EFFECTS OF SELECTIVE LOGGING METHODS ON SUSPENDED SOLIDS CONCENTRATION AND TURBIDITY LEVEL IN STREAMWATER

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ZULKIFLI, Y. & ANHAR, S. 1994. Effects of selective logging methods on suspended solids concentration and turbidity level in streamwater. The impacts of 'conventional' and 'closely-supervised' selective logging methods on streamwater quality were studied in three small catchments in the Berembun Forest Reserve, Negri Sembilan, Peninsular Malaysia. The former method was typical of present commercial logging practices while in the latter, additional conservation measures were imposed and strictly adhered to during logging. Treatment effects were determined by comparing changes in the quality of streamwater in the logged catchments against an unlogged catchment during a three-year calibration period and a five-year post-treatment period. Before logging, streamwater was of clear quality during baseflow period but levels of suspended solids and turbidity increased considerably during storm events. In the first year after conventional logging, annual means were 12 and 9 times those of the control catchment for suspended solids and turbidity respectively. These high levels persisted until the fifth year after logging. Another catchment where logging operations were closely-supervised showed only about two-fold increases for both suspended solids and turbidity levels; they recovered to the original levels within two years. Logging effects intensified during storm events with stormflow means in the first year after the conventional logging of 502 mg l^{-1} and 295 NTU for suspended solids and turbidity respectively, compared with 10 mg l^{-1} for suspended solids and 5.8 NTU for turbidity during baseflow period.

Key words: Tropical rainforest - selective logging - suspended solids - turbidity - recovery periods

ZULKIFLI, Y. & ANHAR, S. 1994. Kesan pembalakan memilih ke atas kepekatan pepejal terampai dan paras kekeruhan di dalam air sungai. Kesan tebangan memilih ke atas kualiti air sungai telah dikaji menggunakan tiga tadahan kecil di Hutan Simpan Berembun, Negeri Sembilan, Semenanjung Malaysia. Dua kaedah pembalakan

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iaitu "konvensional" dan "penyeliaan rapi" telah dikaji. Kaedah pertama menyerupai cara pembalakan komersial seperti yang diamalkan dewasa ini sementara bagi kaedah kedua, beberapa langkah pemuliharaan tambahan telah dikenakan di samping pengawasan rapi ketika pembalakan sedang berlangsung. Kesan rawatan telah ditentukan dengan membanding perubahan kualiti air di dalam tadahan yang dibalak dengan tadahan kawalan semasa tiga tahun fasa kalibrasi dan lima tahun fasa pasca-rawatan. Sebelum pembalakan, kualiti air sungai semasa aliran dasar adalah jernih tetapi paras kekeruhan dan pepejal terampai meningkat dengan ketara semasa kejadian ribut. Dalam tahun pertama selepas pembalakan konvensional, paras pepejal terampai dan kekeruhan telah melebihi nilai di tadahan kawalan sebanyak 12 dan 9 kali ganda, masing-masing. Paras yang tinggi ini berlarutan hingga tahun kelima lepas dibalak. Sebaliknya pepejal terampai dan kekeruhan hanya menunjukkan kenaikan sederhana selepas pembalakan penyeliaan rapi; parameter ini kembali ke paras asal dalam tempoh dua tahun. Kesan yang lebih ketara berlaku berikutan kejadian ribut dengan purata tahunan semasa aliran puncak pada tahun pertama lepas pembalakan konvensional adalah 502 mg l^{-1} dan 295 NTU bagi pepejal terampai dan kekeruhan, masing-masing; berbanding dengan 10 mg l^{-1} untuk pepejal terampai dan 5.8 NTU untuk kekeruhan semasa aliran dasar.

Introduction

Systematic conversion of forest to other land uses has reduced the forest areas in Malaysia to about 59% of the total land area (MPI 1992). Most of the lowland areas have been cleared and planted with commercial crops, especially rubber and oil palm. The shortage of suitable land for agriculture and the need for expanding this sector to support the economic growth have led to the clearing of steepland (Salleh 1987). Consequently, the remaining forests for timber production are now mostly confined to hilly areas which largely constitute the main sources for domestic water supply. Meanwhile, logging activities have always been criticised for the degradation of water quality in the upland catchments.

Due to its steep slope, hilly areas are characterized as sensitive to man-induced disturbances and are a potential source of pollutants in the forms of solids and sediments (Megahan & King 1985). Partial or complete removal of forest cover may accelerate erosion, causing excess sediment in streams. This leads to related consequences such as reduction in reservoir capacity for flood mitigation, irrigation storage and hydropower generation, damage to turbines and water pumps, and obstruction to navigation. Turbid water also reduces light penetration, thus affecting the productivity and metabolism of aquatic flora and fauna.

Notwithstanding the number of sediment-related studies reported locally, including those resulting from logging activities (Salleh *et al.* 1983, Lai & Shamsuddin 1985, Lai & Rentap 1987), none has quantitatively examined the impact, and more importantly, its rate of recovery on a long term basis. In fact as reviewed by Bruinjzeel (1990), no such studies have been reported in the tropics. This paper presents results of a catchment study on the impact of "closely-supervised" and "conventional" selective logging methods on suspended solids and turbidity levels in a tropical rainforest site. The study is part of a much wider programme aimed at quantifying the effects of selective logging on hydrological attributes. Data over eight years are presented, covering a three-year pre-logging period and a five-year post-logging period. The results are considered useful in providing a firm data bank on which the development of guidelines and strategies for water resources management can be based.

Materials and methods

Site description

The study was carried out in the Berembun Forest Reserve, Negri Sembilan, Malaysia at approximately 2° 46'N latitude and 102° 06'E longitude. The area consists of three adjacent small catchments, namely Catchment 1 (C1), Catchment 2 (C2) and Catchment 3 (C3) (Figure 1). Except for the sizes, which ranged from 4.6 to 30.8 ha, the three catchments generally share quite similar physical characteristics (Table 1). The catchments are underlain by a homogeneous granitic body of middle to upper Triassic age which makes up part of the sourthern portion of the Main Range. The rock consists of medium coarse grained porphyritic biotite granite with both quartz and feldspar as phenocryst. The soil contains a high proportion of sand with deeply weathered profile and belongs to the clayey kaolinitic isohyperthermic family of the Typic Paleudult. Detailed description of the geology and soil is given by Adzmi and Ghazali (1989).

Prelogging vegetation survey showed that the area was dominated by *Shorea* species mainly of *Shorea laevis, S. leprosula* and *S. acuminata.* Other commercial tree species such as *Koompasia malaccensis* and *Intsia palembanica* are also common. The understory was moderately dense consisting of temin *(Streblus taxoides)* and minyak berok (*Xantophylum* spp.). Wyatt-Smith (1963) classified the forest of this area as 'Red-Meranti-Keruing Forest' type.

