EFFECTS OF SELECTIVE LOGGING METHODS ON WATER YIELD AND STREAMFLOW PARAMETERS IN PENINSULAR MALAYSIA

Abdul Rahim Nik

Forest Research Institute Malaysia, Kepong, 52109 Kuala Lumpur, Malaysia

Don Harding

University of North Wales, Bangor, Gwynedd LL57 2UW, United Kingdom

Received February 1992

ABDUL RAHIM NIK & HARDING, DON. 1992. Effects of selective logging methods on water yield and streamflow parameters in Peninsular Malaysia. An experimental forest watershed, consisting of three small catchments at Berembun Forest Reserve, Negri Sembilan in Peninsular Malaysia was monitored from 1979 to 1987. Adequate instruments were installed for continuous collection of hydrologic and climatic data. The calibration and post-treatment phases lasted for three and four years respectively. Two types of treatments were imposed, namely, commercial selective logging and supervised selective logging in Catchment 1 and Catchment 3 respectively, while Catchment 2 remained as a control. Pertinent logging guidelines were prescribed and assessed in Catchment 3 in terms of hydrologic responses. Significant water yield increases were observed after forest treatment in both catchments amounting to 165 *mm* (70%) and 87 *mm* (37%) respectively in the first year; increases persistently till the fourth year. Magnitude and rate of water yield increase primarily depended on the amount of forest removed and the prevailing rainfall regime and the increase was largely associated with baseflow augmentation. Conservation measures introduced in this study - the use of buffer strips, cross drains, an appropriate percentage for the forest road network - were found to be effective and beneficial in ameliorating the hydrological impacts.

Key words: Selective logging - forest catchments - calibration - water yield - paired-catchment - conservation measures

ABDUL RAHIM NIK & HARDING, DON. 1992. Kesan kaedah tebangan memilih ke atas parameter-parameter hasil air dan aliran sungai di Semenanjung Malaysia. Kajian tadahan hutan yang mengandungi tiga tadahan kecil di Hutan Simpan Berembun, Negri Sembilan, Semenanjung Malaysia telah dimonitor mulai 1979 hingga 1987. Peralatan yang sesuai telah dipasang bagi pengutipan data hidrologi dan iklim. Tempoh fasa kalibrasi dan pasca-rawatan adalah tiga dan empat tahun, masing-masing. Dua kaedah rawatan telah dilaksanakan, iaitu 'pembalakan memilih perdagangan' bagi Tadahan 1 dan 'pembalakan memilih terselia' bagi Tadahan 3 manakala Tadahan 2 dijadikan tadahan kawalan. Panduan pembalakan yang sesuai telah dikenakan serta dinilai dari segi tindakbalas hidrologi bagi tadahan 3. Hasil air menunjukkan pertambahan yang bererti selepas rawatan untuk tahun pertama bagi kedua-dua tadahan masing-masing berjumlah 165 *mm* (70%) dan 87 *mm* (37%); pertambahan ini berterusan sehingga tahun keempat selepas rawatan. Magnitud dan kadar pertambahan hasil air sangat bergantung kepada jumlah hutan yang dibalak dan regim hujan yang diterima. Walau bagaimanapun, pertambahan ini lebih berkait rapat dengan pertambahan aliran dasar. Langkah-langkah pemuliharaan seperti mengekal jaluran tampan, pemasangan parit lintang dan mengekalkan jalan hutan pada peratusan yang bersesuaian didapati berkesan dan bermanfaat bagi mengurangkan impak hidrologi.

Introduction

There has been an upsurge of interest in the effects of tropical forest disturbance on catchment hydrology. This is partly because of the alarming rate of tropical forest exploitation and conversion to other land uses in the last two decades (FAO 1986). Estimates of the areal extent of forest cover in the humid tropics and the rate at which these forests are disappearing vary considerably between workers (FAO & UNEP 1982, Myers 1984, Lanly 1989). At whatever rates quoted, the exploitation and disappearance of tropical rain forests may cause a major problem to the environment at large including the hydrological functions.

Realising the potential problems of watershed degradation and subsequent hydrological impacts, the recent UNESCO International Colloquium on the Development of Hydrologic and Water Management Strategies in the Humid Tropics has expressed its strong concern regarding the hydrological impacts of the rapid rate of natural resource exploitation in countries of this region (UNESCO 1989):

> "...the humid tropics play a pivotal role in the maintenance of the global hydrological cycle which to a great extent determines the capacity of the world to continue to support the agriculture, industry and infrastructure required to enable all countries to meet the expectations of their people..."

Up to now, there have been several state-of-the-knowledge reviews on the effects of forest cover removal and forest logging in the humid tropics on water attributes (Hamilton & King 1983, Oyebande 1988, Bruijzeel 1990), although there is little quantification of processes. Similarly, a number of tropical paired-catchment studies have been initiated during the last decade, for example, in French Guyana (Roche 1981), Indonesia (Bruijnzeel 1986), Malaysia (Abdul Rahim 1987) and Thailand (S. Suksawang in preparation). Some of these experiments are still in progress.

Studies in tropical countries on conversion and removal of forest cover to other land uses in Australia (Gilmour 1977), Tanzania (Edwards 1979), Kenya (Blackie 1972), French Guyana (Fritsch 1983) and Taiwan (Hsia & Koh 1983) characteristically revealed increases in water yield. In Tanzania, East Africa, the Mbeya catchment study, which commenced in 1958, produced an average increase of 220 *mm* y^{-1} after the conversion of evergreen montane forest to agricultural land use. Most of the increase occurred during the dry season while overland flow contributed very little due to a remarkably high infiltration capacity of its volcanic soil. In another study conducted in a high rainfall region of Zambia (c. 1400 *mm*), Mumeka (1986) reported increases in water yield following the clearance of *Brachystegia* woodland to agricultural land use. The average annual increase ranged from 194 to 230 *mm* or 56 and 74% for the two treated catchments respectively. Clear cutting of mixed evergreen hill forest in Taiwan saw a greater increase of 448 *mm* y^{-1}. In this study, the surface disturbance was kept to a minimum as skyline logging was employed; roads were constructed around the basin periphery, away from the stream (Hsia & Koh 1983).

Logging of a lowland rain forest in Babinda, Queensland, with high mean annual rainfall (c. 4035 *mm*), produced little detectable change, but a clearing operation produced a 7.0% and 13.4 % or 264 and 323 *mm* increase in yield in the first and second year following clearing respectively (Gilmour 1977). It was also observed that soil moisture levels remained higher because of reduced transpirational demand; soil moisture deficits were therefore critically reduced. Clearcutting of a primary lowland rain forest in French Guyana, with fairly high prevailing rainfall, resulted in an increase of 408 *mm* or about 26% in the first year (Fritsch 1983). However, the size of the catchment used, about 1 *ha*, was quite small for a detailed evaluation of water yield changes in a paired watershed study.

The highest increase in yield ever reported resulting from rain forest clearance was observed at Sg. Tekam, Malaysia (DID 1986, Abdul Rahim 1988). After the dipterocarp forest was completely cleared and converted to oil palm plantations, the water yield increase was 822 $mm\ y^{-1}$ but the average annual increase over a four-year period only amounted to 314 *mm*. In this regard, it is worth noting that the area received on average some 1730 *mm* of rain per year, about 200 *mm* below the country average. In fact, this area is located in a relatively low rainfall region according to the classification of hydrological regions in Malaysia (Law & Ahmad 1989).

It has been well documented that following clearance of forest cover and conversion to other types of land use, there is an initial increase in total streamflow both in temperate areas (Bosch & Hewlett 1982, Hewlett 1982) and in the tropics (Bruijnzeel 1986, Abdul Rahim 1988, 1989). This increase may be permanent when converting tall forest to grassland or shallow rooted agricultural crops, or temporary in the case of conversion to tree plantations (Bruijnzeel 1989).

While most studies cited above reported on the effects of forest conversion on hydrological parameters, little quantitative data are available documenting the effect of partial forest removal or the selective logging approach which generally forms the basis for sustainable forest management particularly in the humid tropics. Therefore, this paper aims to quantify the effects of two types of selective logging methods on hydrological parameters based on a seven-year period of monitoring in Peninsular Malaysia and with reference to other hydrological studies in Malaysia.

