SURFACE RUNOFF AND SOIL LOSS FROM A SKID TRAIL AND A LOGGING ROAD IN A TROPICAL FOREST

Baharuddin K.,

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

Mokhtaruddin A. M. & Nik Muhamad M.

Faculty of Agriculture, Universiti Pertanian Malaysia, 43400 Serdang, Selangor, Malaysia

Received July 1993

BAHARUDDIN, K., MOKHTARUDDIN, A.M. & NIK MUHAMAD, M. 1995. Surface runoff and soil loss from a skid trail and a logging road in a tropical forest. Skid trails and logging roads have been identified as main sources of sediment in stream water of logged-over forests. Scientific information on these problems is still lacking particularly in the tropical forest in Malaysia. Surface runoff and soil loss were measured using erosion plots from an undisturbed forest, a skid trail and a logging road. Results from a two-year study revealed that the average surface runoff from the undisturbed forest, skid trail and logging road were 62.9, 391.4 and 545.2 mm y^{-1} respectively. The values were 2.3, 14.5 and 20.3% of the total rainfall. This surface runoff generated 453.7, 10 069.7 and 13 340.7 kg ha^{-1} y^{-1} of soil loss from the undisturbed forest, skid trail and logging road respectively in the first year after logging. In the second year, the losses decreased by 80% to 2111.3 kg ha^{-1} y^{-1} for the skid trail and by 77% to 3146.7 kg ha^{-1} y^{-1} for the logging road. Drastic reduction in the soil loss was probably due to a rapid recovery in soil stabilization arising from fast re-establishment of ground cover and emergence of seedlings on the logging road and skid trail.

Key words: Surface runoff - erosion - logging road - skid trail - tropical forest

BAHARUDDIN, K., MOKHTARUDDIN, A.M. & NIK MUHAMAD, M. 1995. Air larian permukaan dan tanah terhakis di jalan tarik dan di jalan balak di hutan tropika. Jalan tarik dan jalan balak telah dikenalpasti sebagai punca-punca utama sedimen dalam air sungai di hutan telah dibalak. Maklumat saintifik berhubung dengan masalah ini masih kurang terutama bagi hutan tropika di Malaysia. Air larian permukaan dan tanah terhakis telah diukur menggunakan petak-petak hakisan di hutan asli, jalan tarik dan jalan balak. Keputusan dari dua tahun kajian menunjukkan purata air larian permukaan dari hutan asli, jalan tarik dan jalan balak adalah 62.9, 391.4 dan 545.2 mm th^{-1}, masing-masing. Nilai ini bersamaan 2.3, 14.5 dan 20.3% daripada jumlah hujan. Air larian permukaan ini menyebabkan 453.7, 10 069.7 dan 13 340.7 kg ha^{-1} th^{-1} tanah terhakis masing-masing dari hutan asli, jalan tarik dan jalan balak bagi tahun pertama selepas pembalakkan. Dalam tahun kedua, tanah terhakis telah berkurangan sebanyak 80% kepada 2111.3 kg ha^{-1} th^{-1} dari jalan tarik dan sebanyak 77% kepada 3146.7 kg ha^{-1} th^{-1} dari jalan balak. Penurunan yang drastik ini mungkin disebabkan oleh kestabilan permukaan tanah akibat pertumbuhan semula tumbuhan tutup bumi dan anak-anak pokok di jalan tarik dan jalan balak.

Introduction

Forest logging modifies the ecological balance of a forest ecosystem. It compacts the soil and greatly reduces the infiltration rate. Many studies in temperate as well as in tropical regions have shown that forest logging operations cause an increase in surface runoff, sediment concentration and soil disturbance. Ponnadurai (1982) reported that selective logging in a wet zone of a forest catchment caused a significant increase in sediment yield by 74% and an increase in rainfall/runoff ratio, i.e from 0.40 in unexploited catchments to 0.54 in exploited catchments.