The annual rainfall over eight years (July 1980 - June 1988) ranged from 1442 to 2611 mm and averaged 2549 mm. Water years 1980/81, 83/84 and 85/86 were characterised as wet years as their annual rainfalls exceeded the annual average over 25%. On the other hand, the 82/83 water year was the driest throughout the study period. The monthly rainfall pattern generally shows a two-maxima in the months of November and April which coincides with the northeast monsoon and the transitional period of the northeast and the southwest monsoons. The median rainfall intensity was 18 mm h^{-1} and the average number of rainday was 163 y^{-1}. Detailed climatic conditions of the study site have been reported by Abdul Rahim (1983, 1990), and Abdul Rahim and Harding (1992).

Table 1. Physical characteristics of the three catchments at Berembun Forest Reserve

	C1	C2	C3
Area (ha)	13.3	4.6	30.8
Elevation (m.a.s.l)			
Highest	272	239	302
Lowest	170	175	171
Mean slope (%)	27	21	24
Aspect	South	South	South
Drainage density			
(km km^{-2})	6.17	5.37	4.68
Form factor 0.34	0.34	0.33	0.38
Catch. circularity	0.69	0.71	0.6

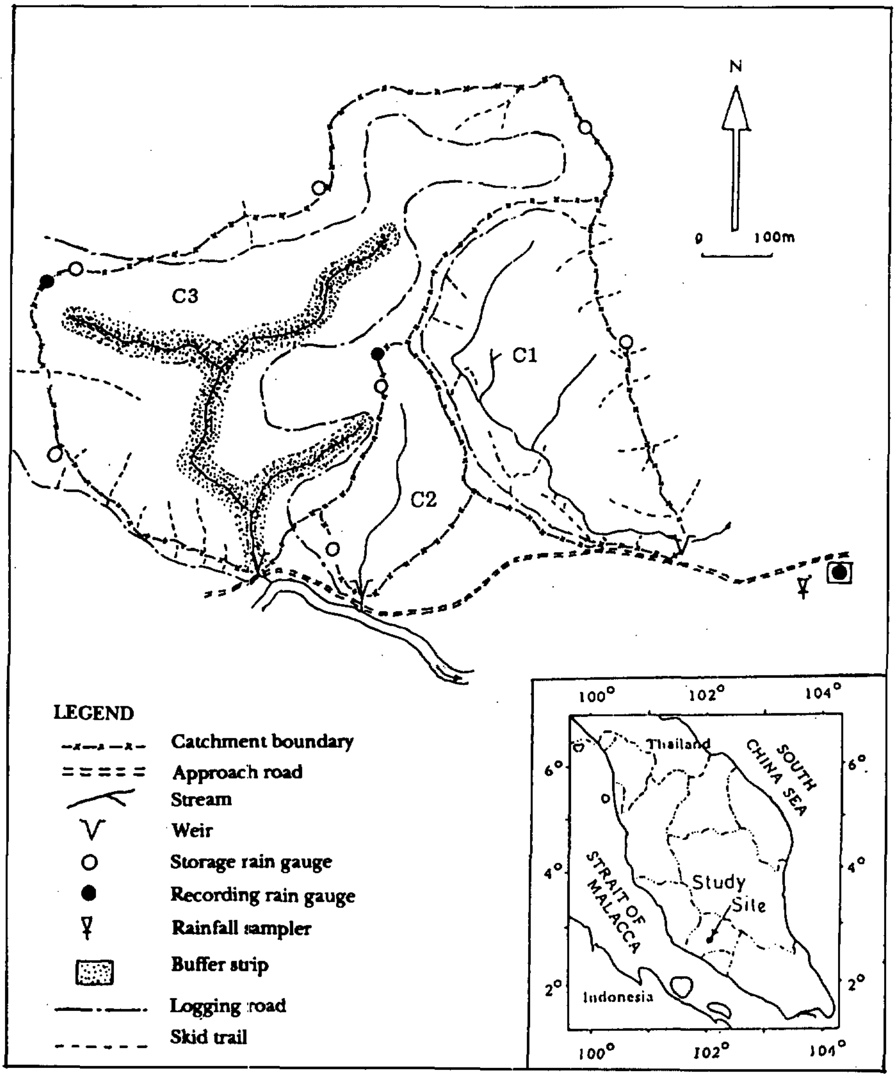

Figure 1. Layout of the Berembun Experimental Forest

Methods

The experimental site had been equipped to monitor climatic and hydrological parameters. Rainfall was measured by three tipping-bucket recording gauges and eight storage gauges, strategically distributed over the study area (Figure 1). Streamflow was measured at a 120° V-notch weir, fitted to a concrete pond with a cut-off wall of 1.5 m depth. A floating-type Steven F-recorder was installed for continuous recording of stage-height.

Streamwater was sampled since July 1980 on a weekly basis and a storm basis by a grab sampling technique. The weekly samples usually represented the baseflow period, except when they coincided with storm events, where samples were then treated as stormflow samples. Stormflow sampling was carried out when there was an effective increase in stage height (usually when rainfall exceeded 15 mm). The sampling exercise followed a sequence of C1, C2 and C3 and was usually completed within 15 min. Stream water was sampled using a four-litre polyethylene bottles, about 1 m above the concrete pond. Water samples were kept in ice-cooled containers prior to laboratory analyses for physical and chemical parameters. Suspended solids were determined gravimetrically by filtering 250 ml sample through a pre-weighed glass microfiber filter (pore size of 1.2 μm). The residue left on filters was then ovendried at 108 °C for two hours, kept in a desiccator to cool to room temperature and reweighed. The suspended solids reported in this study should not be confused with another closely related parameter - sediment. The latter excludes the organic matter content through ignition at 550 - 600 °C during laboratory analysis. Suspended solids, because of the lower ovendried temperature, retain their organic matter contents which are therefore, determined with the inorganic fractions. Turbidity was determined using HACH 2100A turbidimeter which measures the amount of light being scattered by particles in water samples.

Catchment treatment

After a three-year calibration period (July 1980 - June 1983), C1 and C3 were selectively logged in July 1983. Two logging methods were prescribed, namely 'conventional' for C1 and 'closely-supervised' for C3. Catchment 2 (C2) remained unlogged and served as a control. For the conventional logging method, the operations were typical of present commercial logging practices with cutting regimes of 60 and 45 cm DBH for dipterocarp and non-dipterocarp respectively.