Description of study area

The study site, located in the Berembun Forest Reserve, Negri Sembilan, Malaysia, consists of three small catchments, Catchment 1 (C1), Catchment 2 (C2) and Catchment 3 (C3) occupying areas of 13.3, 4.6, and 30.8 *ha* respectively (Figure 1). The catchments situated adjacent to each other are in the headwater of Sg. Kelinchi, a tributary of Sg. Muar, Negeri Sembilan and also known as the Berembun Watershed. It is situated at about 2° 46' N Latitude and 102° 06' E Longitude with elevation ranging from 170 to 302 *m* a.s.l. The entire basin has a southern aspect and slope angles range from 4 to 61%, with an average of 37%. The soils are deep and moderately developed, varying from coarse sandy clay to sandy clay loam belonging to the Berembun Series (Adzmi & Ghazali 1988). Geologically, this area is underlain by a single granitic body known as Senaling Granite believed to be middle to upper Triassic (Bignell & Shelling 1972). The detailed descriptions of morphometric properties of the three catchments are given in Table 1.

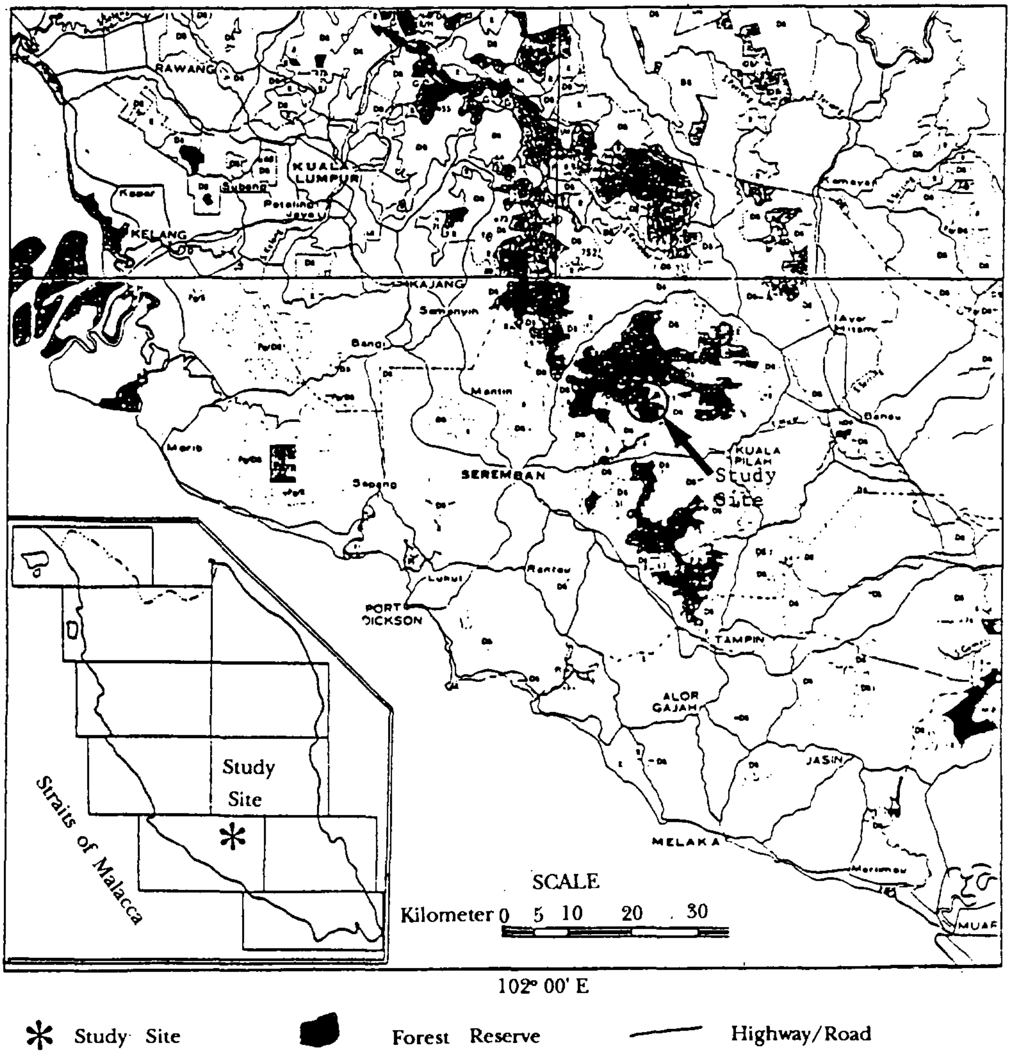

Figure 1. Location of Berembun experimental watershed (BEW) in Peninsular Malaysia

Forest cover

The forest of this area is of the 'red-meranti-keruing' type (Wyatt-Smith 1963, 1987). The forest is rich in commercially important timber species such as *Shorea leprosula*, *S. acuminata*, *S. laevis*, *Koompassia malaccensis* and *Intsia palembanica*. The mean basal area of all trees for the entire watershed is 26.9 m^2 ha^{-1} which indicates that the forest is quite well-stocked.

Table 1. Summary of morphometric properties of the three catchments

	C1	C2	C3
A. Linear aspects			
Length of main stream (*m*)	648	248	1000
Stream order	2	1	2
Aspect	S	S	S
B. Areal aspects			
Area (*ha*)	13.3	4.6	30.8
Drainage density ($km\ km^{-2}$)	6.17	5.37	4.68
Form factor	0.34	0.33	0.37
Elongation ratio	0.66	0.65	0.69
Circularity ratio	0.69	0.71	0.68
Lemniscate	0.73	0.76	0.66
C. Relief aspects			
Elevation (*m* a.s.l.)			
Max	289	272	302
Min	171	175	171
Mean slope (%)	42	47	34
Relief (*m*)	101	114	131

Climatic description

The general climatic condition of BEW has been described by Abdul Rahim (1990) based on seven years of records taken from the climate station located near the Watershed (Table 2; Figure 2). The annual rainfall ranges from 1442 to 2611 *mm*, with a mean of 2126 *mm*. The monthly rainfall distribution exhibits a two-maxima pattern which normally coincides with the northeast monsoon and the transitional period (Figure 3); the two maxima occur in the months of November and April. The bulk of rain mostly falls during the afternoon and late evening, this being characteristic of the convectional type of rainfall. The air temperature shows little variation throughout the year, with a monthly mean of 26.5°*C* and small annual temperature range (about 1.6°*C*), while relative humidity seldom drops below 75%. Expectedly, evaporation normally assumes a conservative figure and shows minimal monthly variations over the years; mean daily evaporation computed by the Penman Method is 4.1 $mm\ dy^{-1}$ with an annual total of 1471 *mm*.

Table 2. Climatic conditions of BEW based on a seven-year period (1980/81 - 1986/87)

Annual rainfall		2126 *mm*
No. of raindays		163
Air Temperature		
Mean		26.5° *C*
Mean Max		35.4° *C*
Mean Min		19.6° *C*
Relative humidity		83.6 %
Windrun		17.5 $km\ dy^{-1}$
Sunshine hours		147 $h\ mth^{-1}$
	or	4.9 $h\ dy^{-1}$
Evaporation		
US 'A' Pan		3.5 $mm\ dy^{-1}$
Penman Method		4.1 $mm\ dy^{-1}$