In Malaysia, Baharuddin (1988) reported that suspended sediment yield increased by 97 % following selective logging operations. In another study, Lai and Rentap (1986) found that the suspended sediment concentration from logged-over forest ranged from 3.5 mg l^{-1} during lowflow to 7688 mg l^{-1} in the peakflow. High suspended sediment concentration was observed during the stormflows. Such a high variation was also reported by Salleh *et al.* (1981). The study found that the sediment concentration in logged-over catchments at Kedah and Selangor ranged from 3.1 to 53.9 mg l^{-1}, and from 126.0 to 5958.0 mg l^{-1} respectively.

All these studies carried out on a watershed basis were unable to indicate the main sources of sediment, whether from road construction, tree felling, skidding or other factors. Identification of sediment sources is vital so that logging operations can be modified in order to minimize soil erosion.

In fact, logging roads, skid trails and skidding operations were the major contributors to these problems. In other parts of the world, this aspect has been intensively studied. For example, Anderson and Potts (1987) reported that suspended sediment concentration increased by 7.7 fold in the first year following road construction. The sediment yield in a sloping area in Central Idaho, United States, increased by 750 times following the construction of logging roads (Megahan & Kidd 1972). Further more, Megahan (1972) reported that surface erosion on roads increased by 220 times whereas the increase in sediment for the entire watershed was only 45 times. In Sabah, Douglas *et al.* (1992) reported that selective commercial logging changed the monthly suspended sediment yield ratio from 1:1 before disturbance to 4:1 after logging roads had been built across the head of the catchment.

As stated earlier most of these studies were based on experimental watersheds. There is still a lack of scientific information on soil loss from logging roads and skid trails, particularly in Malaysia. Such information is necessary for the formulation of preventive and soil erosion control measures in sustainable forest management. This paper quantifies the amount of surface runoff and soil loss from a skid trail and logging road in a logged-over forest using small plots.

Site description

Location and topography

The study area was located at the Jengka Experimental Basin in Tekam Forest Reserve, Pahang, Malaysia, approximately 250 km northeast of Kuala Lumpur, at about 4° 15' N and 102° 37' E with elevation ranging from 80 to 325 m above sea level. The area was about 56.5 ha. It had a southeastern aspect and consisted of three catchments (Figure 1). The topography was undulating to hilly. The average slopes were 28, 36 and 34% for catchments one, two and three respectively.