A stricter cutting regime coupled with several additional control measures (Table 2) was imposed on the closely-supervised logging. This includes alignment of logging roads along the contour, proper drainage for road runoff, construction of cross-drains at 45 - 60° across logging roads, and installation of culverts or hollow logs for vehicular stream crossing. No logging was allowed within buffer strips of no less than 20 m on both sides of perennial streams. Logging operations generally involved tree felling and bucking using chainsaws, upslope skidding of logs using crawler tractors (KOMATSU D4 and D6), and transporting of logs using winch

Table 2. Logging prescription in the supervised and unsupervised catchments in the Berembun Forest Reserve

Prescription	Conventional (C1)	Supervised (C3)
Cutting regimes (cm DBH)		
- Dipterocarp	60	90
- Non-dipterocarp	45	60
Stocking Removed (%)	40	33
Logging road and skid-trail (km ha^{-1})	0.14	0.10
Road planning	not specified except what is in the permit	- road grade < 20% - culvert/hollow logs for stream crossing - cross-drains along logging road
Buffer strip	not specified	20 m on both sides of streams
Area disturbed (%)	7.3	5.1

lorries. Several log-yards were constructed outside the catchment area, and one was on the boundary of C3, but this did not affect the other catchments. Information on sizes and the exact location of these log-yards is, however, unavailabe. The logging operations removed about 33 and 40% of the standing volume from C1 and C3 respectively. Soil disturbances due to logging roads and skid-trails were estimated to be 7.3% and 5.1% of the area of C1 and C3 respectively.

Data analysis

A total of 1695 streamwater samples were collected from all the three catchments during eight years. The study period was divided into three phases: a three-year calibration period (July 80 - June 83), a two-year transition period (July 83 - June 85), and a three-year recovery period (July 85 - June 88). Water quality data were computed for three types of discharge-weighted means on a monthly basis namely, overall monthly mean (both, weekly and stormflow samples), baseflow monthly mean (weekly samples only) and stormflow monthly mean (stormflow samples only).

Treatment effects on water quality parameters were evaluated using the group t-test (Gill 1978). The technique generally involves comparing the monthly means of streamwater parameters of a treated catchment against the corresponding means for the control catchment. Analyses were carried out separately for each phase of the study periods (calibration, transition and recovery) as well as for the three types of discharge weighted means (overall, baseflow and stormflow).

Initially, the data sets were examined for normality and equality of variance. Normality was determined by visual comparison of the observed frequency

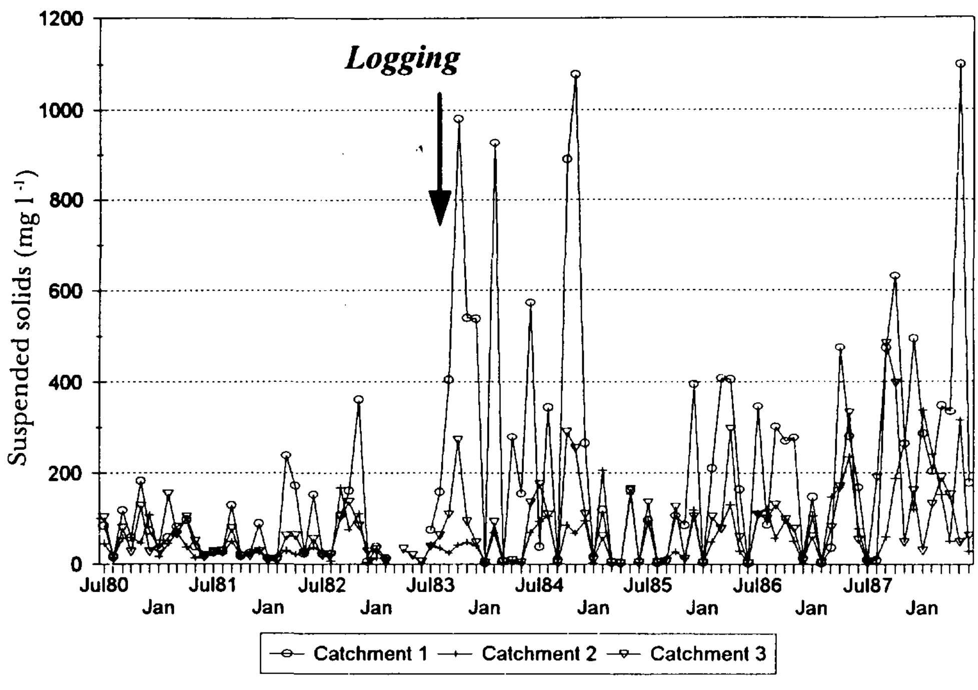

Figure 2. Overall monthly means of suspended solids (mg l^{-1}) in C1, C2 and C3

polygons with that of the theoretical one and double-checked by Pearson's Chi-square tests. Equality of variance was determined by F-tests (Steel & Torrie 1981). Data sets that failed to satisfy the underlying assumptions were transformed to Log_e (Tiedemann *et al.*, 1988), so as to permit the use of a parametric test which was generally more robust than its non-parametic counterpart (Montgomery & Loftis 1987). A non-parametic test, the Wilcoxon Rank-Sum test (Steel & Torrie 1981), was resorted to when the underlying assumptions for the t-test were still unsatisfied even after data transformation.

Results

Impact on suspended solids

Overall monthly means of suspended solids concentration during the calibration period ranged from 4 to 360 mg l^{-1} and averaged 54 mg l^{-1}. Substantial increase in concentrations was observed following conventional logging (C1) with a mean overall during the first year of 386 mg l^{-1} whereas means for the closely-supervised logging (C3) and control catchment (C2) were 72 mg l^{-1} and 32 mg l^{-1} respectively (Table 3). Although the overall monthly means for C3 subsided to background levels in the third year after logging, the values for C1 were still remarkably higher compared with the control (Figure 2). As illustrated in Figure 3, the overall monthly patterns of suspended solids were closely dependent on the monthly rainfall during calibration period (Figure 4). The same pattern can be expected for the post-treatment period. For all catchments, the highest means were observed in October 1983 (981 mg l^{-1}) and November 1984 (1077 mg l^{-1}) which corresponded with high monthly rainfalls (237 mm and 247 mm respectively). The monthly overall means of suspended solids for the conventional logging continued to be significantly different from those of the control catchment throughout the recovery period (Table 4).