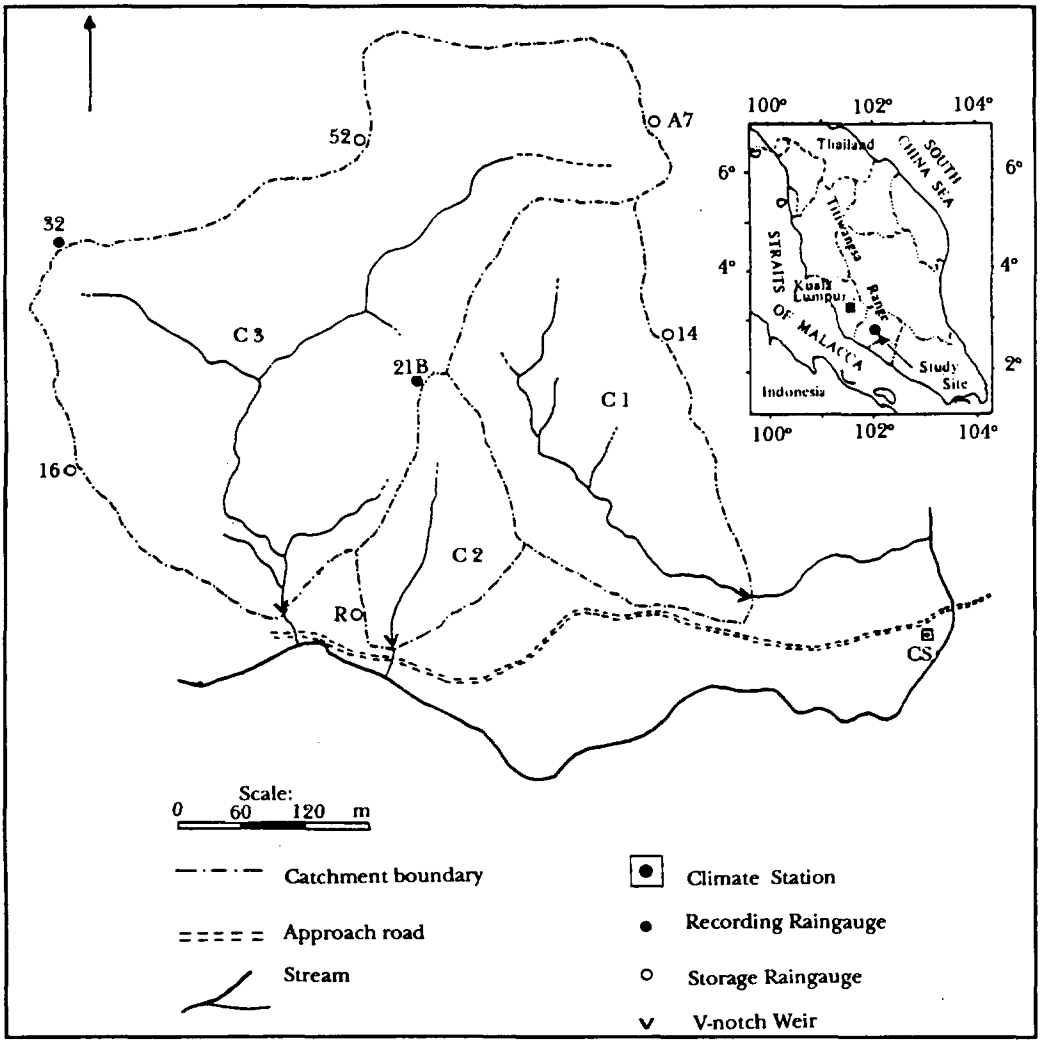

Figure 2. Instrumentation in Berembun experimental watershed (BEW)

Instrumentation and methodology

The study area has been instrumented with necessary equipment for continuous monitoring of climatic and hydrologic parameters. A climate station located at the base-camp, some 0.5 *km* to the east of the Watershed, is being operated in conformity with the Malaysian Meteorology Department's regulations. Data collected from this station include air temperature, humidity, windrun, sunshine hours and pan evaporation. A real rainfall is measured by tipping-bucket recording gauge at three stations as well as a network of eight storage gauges (Figure 2). These rainfall stations are located randomly in the Watershed in order to obtain a representative measurement of rainfall. Some gauges are placed on 11 *m* poles to obtain the needed exposure in the forest environment. All gauges

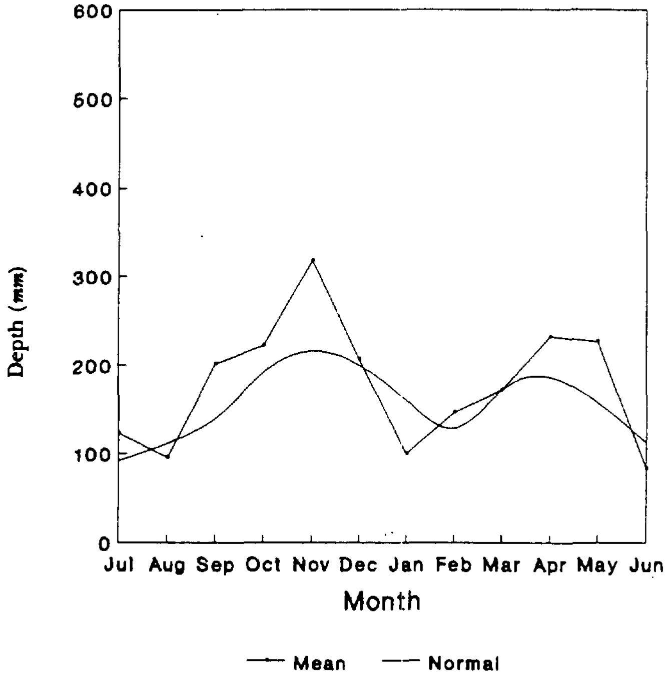

Figure 3. Mean monthly rainfall of BEW and the normal rainfall

are serviced weekly except the one in the climate station which is read daily. Rainfall depth is measured with an accuracy of 0.5 *mm* and 0.1 *mm* for recording and storage gauges respectively.

Stream flow is measured at 120° V-notch weirs fitted to concrete ponds with a cut-off wall of 1.5 *m* depth. Stage heights are recorded by Steven F-recorders using a float-type mechanism with an accuracy of 0.2 *mm* at the scale of 1:2. These recorders are serviced weekly. A field volumetric calibration for every weir was conducted to establish and verify respective rating tables. Rainfall charts and streamflow hydrographs were processed and digitised using computer facilities.

Calibration approach and watershed treatment

The present paired watershed research study involved at least three stages of experimentation, namely, the calibration, treatment and post-treatment phases or period. The calibration period for this study lasted for three hydrologic years whilst the post-treatment period only considered the following four years after the treatment had taken place. The treatment in the form of selective logging only lasted for three months. The hydrologic or water year, as a period of record, runs from July 1 to June 30 of the following year. Thus, all data referred to in the present paper consistently follow the above period.

After three years of calibration (July 1980 - June 1983), two of the catchments were selectively logged, namely Catchment 1 and 3 whilst Catchment 2 remained as a control. Strong regression relationships between treated and control catchments indicated the adequacy of calibration equations ($r^2 = 0.926$ and 0.929). The selective logging is the most common method of forest harvesting in Malaysia (Ministry of Primary Industries 1988). In this treatment exercise, two methods of forest logging were separately prescribed - a commercial selective logging method in C1 and a supervised selective logging in C3. Several conservation measures were instituted for the concessionaire during the logging operation while incorporating some of the present guidelines which can be categorised into four major areas, namely, road planning and construction, logging operations, landings and maintenance of roads. A summary of these prescriptions is given in Table 3. Approximately 40 and 33% of the forest stocking were removed during logging in C1 and C3 respectively.

Table 3. Logging prescriptions in Catchment 1 and Catchment 3 of BEW

Prescriptions	C1 (Commercial)	C3 (Supervised)
Cutting regimes (*cm*, at dbh)		
Dipterocarp	60	90
Non-dipterocarp	45	60
Stocking removed (%)	40	33
Road planning	not specified except what is in the permit	-road area <6 % -road grade 20% -culvert if road crosses stream -cross-drains installed along logging road
Road system (*km ha*$^{-1}$)		
Logging road	0.06	0.07
Skid trail	0.08	0.03
Buffer strip	not specified	min. 20 *m* from each side of the stream

Statistical analysis and data reduction

Both qualitative and quantitative approaches were employed in the analysis of streamflow parameters and water yield changes resulting from the treatment. The former method includes double-mass curves, flow duration curves and baseflow recession curves, comparing the calibration period with the post-treatment period. The latter method involves statistical regression techniques which provides a quantitative measure to determine the treatment effects on water yield. A 'dummy variable regression technique' as proposed by Gujarati (1970,1988) was employed to test the significance of hydrological response due to forest logging as it has been widely applied in detecting water yield changes following treatment in watershed studies (Swindel *et al.* 1983, Hewlett *et al.* 1984, Hsia 1987, Abdul Rahim 1989). In essence, this method involves comparing the residual errors from a full model containing a treatment effect with a reduced model without the treatment effect by treating calibration and treatment periods in the same regression. The dummy variable (T) is assigned and coded '0' and '1' during calibration and treatment respectively, using runoff (Q) as a variable of interest:

During the calibration period, T=0, a reduced model results:

$$Q_t = b_0 + b_2Q_c + E_i \quad \text{.......................................} \quad \text{Equation 1}$$