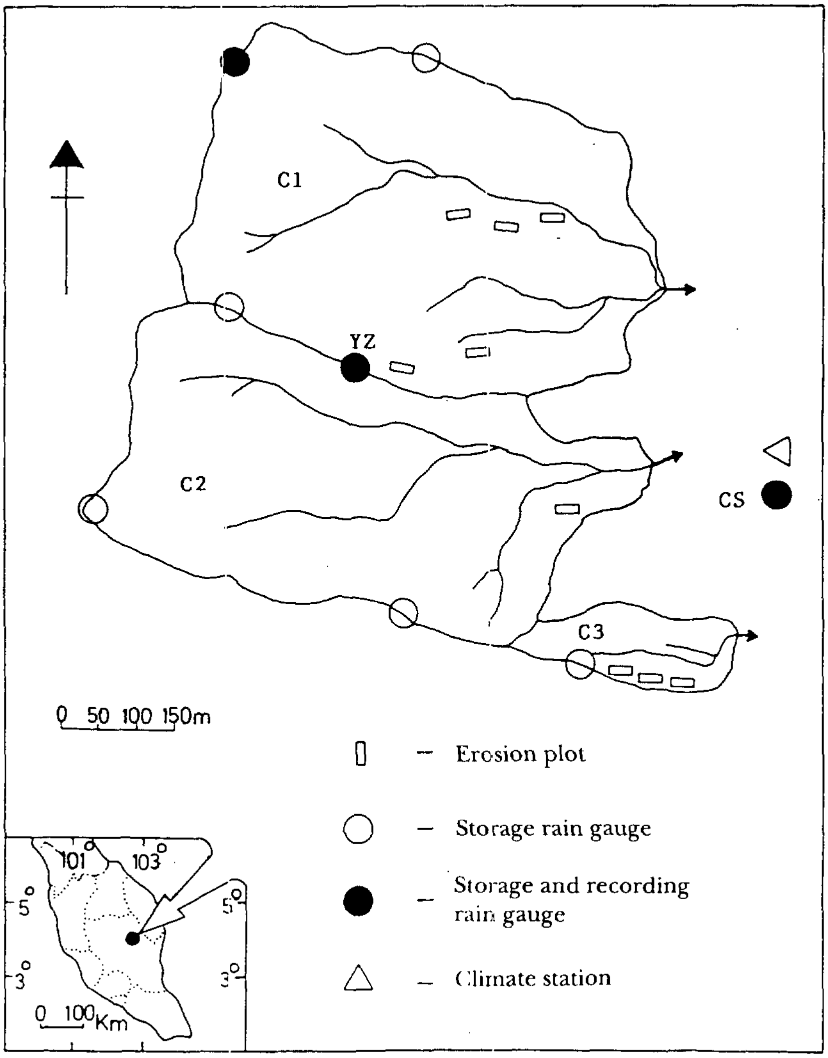

Figure 1. Erosion plots and instrument layout at the Jengka Experimental Basin

Geology, soil and vegetation

The geology of the basin is underlain by Upper to Middle Triassic sedimentary rocks with parent materials predominantly made up of shales and sandstones (Abdul Rahim *et al.* 1986). The soils in this area can be classified as sedentary soils derived from pyroclastic and volcanic rocks which are interbeded mainly with shales and sand stones of argillaceous strata and arenaceous materials giving rise to clayey and sandy textures respectively (Amir Husni 1989). The major soil series found in the area are Tajau (Typic Paleudult), Jempol (Typic Paleudult), Bungor (Typic Paleudult), Jengka (Rhodic Paleudult) and Jeram (Typic Paleudult). The vegetation is typical of hill dipterocarp forest. The forest is dense and made up of three layered canopy; the upper emergent storey or first layer is about 30 - 40 m high, the main storey or second layer about 20 - 30 m high and the ground storey or lower layer 0 - 20 m high (Wyatt-Smith 1963).

The dominant species found in the area are *Shorea leprosula, Shorea bracteolata, Dipterocarpus cornutus, Eugenia* species and *Cryptocarya* species (Abdul Rahim *et al.* 1986). The lower layer consists of palms, shrubs and is dominated by saplings of the upper two storeys.

Methodology

Establishment of the erosion plots

Nine erosion plots, with a total area of 0.007 ha and measuring 22 m by 3 m, were established on three different sites, namely a logging road, a skid trail and an undisturbed forest as a control. The control plots were located in an undisturbed area fully covered by vegetation and thick litter layer, whereas the skid trail and logging road plots were partly covered and some were totally exposed. Each plot was bounded by a polyvinyl chloride (PVC) sheet of 0.2 cm thickness and 20 cm width of which half was inserted into the ground. At the lower end of each plot a PVC trough was installed to direct runoffs and sediments from the plot into the collecting tank. A series of collecting tanks connected to each other were installed in order to collect the total surface runoff. On each site, plots were placed in three different slopes of 10, 20 and 30 %. The logging road in this study was a path used by the "San-Tai-Wong" or winched lorry for transporting logs from temporary landing areas to the log yard. The skid trail was a primary track used by a crawler tractor to skid or haul the logs to temporary landing areas.

Data collection

Rainfall was measured at two rainfall stations, namely YZ and CS (Figure 1). The stations were equipped with automatic recorders. The gauges were placed on 11 m poles to obtain the needed exposure, free from vegetative cover. The total surface runoffs collected in the collecting tanks were measured and about 500 milliliters of water sample were taken by grab-sampling technique to determine the sediment concentration on a storm or daily basis. Soil loss was calculated by the product of the sediment concentration (mg l^{-1}) and volume of surface runoff (l), and expressed in kilogram per hectare (kg ha^{-1}).