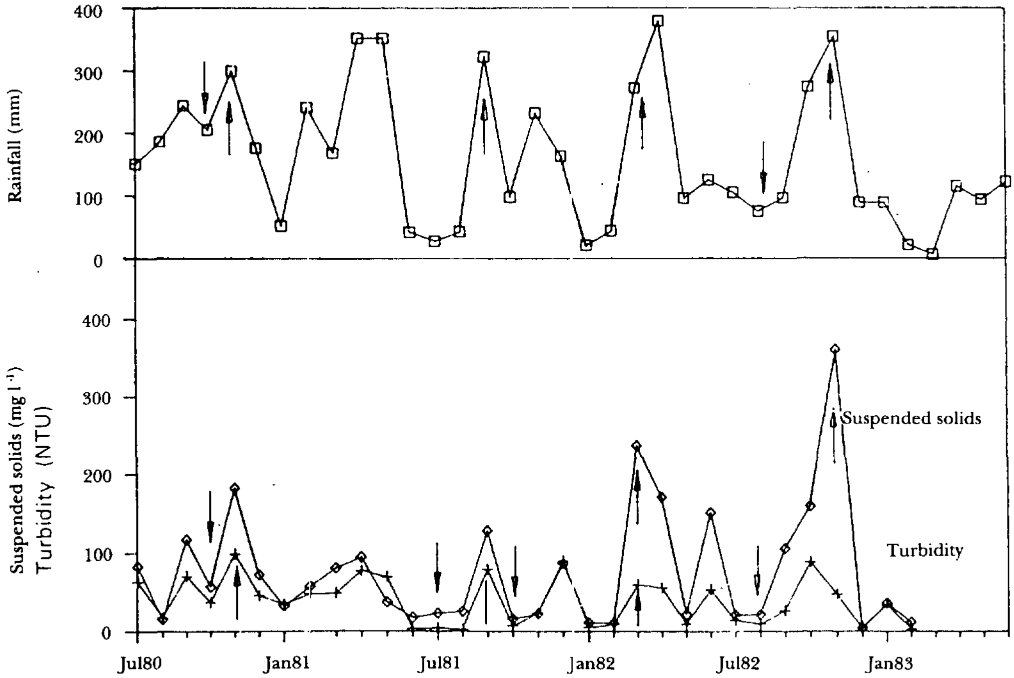

Figure 3. Relationships between overall monthly means of suspended solids, turbidity, and monthly rainfall in C1 during the calibration period (arrows indicate months having most obvious relationship)

As shown in Figure 4a, about 50 to 60% of the samples during the calibration period registered suspended solids concentrations below 20 mg l^{-1}. The distribution pattern remained quite the same during the post-logging period for these lower ranges. In contrast, the percentage of events with higher ranges of concentrations increased substantially after logging as illustrated by the distint shift to the right of the curves for C1 and C3. In the first year after logging, the curve for C1 flattened at approximately 85% level, i.e. 15% of the remaining samples registered suspended solids concentration over 300 mg l^{-1} (Figure 4b). Some degree of recovery was, however, observed in the second year after logging as indicated by the fact that the frequency distribution curves for C1 and C3 reverted somewhat towards the curve for C2 (Figure 4c).

Monthly mean concentrations during stormflow period were many times higher than during baseflow period (Figure 5), suggesting a greater runoff transporting capacity during wet months. In C1, mean stormflow concentrations increased substantially from an average of 119 mg l^{-1} during the calibration period to 501 mg l^{-1} in the first year after logging whereas corresponding values for C2 did not change significantly and modest increase up to 79 mg l^{-1} was observed for C3 (Table 3). In the second year, mean stormflow concentration for C1 was still about five times higher than the pre-logging level and it remained high throughout the recovery period. Conversely, the annual mean stormflow of suspended solids in C3 showed only marginal increases against the control. Unlike stormflow, baseflow generally contains low concentration of suspended solids. The monthly mean during baseflow period seldom exceeded 20 mg l^{-1}, even immediately after the logging operations.

Table 3. Annual mean of suspended solids concentrations (mg l^{-1}) in the logged and unlogged catchments at Berembun Forest Reserve

Year	Conventional logging (C1)	Control (C2)	Supervised logging (C3)
		Overall mean	
1980/81	70.88(47.2)	43.53(27.2)	66.66(46.3)
1981/82	75.95(77.8)	25.27(9.5)	34.20(22.7)
1982/83	90.69(121.9)	51.69(60.3)	43.65(43.97)
Logging			
1983/84	386.05(335.2)	32.02(23.6)	71.70(77.4)
1984/85	244.07(365.2)	68.52(67.7)	98.51(103.4)
1985/86	157.30(161.9)	46.56(47.3)	77.25(86.0)
1986/87	199.58(148.2)	97.59(66.9)	101.85(86.3)
1987/88	360.19(296.5)	147.86(120.4)	57.77(147.5)
		Baseflow mean	
1980/81	12.46(4.9)	12.86(7.7)	14.84(8.1)
1981/82	19.62(6.2)	18.50(5.0)	18.71(6.8)
1982/83	11.47(8.6)	6.49(4.0)	8.58(8.0)
Logging			
1983/84	10.11(7.3)	5.54(3.4)	5.82(4.2)
1984/85	12.89(8.7)	4.59(2.6)	5.79(3.9)
1985/86	5.62(3.2)	3.77(2.8)	3.76(1.9)
1986/87	13.39(12.7)	7.29(5.4)	7.92(7.1)
1987/88	14.98(12.5)	10.92(10.8)	6.36(2.3)
		Stormflow mean	
1980/81	85.49(47.7)	54.77(30.7)	68.41(53.0)
1981/82	123.79(111.2)	26.78(11.9)	42.22(25.3)
1982/83	174.24(186.1)	71.05(66.7)	65.22(49.83)
Logging			
1983/84	501.62(335.9)	40.24(22.8)	79.16(79.5)
1984/85	507.25(427.3)	118.50(60.3)	171.90(89.5)
1985/86	253.05(153.4)	73.98(47.3)	126.00(88.8)
1986/87	271.62(120.8)	135.02(60.42)	122.06(88.5)
1987/88	510.00(273.1)	173.25(146.5)	176.60(156.6)

Note: Standard deviations of the monthly values are given in parentheses.