During the treatment period, T=1, a full model results:

$$Q_t = b_0 + b_1T + (b_2+b_3T)Q_c + E_i \quad \text{..................} \quad \text{Equation 2}$$

where:

Q = monthly runoff
t = treated catchment
c = control catchment
T = dummy variable
$b_0=b_1=b_2=b_3=b_4$= parameter estimates
E_i = error term

The null hypothesis that treatments have no effect on runoff is tested by the F-statistic computed from the above two analyses:

$$F = \frac{(SS_1 - SS_2)/(df_1 - df_2)}{EMS}$$

where:

SS_1 = sum of squares due to regression of full model
SS_2 = sum of squares due to regression of reduced model
df_1 = degree of freedom associated with full model
df_2 = degree of freedom associated with reduced model
EMS = error mean square of full model

A three-year calibration period is deemed sufficient to account for climatic variations prevailing at this station. In fact, the calibration period embraced extreme rainfall regimes in that both wet and dry years were experienced. The monthly runoff of treated catchments (C1 and C3) serves as the dependent or response variables against selected variables of the control catchment as independent or predictor variables. The step-wise regression suggests that the likely predictor variables for the above models are monthly runoff (Q_2), monthly rainfall (P_2) and one-month antecedent runoff (Q_{2a}). The best fit for calibration equations based on statistical indices comprises Model 1 and 2; essentially both models use runoff and rainfall as predictor variables (Table 4). The test for presence of any serial correlation in the equation was provided by the Durbin-Watson (D. W.) values.

Table 4. Parameter estimates of the regression models

#	Y	Predictor variables Q_2	P_2	Q_{2a}	r^2	s.e.	D.W.
1	Q_1	0.7900 (12.797)**	0.0165 (1.696)*		0.9293	4.517	1.872
2	Q_3	0.6985 (13.478)**	0.0236 (2.900)**		0.9425	3.792	1.731

Numbers in brackets indicate t-values; **significant at $p<0.001$; * significant at $p<0.01$; ^{ns}not significant

Hence, the above model specification indicates the adequacy of the equation for prediction purposes. Incidentally, similar model specifications have been employed by DID (1989) and Hewlett *et al.* (1984) in detecting water yield changes in Malaysia and the USA.

The adequacy of fit of a particular model can be further validated using a residual analysis. Examination of the fitted regression around the observed data shows that all data are within the 95% confidence interval for both equations while the normal probability plot validated the assumption of error terms (E_i) which are normally independently distributed with 0 mean and constant variance.

Results

In the present analysis, seven water-years of data (1980/81 to 1986/87) were used comprising three water-years of calibration and four water-years of post-logging periods respectively.

Rainfall

The annual totals range from 1442 to 2611 *mm*, with a mean of 2126 *mm*. Water years 1980/81, 83/84 and 85/86 can be considered as wet years with annual totals fluctuating about 35, 28 and 27% higher than the normal rainfall which is 1902 *mm* based on the nearby station, Kuala Pilah, 15 *km* away (Figure 4). On the other hand, the water year 82/83 was a dry year with rainfall 24% below normal. The monthly rainfall pattern generally shows a double-maxima or two-peak distribution which normally coincides with the northeast monsoon and the transitional period (Figure 3). The monthly mean of the entire watershed is 177 *mm* with the coefficient of variation of 4.0%. The average number of raindays per year is 163 and the highest number per month is 20, this normally occurring during the northeast monsoon. In the analysis of storm frequency, a storm event of 5 *mm* and greater was used and analysed. The monthly frequency of storm computed using seven years of data indicates a double-maxima pattern, resembling that of the monthly areal rainfall (Figure 5). Two prominent periods of 'dry-spells' can be identified, the first beginning from June to August and the second from January to February, with an average number of storms of less than of the annual total 5% per month. Diurnal rainfall frequency indicates that most storms occur during the late afternoon and early evening; as indicated earlier, this is highly characteristic of convectional rainfall (Lauer 1989).

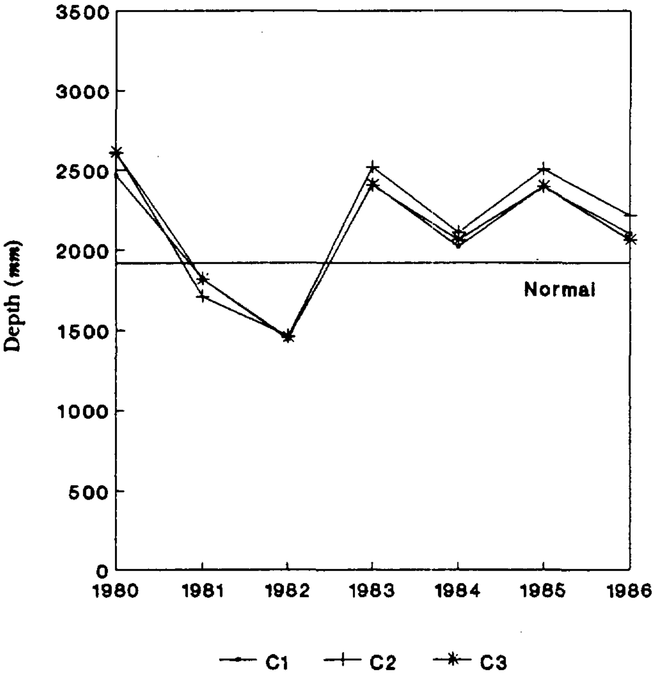

Figure 4. Annual rainfall of BEW

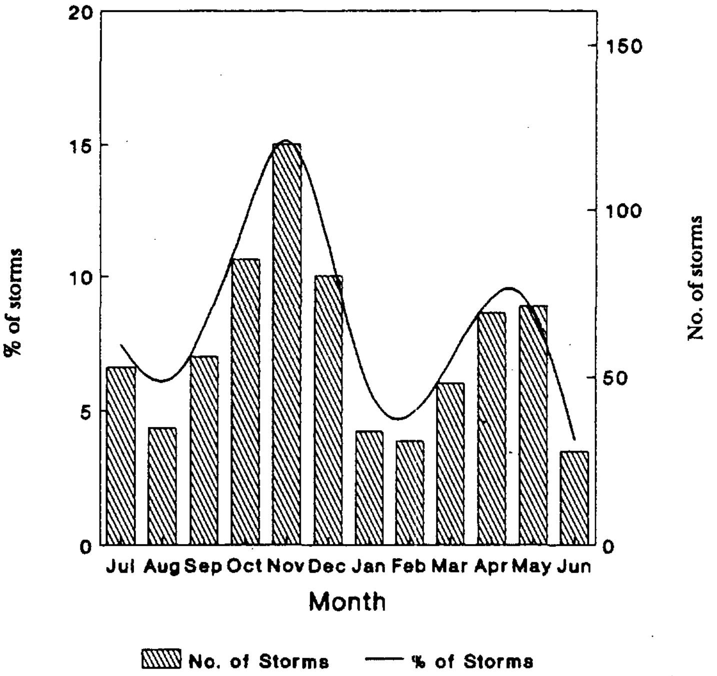

Figure 5. Monthly storm frequency (≥ 5.0 mm) at BEW

Runoff characteristics

The runoff pattern for the three catchments during the calibration period (July 1980 to June 1983) closely follows that of the rainfall, in that the water year 1982/83 was a dry year with consequent low flows (Figure 6). The monthly runoff coefficient ranges from 9.5 to 16.5%, averaging 12.2%. The rather low runoff coefficients observed in this watershed are quite acceptable due to its location in the upper reaches of a river system which are covered by rain forest. After the treatment of Cl and C3 in July 1983, both catchments showed some increases in the annual runoff or water yield as compared to C2, the control. The observed increases are also reflected in the corresponding runoff coefficients which ranged from 13.4 to 19.8 % in Cl and 13.4 to 17.2 in C3. Interestingly, the annual increase of water yield in Cl seems to be larger than C3. In the dry year of 1982/83, a zero flow intermittently occurs in all catchments, although duration varies between them (Figure 7). However, after the treatment operation, the zero flow ceases to occur in Cl and C3, but persists in C2. The mean monthly flow runoff of the three catchments, based on the calibration records, indicates a similar pattern to that of the monthly rainfall. There is apparently no lagging effect of runoff evident in the regime except during minimum flows where a one-month lag from that of monthly rainfall has been observed.