Results and discussion

Rainfall

The total annual rainfalls for the two-year study period were 3084 and 2308 mm y^{-1} respectively. The second year can be considered a dry year because the amount of rainfall received was less than the average annual rainfall for Peninsular Malaysia, 2670 mm (Dale 1959). The monthly rainfall distribution showed that the lowest rainfall occurred in February 1989 (27.8 mm), while the highest was in November 1988 (536.3 mm) (Figure 2).

Generally, the monthly rainfall distribution was bimodal with the two maxima occurring during April and November. Figure 2 also gives the number of days with measurable rainfall (0.5 mm or more). The highest number of rain days was 24 in November 1987. December 1988 had the lowest number of eight days.

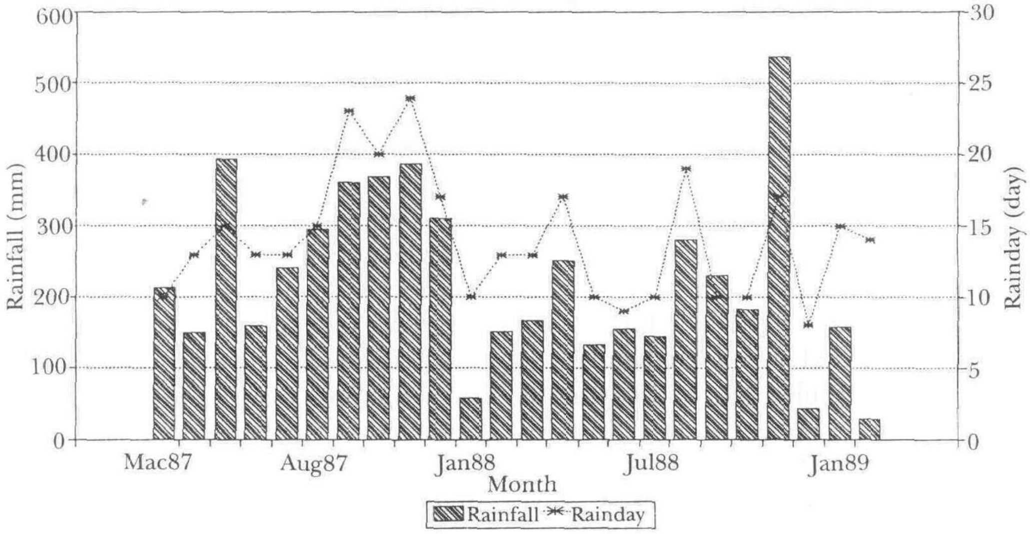

Figure 2. Monthly rainfall distribution during the two-year study period from March 1987 to February 1989

Surface runoff

The surface runoff for the undisturbed area was about 74.4 mm and 51.1 mm in the first and second year or 2.4 and 2.2% of the rainfall respectively (Table 1). These percentages are comparable to those obtained in the primary dipterocarp forest of Sarawak (2.0%) (Phang 1986). The low runoff rate on the undisturbed plots was probably due to soil characteristics, such as low bulk density, high total porosity, high organic matter content and high infiltration rate.

Table 1. Annual rainfall (P), runoff (Q) and runoff/rainfall coefficient from the undisturbed and disturbed sites of the Jengka Experimental Basin

Site	Period (year)	P (mm)	Q (mm)	Q/P (%)
Undisturbed forest	1st	3084.0	74.4	2.4
	2nd	2308.0	51.5	2.2
Skid trail	1st	3084.0	468.9	15.2
	2nd	2308.0	313.8	13.5
Logging road	1st	3084.0	604.8	19.6
	2nd	2308.0	485.6	21.0

The low surface runoff in the undisturbed forest was also probably influenced by the vegetative cover in the plots. Vegetative cover intercepts a certain amount of gross rainfall which thus subsequently evaporates to the atmosphere and hence reduces the amount of surface runoff.