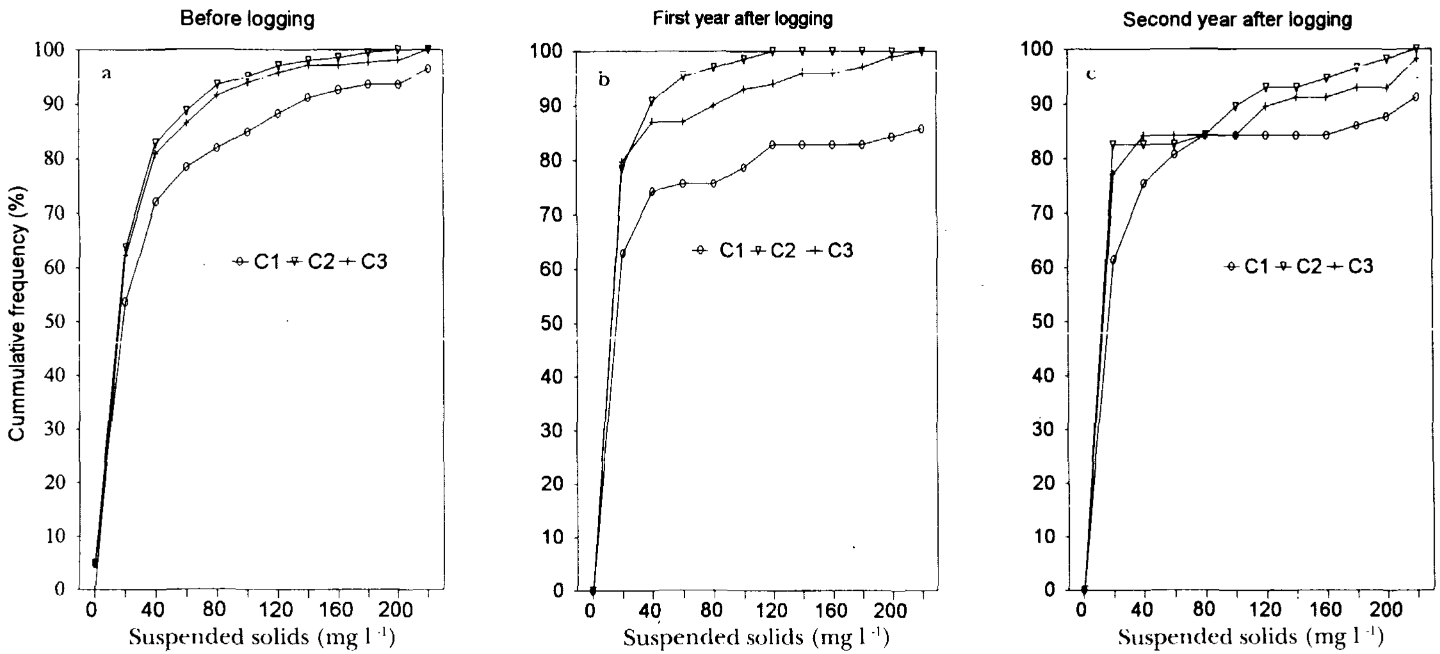

Figure 4. Frequency distribution curves of suspended solids concentrations (mg l-1) for C1, C2 and C3

Table 4. Summaries of the two samples test for detecting changes in the monthly means of streamwater quality parameters

Period	Test	Conventional logging (C1)	Control (C2)	Supervised logging (C3)
		Suspended solids (mg l $^{-1}$) Overall mean		
C	w	77.73^{ns}	38.72	48.30^{ns}
T	w	315.06**	50.94	85.11^{ns}
R	w	239.02**	97.34	112.29^{ns}
		Baseflow mean		
C	t	14.74^{ns}	13.19	14.20^{ns}
T	l	9.06**	5.11	4.90^{ns}
R	w	11.33**	7.33	6.01^{ns}
		Stormflow mean		
C	l	119.93**	49.51	59.13^{ns}
T	w	503.81**	92.46	115.23^{ns}
R	l	351.45**	132.68	143.10^{ns}
		Turbidity (NTU) Overall mean		
C	l	39.11^{ns}	25.89	24.51^{ns}
T	l	150.01**	26.47	46.45^{ns}
R	l	61.51**	29.37	29.74^{ns}
		Baseflow mean		
C	w	6.11^{ns}	6.26	6.76^{ns}
T	l	21.48**	6.51	11.42*
R	w	9.97**	6.36	6.47^{ns}
		Stormflow mean		
C	w	54.60**	35.01	35.24^{ns}
T	w	265.91**	42.12	75.02^{ns}
R	l	93.86**	40.08	40.02^{ns}

Note: The test involved comparing monthly means of the control and a logged catchment.
t: t-test without transformation
l: t-test but data were transformed to Log_e
w: Wilcoxon Rank-Sum test
ns: Not significant at p=0.05
*: Significant at p=0.05
**: Significant at p=0.01
C,T,R: Calibration, Transition and Recovery periods respectively

Impact on turbidity

Prior to logging, overall monthly means of turbidity for all catchments ranged from 3 to 99 NTU and averaged 54 NTU. Monthly mean patterns for turbidity were

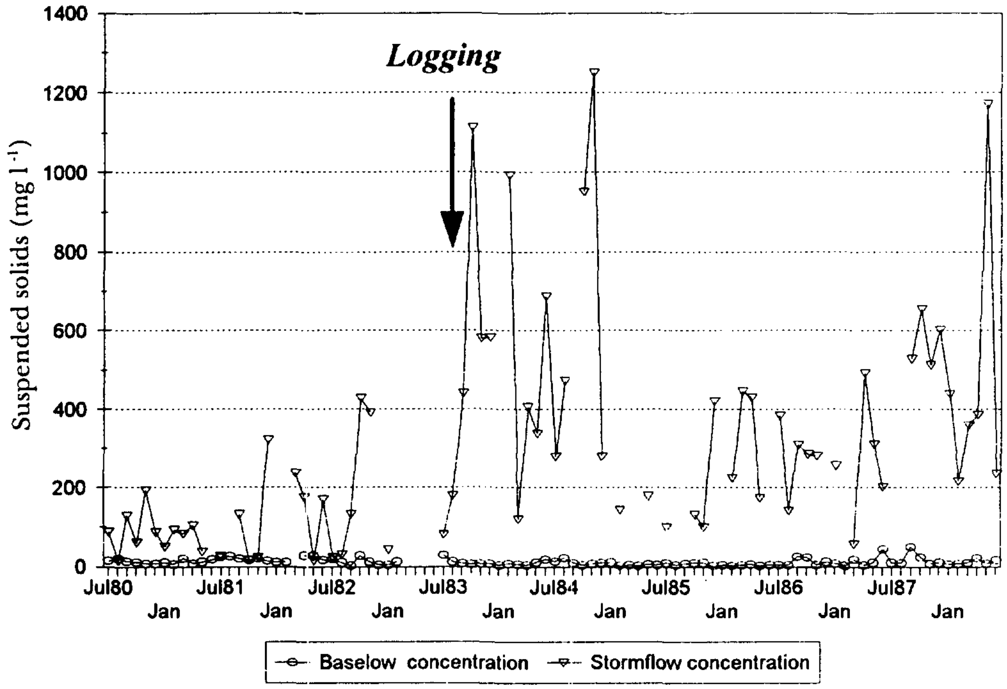

Figure 5. Baseflow and stormflow monthly means of suspended solids (mg l^{-1}) in C1