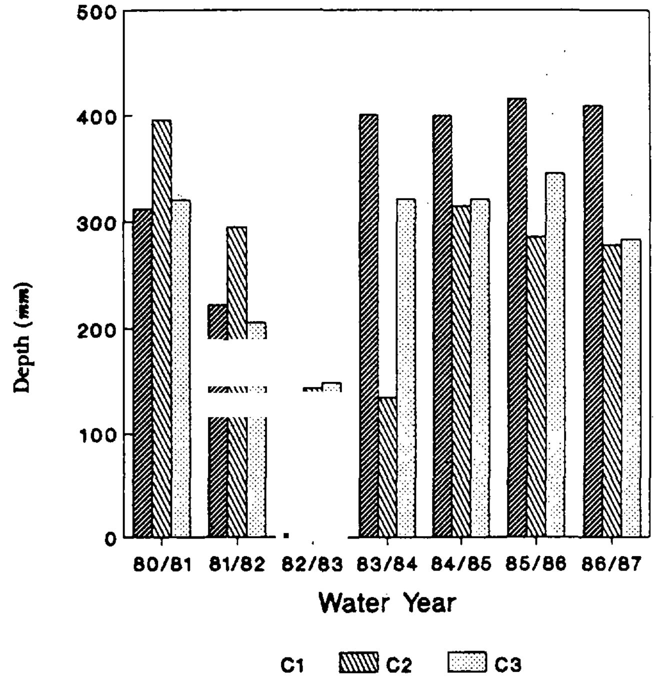

Figure 6. Annual runoff of the three catchments in BEW

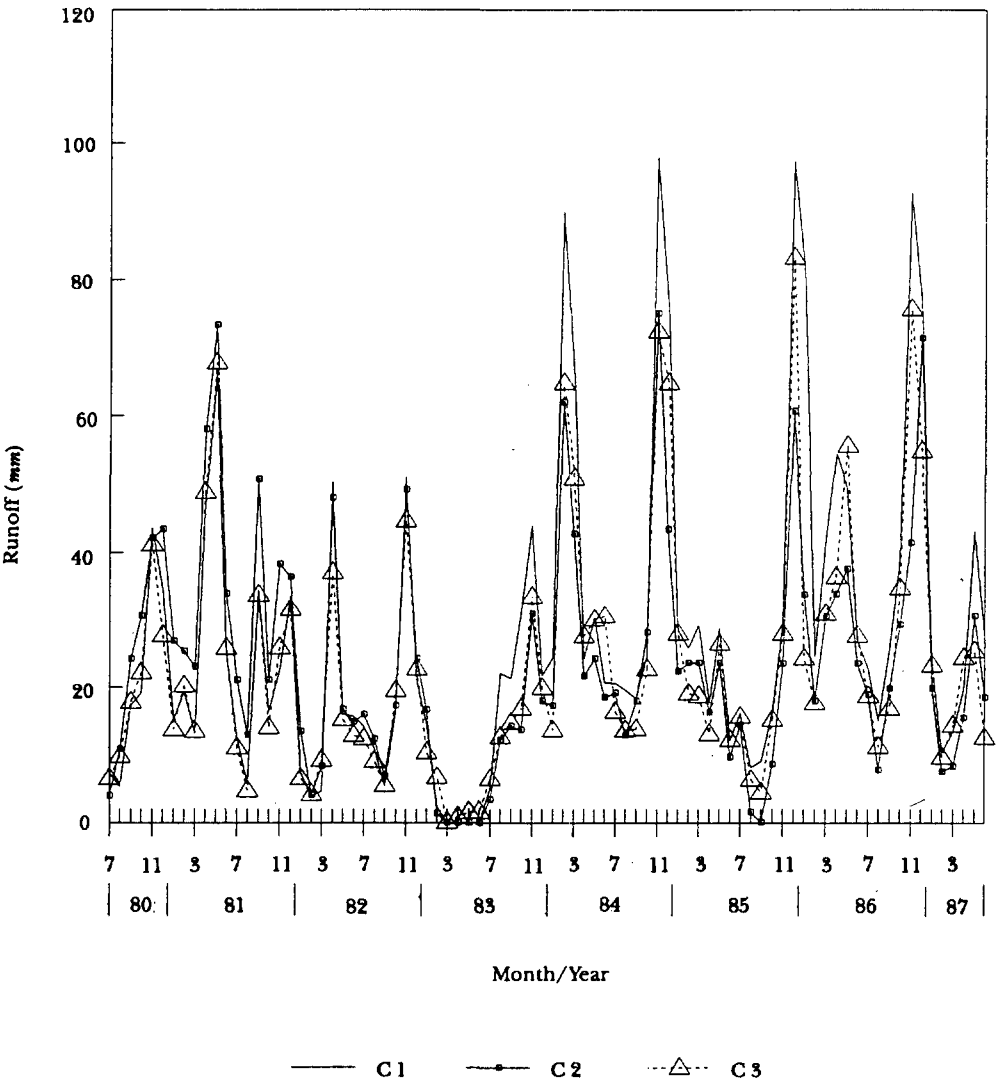

Figure 7. Monthly runoff of the three catchments in BEW

The double-mass curves were computed using monthly flows of treated catchments, C1 and C3, against the control to detect changes in runoff. These curves comprised six years of runoff including three years of post-treatment. The double-mass curves of C1 and C3 clearly show a break in the slopes commencing with the start of forest logging operations and continuing thereafter (Figures 8 and 9). The above characteristics provide further evidence of the effects of treatment on discharge immediately after forest harvesting. However, conclusions drawn from the double-mass curves may be fraught with hidden correlations between variables while the combined effects of site and treatment on streamflow cannot be separated from one another (Hewlett 1982).

The flow duration curves can provide a convenient means not only of evaluating the flow characteristics of each catchment but also of comparing them. Clearly, the

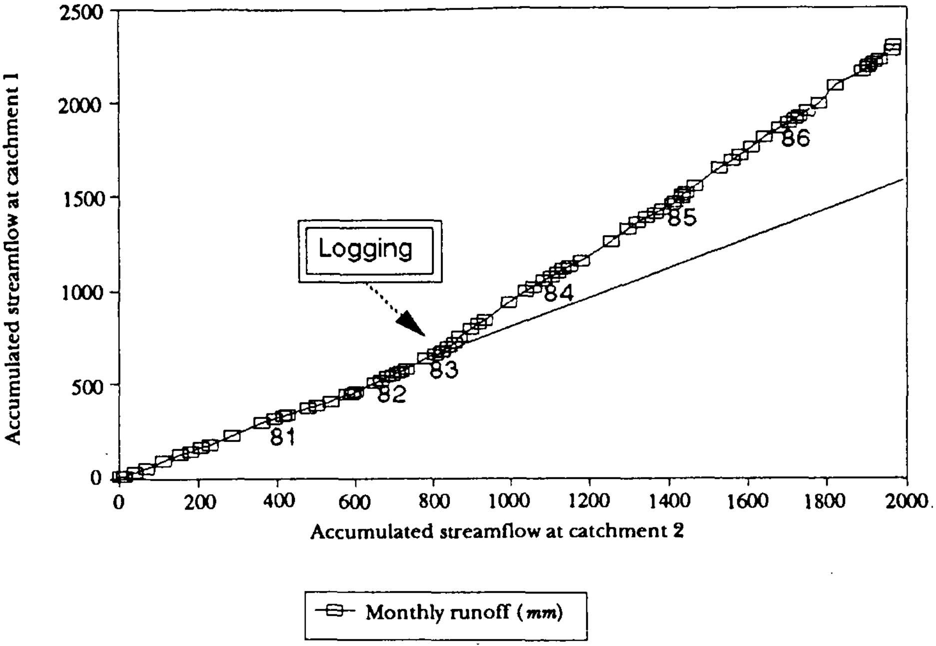

Figure 8. Double-mass curves of streamflow at Catchment 1 against that from Catchment 2 at BEW

