yusop (1994) was inundated following reservoir construction shortly after their study. It is, therefore, very important that the rainfall and riverflow monitoring within the Baru Experimental Catchment continue for many more years to see if changes in the vegetation eventually have a significant impact on the evapotranspiration. Clearly, it would be helpful to re-establish the wet-canopy evaporation studies within the same catchment (see Chapter 6) at a latter date, and to establish long-term transpiration studies, as this may allow future P-Q to be interpreted. Without doubt, long-term water balance studies are urgently required in managed forests, both natural forests and plantations, elsewhere within the tropics.

Lastly, the reliability of both the hydrograph separation and water-balance analyses relies on the use high quality data-series. There is therefore the need for further research explicitly addressing the QAA of the existing Baru riverflow data, but also the rainfall data in light of the conclusions of Chapter 4.

8.5. Recommendations for further research

A series of 6 recommendations for further avenues of ecohydrological research have arisen out of this study.

(1) More extensive testing of the errors of raingauges used to measure gross and net rainfall is required. This is particularly important for wet-canopy evaporation studies where rates are derived by dividing a small value (*i.e.*, gross rainfall minus net rainfall) by a large value (*i.e.*, gross rainfall) where the net rainfall is highly variable. These errors should always be propagated to give uncertainties in the final wet-canopy evaporation estimates.

(2) The analysis of the spatial variability in the rainfall within the 4 km^2 Sapat Kalisun Experimental Catchment should be taken further. Further geostatistical analysis, leading to a kriged rainfall map, is currently being undertaken, as this may help explain the patterns of rainfall. This is, however, not trivial given the significant role of the topography in generating 'deterministic drift' within the variogram (Chappell *et al.*, 2001), which must be removed (*i.e.*, modelled) before the true stochastic nature of the variogram can be accurate characterised. The application of a numerical model of the wind fields (*e.g.*, Theilen, 1994) in the 10-30 km^2

region about the Sapat Kalisun Catchment, would aid in this analysis, and would test the conceptual wind fields postulated in chapter 4. Assurance in the modelling of wind fields would really need measurements of the vertical profile of the atmosphere about the Danum Valley area.

(3) The intensively sampled rainfall data for the Sapat Kalisun Experiment Catchment could be used as the basis for the establishment of a model that predicts the temporal sequence of rainfall incidence. Such a model, known as a 'weather generator' (Coe and Stern, 1982), would be very helpful in generating realistic future rainfall series. Such synthetic data may be used to forecast future rainfall-runoff scenarios given changes to catchment properties.

(4) Understanding how much of the rainfall seen at the inland locality of the Sapat Kalisun Catchment is derived from local forest evaporation, and how much from the greater northern Borneo region (perhaps from the Western Pacific during the Northeast monsoon) may give greater understanding of spatio-temporal dynamics of the local rainfall phenomena and the role of local evaporation in these processes. Chemical signatures may be able to be used to attempt this separation process (Douglas, pers. comm. 1990).

(5) This study has focused on the spatial variations in wet-canopy evaporation within a selectively-logged forest. It would be very helpful to establish a parallel study that sought to establish differences in the transpiration rates between the various canopy types observed within selectively-logged terrain. Such work might begin with small-scale measurements screening of individual tree species using porometers and sapflow gauges.

(6) The selectively-logged catchment study of Abdul Rahim Nik and Yusop (1994), showed that the initial forestry activity lead to a reduction the P-Q in the harvesting year, that was sustained for further 6 years. This catchment was however inundated following reservoir construction shortly after their study. It is, therefore, very important that the rainfall and riverflow monitoring within the Baru Experimental Catchment continue for many more years to see if regrowth of the climax vegetation eventually increases the evapotranspiration losses. Clearly, it would be helpful to re-establish the wet-canopy evaporation studies within the same catchment (Chapter 6) at a latter date (and to establish long-term transpiration studies, noted earlier), as this may allow future P-Q to be interpreted. Without doubt, long-term water balance studies are urgently required in other managed forests (both natural and plantations) elsewhere within the tropics.

It is hoped that this work makes a contribution to the fundamental physical behaviour of rainfall and wet-canopy evaporation within a lowland rainforest, and to the debate surrounding the impact of selective forestry on the hydroclimatic system.

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