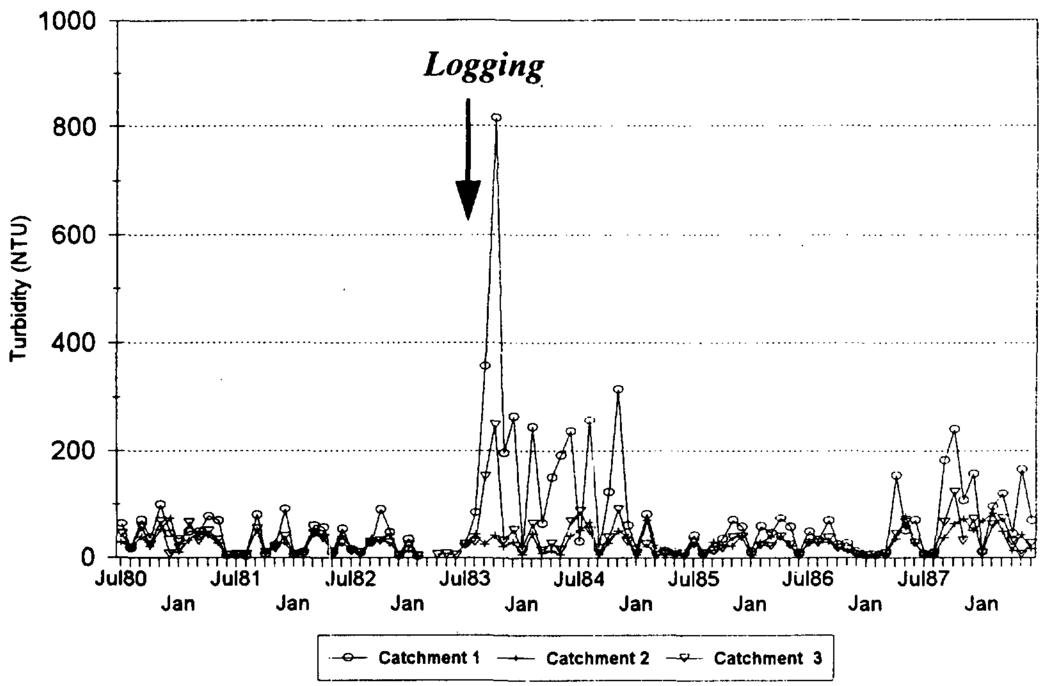

Figure 6. Overall monthly mean of turbidity (NTU) in C1, C2 and C3

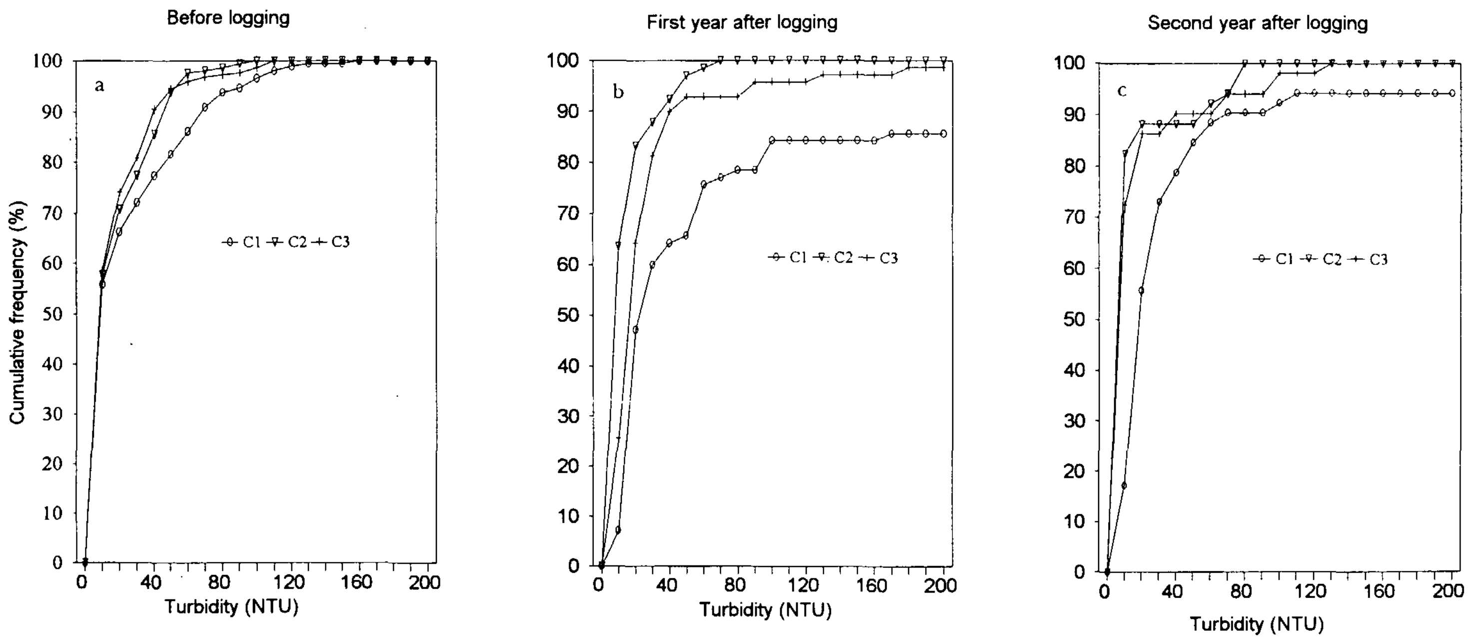

Figure 7. Frequency distribution curves of turbidity (NTU) for C1, C2 and C3

quite similar to the patterns for suspended solids, which followed the monthly rainfall (Figure 3). Remarkable increases in turbidity were observed in the first year after both the conventional and closely-supervised logging operations (Figure 6). The mean overall turbidity in the first year after logging increased by approximately 9 times for C1 and 2.5 times for C3 that of the control catchment (Table 5). The highest overall monthly mean (940 NTU) was recorded for C1 in October 1983 which coincided with a high monthly rainfall of 247 mm. The corresponding value for C3 was 265 NTU while that for the control was only 47 NTU. In the second year after logging, the mean overall turbidity for the supervised catchment decreased remarkably, approaching the value for the control catchment. Nevertheless, turbidity levels for C1 were still about three times higher in the second year, and persisted even in the fifth year after logging (Table 5).

Table 5. Annual means of streamwater turbidity (NTU) in the logged and unlogged catchments

Year	Conventional logging (C1)	Control (C2)	Supervised logging (C3)
		Overall mean	
1980/81	51.33(26.6)	32.86(19.6)	35.73(22.1)
1981/82	33.68(32.5)	23.35(18.3)	22.33(17.7)
1982/83	28.92(29.1)	19.24(15.7)	14.64(11.2)
Logging			
1983/84	220.73(214.3)	25.43(14.8)	62.10(11.2)
1984/85	79.29(103.6)	27.50(26.3)	30.81(31.1)
1985/86	40.50(24.5)	23.64(13.0)	22.51(12.9)
1986/87	43.06(41.9)	22.80(21.2)	23.86(18.9)
1987/88	100.98(75.8)	41.68(7.9)	42.86(36.9)
		Baseflow mean	
1980/81	6.17(2.4)	6.09(2.6)	7.57(3.1)
1981/82	6.35(2.4)	6.74(2.0)	6.84(1.9)
1982/83	5.68(2.7)	5.84(3.9)	5.87(1.9)
Logging			
1983/84	23.25(9.1)	7.41(2.2)	13.93(6.2)
1984/85	19.71(9.4)	5.70(1.7)	8.91(3.2)
1985/86	9.88(2.9)	8.44(7.7)	7.07(3.1)
1986/87	10.05(2.7)	6.03(2.7)	6.71(2.3)
1987/88	9.98(4.7)	4.61(2.3)	5.65(1.8)
		Stormflow mean	
1980/81	60.15(22.7)	38.66(19.4)	44.33(20.7)
1981/82	57.61(31.7)	34.73(16.7)	32.09(15.3)
1982/83	26.17(28.7)	28.71(15.2)	21.31(9.3)
Logging			
1983/84	295.50(239.9)	30.00(13.9)	72.44(72.6)
1984/85	211.67(153.4)	64.33(13.5)	79.75(36.0)
1985/86	64.99(13.6)	33.55(7.3)	32.98(8.4)
1986/87	67.14(42.2)	32.18(21.6)	29.81(19.7)
1987/88	140.73(76.9)	51.30(28.8)	50.80(38.6)

Note: Standard deviations of the monthly mean values are given in parentheses.