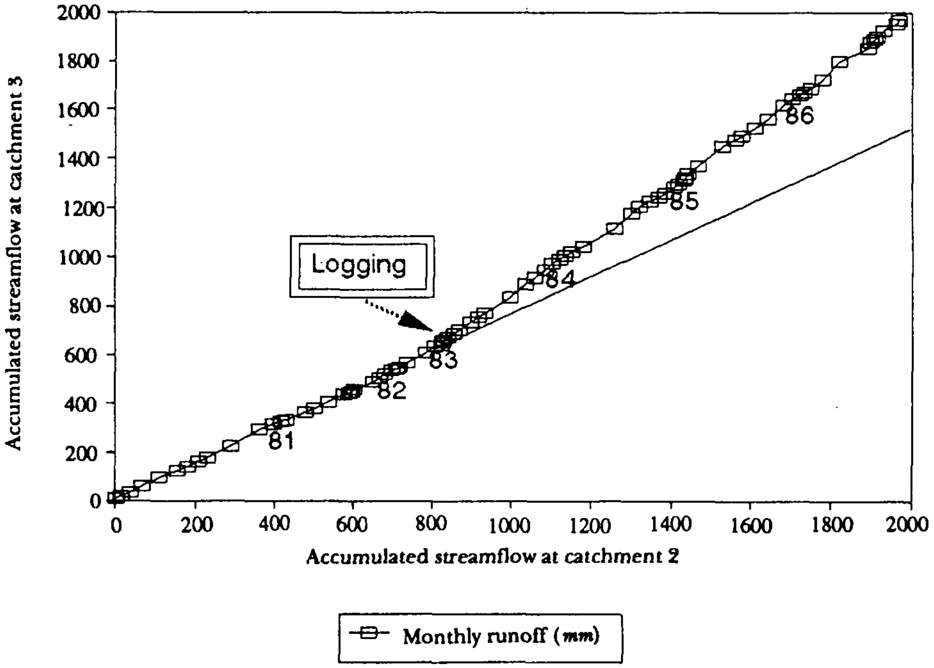

Figure 9. Double-mass curves of streamflow at Catchment 3 against that from Catchment 2 at BEW

duration flow curves of daily discharges of C1 and C3 reveal some changes whilst C2 indicates insignificant change when comparing the calibration period with that of the post-treatment period (Figures 10 and 11). Increases in flow must be attributed to the treatment operation, for the control catchment which experienced similar rainfall regimes, did not show comparable changes in the flow duration curves. Two notable characteristics elicited from the above curves are worth pointing out with regard to C1 and C3. Firstly, a greater change apparently occurred in C1 as compared with C3 as is shown quite clearly by the curves. Secondly, the increase in C1 covered a wider range of discharge whilst in C3, the increment was limited to the lower discharge values, particularly those less than 30 $l\,s^{-1}\,km^{-2}$.

Water yield changes

Models 1 and 2 (Table 4) were employed to predict the monthly runoff for the entire period including four years of the post-logging period for the respective catchments. Subsequently, their deviations from the observed values were computed, representing the differences in water yield after both catchments had been logged (Figures 12 and 13). The streamflow of C1 substantially increased immediately after the forest harvesting. The monthly increase is reliable within standard error of estimates amounting to 4.5 *mm*. Apparently, the water yield increase persisted up to the fourth year after treatment with an average monthly increase amounting to 14 *mm*. Annual water yield increased amounts to 165 *mm* (70%), 142 *mm* (55%), 175 *mm* (72%) and 155 *mm* (67%) in the first, second, third and fourth year respectively following treatment. The mean annual increase over the four-year period is 160 $mm\,y^{-1}$ or approximately 66%.

Similarly, C3 demonstrated an increase in monthly runoff immediately following the treatment, although a few months assumed negative deviations (Figure 13). Therefore, in examining the increments, it is instructive to observe annual yield over the year rather than monthly values which are sometimes subjected to seasonal fluctuation. The water yield increased up to the fourth year following treatment as in C1. In particular, the annual yield increase in C3 in the first four years amounted to 87, 70, 106 and 94 *mm* or 37, 28, 44 and 41% per year respectively. The mean annual increase amounts to 89 *mm* or 38% and the monthly average is about 7 *mm*.

As mentioned earlier, a dummy regression technique (Gujarati 1970) provides a convenient method to test the significance of water yield increase. Multiple linear regressions in the form of Equations 3 and 4 involving 36 observations for both phases were sought and their parameters estimates are listed in Table 5.

$T = 1$ (Full model)

$$Q_t = a_1 + a_2T + (b_1 + b_2T)Q_c + (b_3 + b_4T)P_c + E_i \;\ldots\ldots\ldots\ldots \text{Equation 3}$$

$T = 0$ (Reduced model)

$$Q_t = a_1 + b_1Q_c + b_3P_c + E_i \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 4}$$