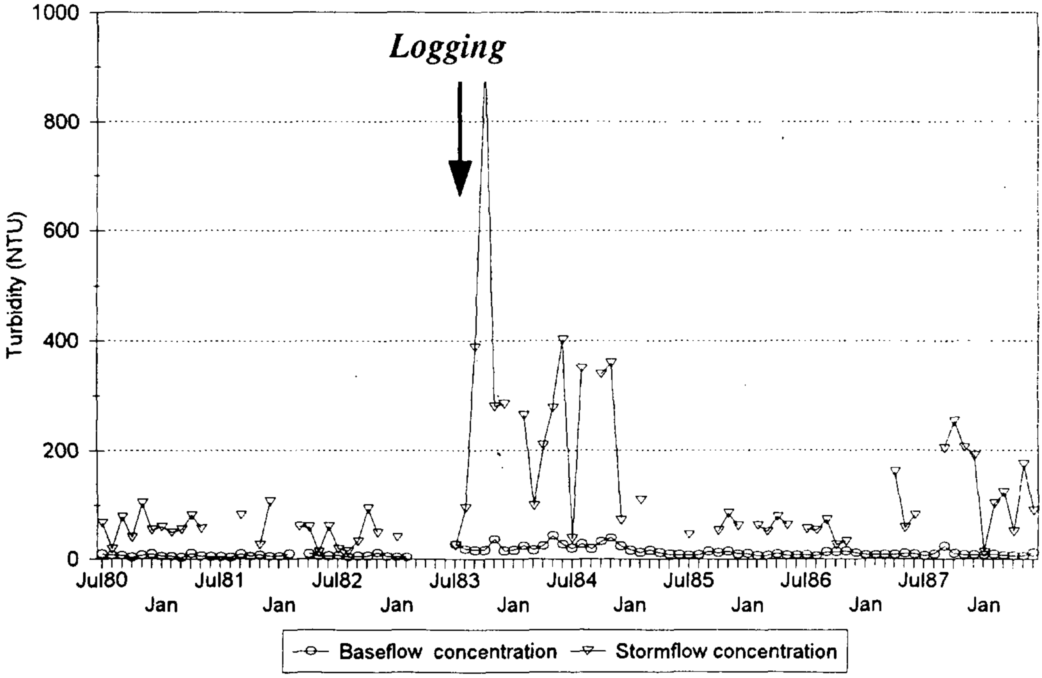

Figure 8. Baseflow and stormflow monthly means of turbidity (NTU) in C1

Streamwater during the calibration period was generally less turbid with 55 to 60% of the samples having turbidity values below 10 NTU (Figure 7a). The percentage, however, decreased in the first year after logging to about 8% for C1 and 25% for C3 whereas the control catchment more or less maintained its percentage at 65% (Figure 7b). In the second year, the curves for both C1 and especially C3 moved closer to the curve for C2. Nevertheless, C1 still exhibited a relatively greater percentage for higher ranges of turbidity values (Figure 7c).

Monthly mean turbidity during baseflow for the pre-logging period ranged from 2 to 15 NTU. Apparently, logging operations imposed minimal effect on the baseflow turbidity, for the highest monthly mean recorded during the first year after the conventional logging was only 43.76 NTU. Corresponding values in the control and the closely supervised catchment were 4.63 and 9.21 NTU respectively. Two years after logging, the baseflow in the treated catchments was relatively clear despite turbidity levels still being significantly different from that of the control (Table 4).

Stormflow water quality was characterized as turbid, especially after logging period (Figure 8). Annual mean turbidity during stormflow period in the first year after logging was almost ten times in C1 and over two times in C3 that of the control catchment. In the second year, the closely-supervised catchment recorded an annual mean of 79 NTU during stormflow period, which was quite close to the value for the control (64 NTU). In contrast, the annual means for catchment logged by the conventional method (C1) were still approximately four times higher in the second year after logging and between two and three times in the subsequent years.

Discussion

The large variation in the monthly means of suspended solids and turbidity could arise from the differences in storm rainfall. Solids concentration also varies with the value of instantaneous discharge on hydrograph, whereby maximum concentrations are usually attained just before or during the peakflow (Gregory & Walling 1973, Walling 1977), with concentrations on the rising limb generally higher than those on the falling limb (Douglas *et al.* 1992). On a long term basis the bulk of solids and sediments transport occurs during infrequent high intensity storms (Douglas 1970, O'Loughlin *et al.* 1978, Douglas *et al.* 1992). The storm runoff especially during larger storm events enhanced stream transporting capacity to levels strong enough to evacuate bedload or coarser particles that are usually deposited during periods of low flow (O'Loughlin *et al.* 1978, Ashmore & Day 1988). On the other hand, the lower ranges of concentrations were mostly attributed to samples during base flow periods where the sources of solids were limited to natural scouring of stream beds and stream banks.

Logging roads and skid-trails have been well identified as the main sources of solids and other forms of non-point sources of pollution (Megahan & Kidd 1972, Dunne 1977, Gilmour 1977). Raindrops loosened and detached soil particles while storm runoff on the compacted surfaces of logging roads carried these particles into streams. However, the fact that the increases in suspended solids and turbidity levels were rather moderate and short-term suggest a less extensive nature of the selective logging operations in the closely-supervised catchment. This can be judged from the small percentage (5.1%) of soil disturbances in the catchment area coupled with the institution of stricter conservation measures.

In this study the relative importance of the various conservation measures imposed was not evaluated individually. However, the effectiveness of buffer strips in ameliorating the impact of logging on sediment transport and hydrological attributes has been highlighted repeatedly (e.g. Cornish 1975, Corbett *et al.* 1978). The riparian zone generally serves as the primary source of storm runoff in undisturbed forested terrain with well-drained soil (Kirkby & Chorley 1967). As such, riparian zone may become a major source of solids once the vegetations are removed. Therefore, the retention of vegetations, especially the undergrowth provides superb protection to the soil near stream channels. Furthermore, undergrowth helps lighten the errosive force of overland flow and may trap materials from upslope on their way to the stream channel (Clinnick 1985). Erosion rates on logging roads in the closely-supervised catchment were presumed to be much lower compared with those in the conventionally logged catchment. Apart from the low road gradient, the series of cross-drains were able to cut down the kinetic energy of storm runoff on logging roads, thus alleviating the development of rills and gullies.