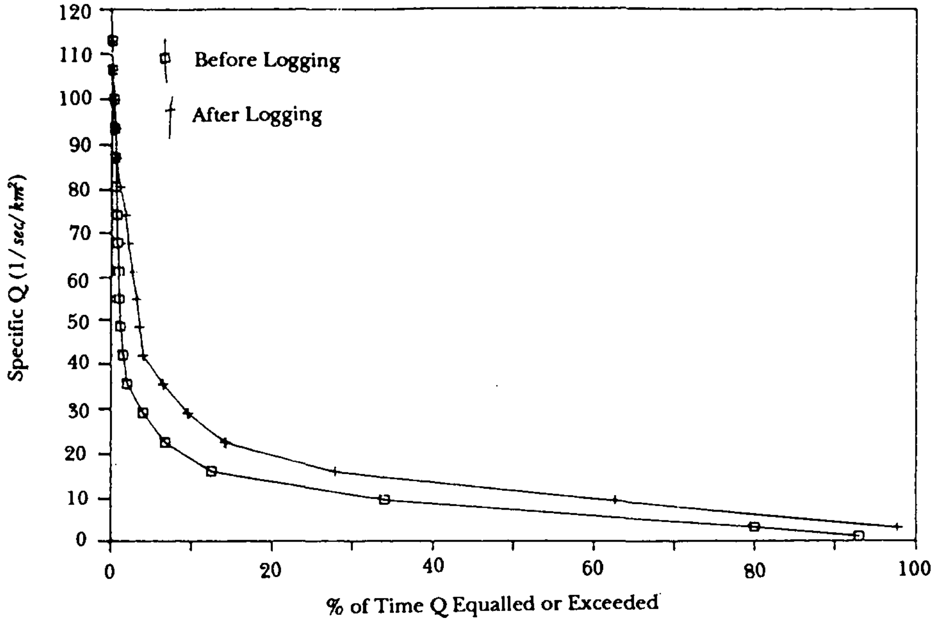

Figure 10. Flow duration curves of Catchment 1 at BEW

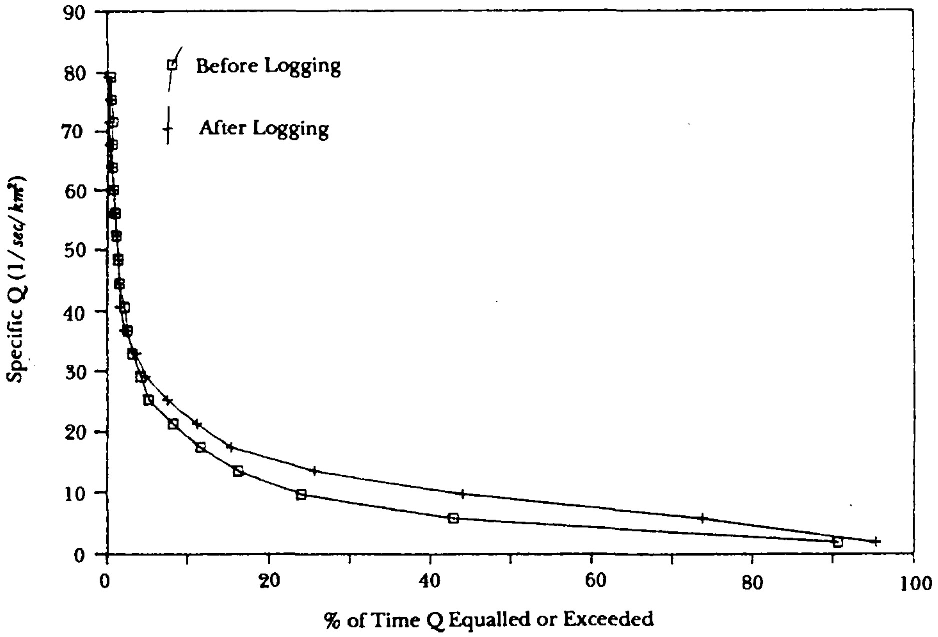

Figure 11. Flow duration curves of Catchment 3 at BEW

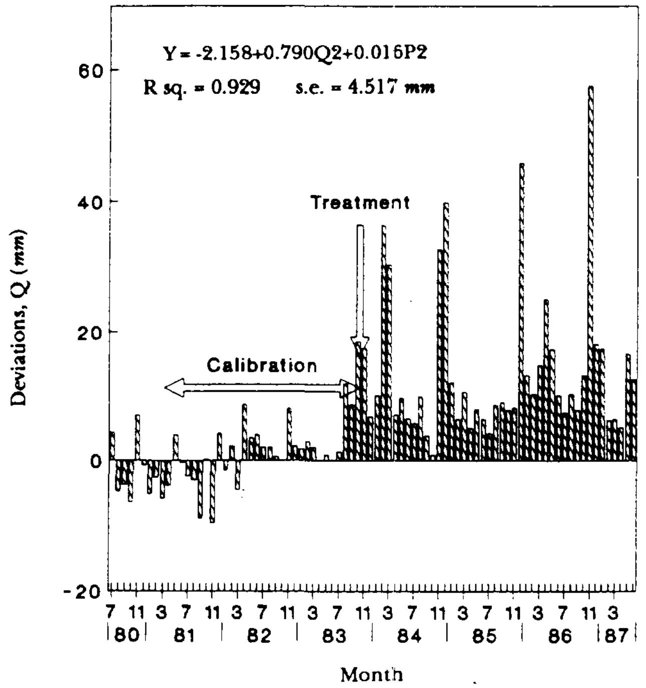

Figure 12. Deviations between predicted and observed runoff (*mm*) for Catchment 1

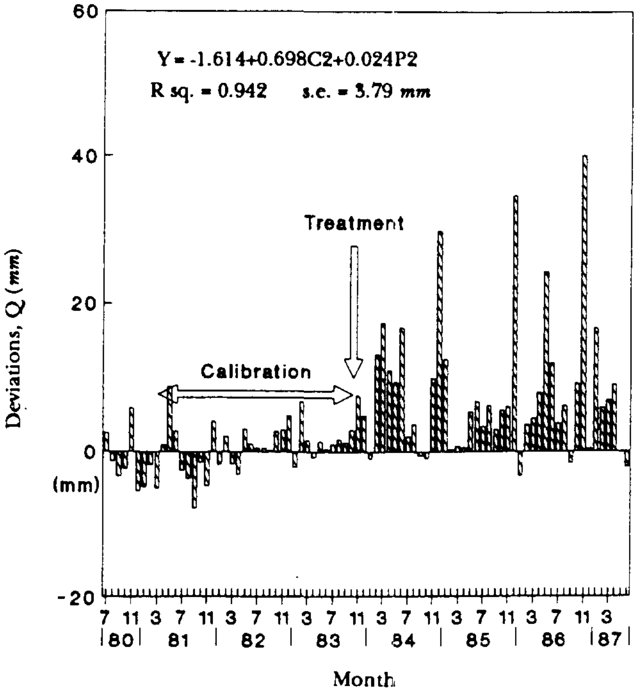

Figure 13. Deviations between predicted and observed runoff (*mm*) for Catchment 3

where:

Q_t = the predicted monthly runoff of the variable Q on the treatment catchment
Q = observed monthly runoff (mm)
t = treated catchments, C1 and C3
c = control catchment
T = dummy variable (T = 0 during calibration phase, T = 1 during post-logging)
a_i and b_i = parameter estimates
E_i = error term

The full models for C1 and C3 apparently explained 94 and 91% of the variation in the monthly runoffs of the respective catchments. Relatively high r^2 and low standard error of estimates for both regression equations suggest the adequacy of the model as previously discussed.

In the above regression models, the dummy variable has been introduced in the models in an additive form (addition of T to the intercept) and in a multiplicative form (T multiplied by Q_2 and P_2). Accordingly, the coefficient a_2 is called a differential intercept whilst coefficients b_2 and b_4 are a differential slope; they can be used in place of the standard analysis of variance as well as the analysis of covariance respectively (Gujarati 1970, 1988). However, the dummy variable approach also allows the testing of intercept and slope simultaneously using the F-statistics on the null hypothesis that the treatments have no effect on the monthly runoff (*i.e.* Ho: $a_2 = b_2 = b_4 = 0$).

Table 5. Regression statistics and parameter estimates of full and reduced models

Model	a_1	a_2	b_1	b_2	b_3	b_4	r^2	s.e.	D.W.
Dependent = Q_1									
T = 1	- 2.158	- 0.093	0.790 (10.339)**	0.533 (4.513)**	0.016 (1.371)^{ns}	0.002 (0.126)^{ns}	0.939	5.592	1.952
T = 0	- 2.158		0.790 (9.519)**		0.016 (2.314)*		0.808	9.704	0.919
Dependent = Q_3									
T = 1	-1.614	2.560	0.698 (9.186)**	0.441 (3.755)**	0.024 (1.976)*	-0.030 (-1.645)^{ns}	0.911	5.564	1.903
T = 0	-1.614		0.698 (11.444)**		0.024 (1.876)*		0.845	7.165	1.329

* significant at $p < 0.01$; **significant at $p < 0.001$; ^{ns}not significant

If the F-statistic does not lead to rejection of the above null hypothesis, then the treatment operation does not have any significant effect on water yield. The observed increases in water yield are highly significant for both catchments particularly in C1 as shown by a relatively large F-value, 47 as compared with C3. The computation of the F-statistics are based on the values from the analysis of variance tables for respective models (Table 6).

The significant increase in water yield reinforces the earlier analyses using the double-mass curves and flow duration curves. In addition, the earlier results also revealed that C1 consistently exhibited a higher streamflow response than C3 in all of the above analyses.

Table 6. The F-Statistics for the full and reduced models

	$F_{(cal)}$	$F_{(tab)}$ at $p < 0.001$
C1	47.3	4.13 (3, 66)
C3	16.1	4.13 (3, 66)

Discussion

The observed differences in water yield response can be chiefly attributed to a different percentage of forest cover removed from the two catchments, in which C1 recorded a slightly larger percentage of forest removal, by 7%. Despite this relatively small difference in forest removal, it translated into more than 55% higher water yield response based on the annual mean. Conceivably, this can be explained by the actual number of trees being extracted or damaged in the process of harvesting. As lower cutting regimes had been prescribed in C1, a greater number of trees were eventually cut and this, in turn, may have resulted in more damage to the residual trees. Logging damage to residual trees in the hill dipterocarp forest has been exceptionally high and can amount to as much as 43% of stems > 10 *cm* DBH (Phillips 1987), or even higher as reported by Burgess (1971). While the degree and type of damage incurred may vary, quite often serious damage may lead to trees dying or to a large portion of the canopy being snapped off. In addition, a higher density of skid trail is normally required in order to provide adequate access to a larger number of trees. This is indicated in C1 where the skid trail density was 60% higher than that of C3 despite the fact that the density of the logging roads was similar. In turn, this resulted in more trees having to be removed or possibly damaged in the construction of these trails. The underlying fact is that C1 was commercially logged which invariably vitiated many of the regulations normally prescribed in the logging exercise.

On the other hand, since catchment C3 was subject to supervised logging, only prescribed trees were taken out following quite stringent cutting regimes and thus, as expected, fewer trees were harvested. Thus a much lower density of skid trails was involved while the damage to the residual trees was kept to a minimum. In this instance, the buffer strip or riparian zone of a minimum distance of 20 *m* from each side of the stream was instituted and strictly enforced. Hence, the ground disturbance has been limited to certain areas such as logging roads, skid trails and landings which amounted to 5.1% as compared to 7.3% in C1.

Based on our analysis, the prevailing rainfall pattern influences the magnitude and extent of water yield response. In fact, the differentials in the annual water yield increases following treatment closely follow the annual rainfall pattern for both catchments (Figures 4, 12 and 13). The first and third year after treatment recorded a higher annual rainfall which accordingly was reflected in the magnitude of water yield increase in both catchments. Similarly, values for the second and fourth years portrayed a rather low rainfall that was reflected in a relatively lower yield of C1 and C3. Thus, undoubtedly, the rainfall regime during and following treatment largely determines the magnitude of any increase.

To compare the above response with a similar setting locally, the Sg. Tekam study may provide a useful comparison on the effect of forest logging followed by clearance (DID 1986, Abdul Rahim 1988). During harvesting and clearance of sub-catchment B at Sg. Tekam, representing about 60% of the total area, the water yield increase for the first three years amounted to 145, 155 and 137 *mm* y^{-1}. The above increases, by and large, are comparable with the responses observed in C1 which underwent a 40% cut. However, in interpreting the above results, two factors are worth pointing out. The first is that the forest cover in the Sg. Tekam Basin prior to logging consisted essentially of a logged-over or secondary forest and secondly, the area is located in a lower rainfall zone in Peninsular Malaysia. The above two factors may have some bearing on the hydrological response to treatment. The logging operation in a logged-over forest tends to be more extensive as most of the large trees had been extracted before. Thus, the hydrological response could be larger.

The normal conclusion of temperate results is that the greatest increase occurs in the first year following treatment, but this is not observed in the present study nor in the Sg. Tekam catchment. In fact, the increase tends to persist for a few years before the runoff reverts back to the normal level, if ever this happens. The above anomaly could be ascribed to the fact that the growth of the rainforest, particularly the dipterocarp species present in Peninsular Malaysia, is remarkably slow and takes a longer time to return to a stable condition. However, the undergrowth on the forest floor and the pioneer species establish themselves much quicker and are thus beneficial in covering up the ground disturbance.

As mentioned earlier, few quantitative data are available on the effect of selective logging practice *per se* from the tropics on water yield. Most of the documented studies so far normally dealt with the effect of clearcutting of natural forests followed by either reforestation or conversion to agricultural land use (Bosch & Hewlett 1982, Oyebande 1988, Bruijnzeel 1986). One exception has been the Babinda study located in tropical northeast Australia where Gilmour (1977) has documented some effects of forest logging followed by clearance.

The present study, on the other hand, revealed a significant increase in monthly runoff and thus the annual yield following selective logging, ranging from 70 to 175 *mm* after extracting 33 to 40% of the forest cover. The above increase is equivalent to approximately 3 to 4 *mm* for every percentage of the forest cover removed and corresponds to 300 to 400 *mm* for a 100% removal or clearcutting. Taking an average value of 350 *mm*, the figure is in agreement with the mean values of the Sg. Tekam Basin, 314 and 358 *mm*, which underwent a complete clearance (Table 7) . It is clear, however, that this projection is much lower than that of Oyebande (1988) who suggested a value of 5.0 *mm* for every percentage of forest removed. In the latter analysis, the author summarized the results of nine tropical catchment studies which encompassed studies on both afforestation and clearcutting practice. However, the plot also included results of South African studies, even though these do not fall under the humid tropics region according to the definition of Chang and Lau (1983). Further, the results of the Sg. Tekam study have not been included. Another reservation relating to the above conclusions is the inclusion of the result of Fritsch (1983) in French Guyana which largely influenced the fitting of the regression lines. In fact, the value quoted from this study only represented the first year of observation (Table 7). Moreover, the small size of the catchment used could form another reservation.

Hibbert (1967) suggested that the upper limit of water yield increase is 4.5 $mm\ y^{-1}$ for each percentage of forest cover reduction. Nevertheless, the author further maintained that most treatments produced less than 2.5 *mm* increase per year with the first year response varying from 34 to 457 *mm*. Obviously, the above review mainly considered studies from temperate areas with the exception of a few studies from Africa.

Considering results of recent studies in the tropics, the water yield response in the first four years after logging could amount to 500 to 800 *mm* as observed in Lien-Hua-Chi, Taiwan and Sg. Tekam, Malaysia. In questioning the conclusion of Hibbert (1967) that water yield response to afforestation and deforestation is unpredictable, Bosch and Hewlett (1982) concluded that coniferous, deciduous hardwood forests, brush and grass cover manifest, in that order, a decreasing influence on water yield compared with bare ground. When inferring results from studies under tropical forests, the rainforest (dipterocarp forest) apparently produces a comparable response to the coniferous forest, if not, perhaps, even larger. However, to summarize the specific ranking as such, more research results from studies in the tropics are required that represent various rainfall regimes and forest types. In addition, future studies should include as many components of the hydrological cycle as possible together with detailed accounts of processes operating in order to explain and understand catchment responses fully in a rigorous manner.

While the present results confirm and update the findings of paired watershed studies conducted elsewhere, both in tropical and temperate areas, the present analysis only covers the first four years of the post-treatment period. Undoubtedly, a much longer duration of observation is needed to quantify the subsequent catchment response on water yield and to find out whether the catchment would revert back to a pre-calibration regime when the forest ultimately recovers.

Conclusions

Results from this paired watershed study, particularly on water yield changes, clearly confirm and reinforce findings of many other studies conducted in the

Table 7. Forest cover transformation in the humid tropics and changes in water yield

Location	Type of transformation	Catchment sizes (ha)	M.A.P. (mm)	Elevation (m a.s.l)	Changes in water yield ($mm\ yr^{-1}$)					Reference
					1^{st} y	2^{nd} y	3^{rd} y	4^{th} y	u	
Babinda, Queensland	Lowland rain forest to grass (35%) & scrub (35%)	18.3	4035	10-200	+264 (7.0%)	+323[a] (13.4%)			+293	Gilmour 1977
Lien-Hua-Chi, Taiwan	Clearcutting of mixed evergreen hill forest; regeneration	5.9	2100	725-785	+448 (58%)	+204[b] (51%)			+326	Hsia & Koh 1983
Kimakia, Kenya	Montane rain forest/ bamboo to *Pinus* plantation; agriculture intercropping (3 y) until canopy closed	36.4	2198	2440	+457	+229	+178		+328	Blackie 1972
Mbeya, Tanzania	Evergreen montane forest (1/3 grass 6 shrub) to agricultural land use (50% annual cropping & 50% grazing land)	20.2	1900	2428					+220	Blackie 1972
St. Emilie, French Guyana	Primary lowland rain forest to plantation of *Eucalyptus*	1.0	3230	<100	+408 (25.9%)					Fritsch 1983
Sg. Tekam (A), Malaysia	Secondary dipterocarp forest to cocoa plantation	37.7	1878	72.5	+110 (117%)	+706[c] (157%)	+353 (94%)	+263 (158%)	+358	Abdul Rahim 1988, DID 1989
Sg. Tekam (B), Malaysia	Secondary dipterocarp forest to oil palm (60%) and cocoa (40%) plantation	96.9	1878	68.5	+145 (85%)	+155 (142%)	+137 (97%)	+822[c] (470%)	+314	Abdul Rahim 1988, DID 1989
Berembun (1), Malaysia	Selective logging (40%) of primary dipterocarp forest	13.3	2126	221	+165[a] (70%)	+142 (55%)	+175[a] (72%)	+155 (67%)	+160	This study
Berembun (3), Malaysia	Selective logging (33%) of primary dipterocarp forest	30.6	2126	236	+87[a] (37%)	+70 (28%)	+106[a] (44%)	+94 (41%)	+89	This study

*Mean annual rainfall [a] Wet year [b] Dry year [c] 100% clearance
(Adapted from Abd. Rahim 1990 & Bruijnzeel 1986)

tropics as well as in temperate areas. The magnitude and rate of the total yield increase largely depend on the amount of cover removed and the rainfall regime during and immediately after forest treatment, and to a lesser extent, the catchment storage and thus soil characteristics of the area. In this instance, the magnitude of water yield changes resulting from cover manipulations (for example, forest logging, forest conversion) is as variable as in temperate areas while qualitatively both tropical and coniferous forests seem to yield a similar magnitude of response as compared with other forest types.

While concrete evidence on the total yield changes has been presented, interesting results emerged on the effects of selective logging on streamflow components. This study indicates that the observed increase in water yield is largely associated with the augmentation of baseflow. The main reason for such responses is essentially the extensive nature of the selective logging operation which left a substantial forest area intact. Thus, there was less ground disturbance while retention of buffer strips ensured minimum disturbance to flow channels.

More importantly, this study demonstrated the positive effects of the supervised selective logging method as compared with the commercial selective one in terms of hydrological responses. Apart from the retention of a buffer strip and the small percentage area to be covered by forest roads, other conservation measures such as installation of cross drains, culvert and proper forest road planning proved beneficial and effective in ameliorating the hydrological impacts.

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