Table 6. Sediments/solids concentrations in catchments affected by forestry activities in Peninsular Malaysia

Catchment	Treatment	Area (ha)	Sediment (mg l^{-1}) Baseflow	Stormflow	Note
1. Kedah					
- Sg.T.Pawang	Forested	1810	4.5	-	-
- Sg. Bujang	Logging in progress	875	17.5	94	A
2. Ulu Gombak F.R., Selangor					
- Sg. Gabok	Forested	574	9.9	114	-
- Sg. Semaping	Recently logged	326	12.2	679	B
- Sg. Batu Asah	Logged-over	356	15.6	1595	C
3. Sg.Tekam, Pahang					
- Catchments A,B,C	Secondary forest	36,95,57	(21-112)+		D
4. Sg.Tekam, Pahang					
- Catchment A	Forest conversion	36	(24-519)+	(73-18808)+	E
- Catchment B	Forest conversion	95	(14-300)+	(198-8126)+	F
5. Air Hitam F.R., Selangor					
- Catchment A	Recently logged	730	8.5	187	G
- Catchment B	Logged-over	470	5.6	41	H
6. Ulu Langat F.R., Selangor					
- Catchment A	Logged-over	309	8.2	1037	I
- Catchment B	Logging in progress	136	22.2	6430	J
7. Berembun, Negri Sembilan					
- C1	Unsupervised logging	13.3	9.1	504	K
- C2	Forested	4.6	5.1	92	-
- C3	Supervised logging	30.8	4.9	115	L

References:
1&2. Salleh *et al.* (1983), 3. Peh (1981), 4. DID (1986), 5. Lai & Shamsuddin (1985), 6. Lai & Rentap (1987), 7. this study.

Notes:
Values for sites 1,2,3,4 and 7 were suspended solids (ovendried at 105-108 °C) whereas site 5 and 6 were suspended sediment (ignited at 550 - 600 °C). Solids values are expected to be higher because of the inclusion of organic fraction.
+: Range of individual samples.
A: Logging started in 1974 to 4/78, data collection from 5/75 to 4/78.
B: Logging started in 4/75 to mid 1977. Data collection from 1/76 to 12/78.
C: Logging between 1974 and 4/75. Data collection from 1/76 to 12/78.
D: Regenerated forest.
E: Activities include: logging, under brushing, burning, mechanical stacking, and planting of oil palm and cover crop. First year data.
F: As E (above) but data is for a three-year average after conversion.
G: First logging in 1930 and second logging in 1983, 35% affected. Six months data in 1984.
H: As G (above) but second logging in 1982 and 14% affected. Six months data in 1984.
I: First logging in 1940, second logging in 1970, 60% affected. Six months data in1985.
J: Logging was on going since 1979, 50% affected. Six months data in 1985.
K: Logging completed within a month, 40% extraction. Two years data after logging.
L: As O but control measures imposed: buffer strip, cross drain and road alignment, 33% extraction.

Another factor that contributed to the relatively fast recovery rate of water quality especially in the closely-supervised catchment was the rapid establishment of undergrowth, and secondary succession of pioneer species. Undergrowth is vital in dissipating raindrop impact, regulating sediment movement, and improving soil infiltration capacity (Kirkby & Chorley 1967). Elsewhere in Malaysia, a secondary succession of pioneer trees such as *Trema orientalis*, *Malatus paniculatus*, *Macaranggа* spp. and wild banana was reported by Kamaruzaman and Nik (1986) on skid trails two years after their abandonment. In Indonesia, Ruslan and Manan (1980) found that despite a high erosion rate on a newly constructed skid-trail (12.9 t ha^{-1} y^{-1}), the rate of recovery was quite rapid: for a skid-trail that had been abandoned for three years, erosion had dropped to 3.2 t ha^{-1} y^{-1}. Similarly, Baharuddin (1992) observed considerable reduction in erosion rate on skid-trail in Jengka, Peninsular Malaysia, from 10.1 t ha^{-1} y^{-1} in the first year after logging to 2.1 t ha^{-1} y^{-1} in the second year. Six months after logging, the plot on skid-trail was covered by grass by approximately 60%, and a 100% coverage was attained within a year. Nevertheless, it has been demonstrated in Sabah, Malaysia, that the soil on former skidder tracks may remain compacted for many years and such areas may remain a source of enhanced stormflow which will have a bearing on stream transporting capacity (Malmer & Grip 1990, Van der Plas & Bruijnzeel 1993).

Local observations for suspended solids/sediments concentration in catchments affected by logging activities and forest conversion are summarized in Table 6. The baseflow concentrations reported for the present site were comparable with the reported values associated with logging activities but were much lower when compared with forest conversion. However, the stormflow concentrations fall within the lower ranges especially for the closely-supervised logging method (C3). The lower means for stormflow concentration could be associated with less intensive sampling during stormflow periods. Douglas *et al.* (1992) noted the need to conduct detailed flow proportion sampling during all storm events to obtain the correct estimate of suspended sediment concentrations. The present grab sampling technique might miss most of the storm peaks where maximum concentration of suspended solids is expected to occur.

Because suspended particles and other particles are often the main contributor to turbidity (Hem 1970), any changes in suspended solids concentration would have a direct influence on turbidity. At this juncture, it is worthwhile to compare the turbidity values of the present study with those from studies in the temperate regions as no such study has been reported in the tropics. Reinhart *et al.* (1963) at the Fernow Experimental Forest, West Virginia and Pearce and Griffiths (1980) at Okarito Forest, New Zealand, found that increases in turbidity might be reduced when stricter conservation measures were imposed. Interestingly, leaving a complete cover of vegetation debris following clear-cutting at the Hubbard Brook Experimental Forest, USA could regulate the detachment of soil particles, thus maintaining the clarity of stream water (Likens *et al.* 1970, Bormann *et al.* 1974).

The most critical zones with regard to solids and sediments production are skid-trails, log landing areas and logging roads especially when poorly maintained (Fredriksen *et al.* 1975, Brown 1974). Therefore, these sediment source areas must be given special consideration in forest planning and operation (Gilmour 1971,, Megahan & King 1985).

Conclusion

Streamwater during stormflow periods generally showed high levels of suspended solids and turbidity even before logging operation started. However, the baseflow over the eight years was of clear quality with levels of suspended solids and turbidity seldom exceeding 20 mg l^{-1} and 10 NTU respectively. Generally, streamwater quality was seriously impaired in the first year after conventional logging method with increases by approximately twelve and nine times observed for suspended solids and turbidity levels respectively. The levels were maintained high even five years after logging. Conversely, the closely supervised logging which imposed additional conservation measures such as higher cutting regimes and leaving buffer strips unlogged resulted in moderate and short-term increases in suspended solids and turbidity levels. For supervised logging, the recovery period for the two parameters was attained within two years. This study reveals that increases in streamwater suspended solids and turbidity levels which are usually associated with logging activities can be significantly reduced if proper control measures are imposed.

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