The higher surface runoff on the logging road and skid trail was due to the compacted soil surface of the area as well as the absence of vegetative protection particularly in the first year after logging. A reduction in the second year was also mainly due to the emergence of seedlings on the plots. Vegetative cover tends to increase the infiltration rate by promoting a thicker soil cover, improving soil structure and reducing impact of raindrops on the ground surface.

As for the skid trail and logging road, there was no significant difference ($p<0.05$) in the runoff/rainfall between the first and the second years despite the presence of grass and other plant species which almost fully covered the plot in the second year. The above characteristics point to the fact that other than vegetative cover, topography and soil characteristics also influence the extent of surface runoff (Megahan & King 1975). In these plots, the role of vegetative cover as a protective agent may not be that effective to control the volume of surface runoff. Therefore, soil characteristics are apparently more important than vegetative cover in controlling surface runoff in these particular sites.

Generally, the values of runoff/rainfall increase as the slope increases, particularly on the disturbed areas, but not in the undisturbed forest (Table 2). Wendt *et al.*, (1986) reported that among the main factors affecting runoff and soil loss in experimental plots are slope, slope length and rainfall.

Figure 3 shows the mean monthly runoff/rainfall variations for the different treatments. The control plot shows a small variation of runoff/rainfall compared to the skid trail and logging road. It means that the runoff generated from the undisturbed forest had a low response to the amount of rainfall. This could be due to its high porosity and infiltration rate. On the other hand, runoff from the skid trail and logging road reacted positively to the amounts of rainfall because the soils were less porous and had a low infiltration rate.

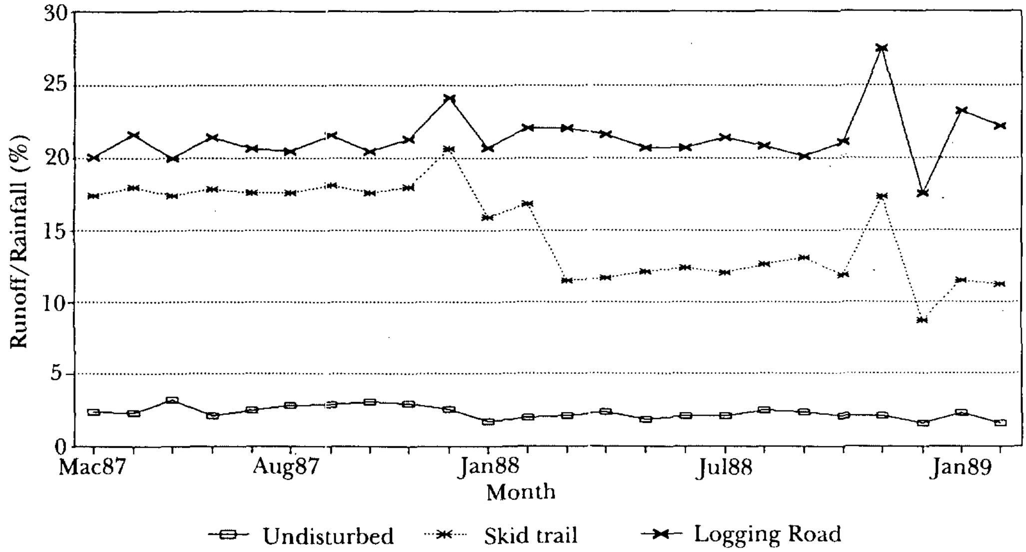

Figure 3. Variation in the monthly runoff/rainfall of the study plots

Soil loss

The total soil loss in the first year from the skid trail and logging road was 10 069.7 and 13 340.7 kg ha^{-1} y^{1} respectively (Table 3). In the second year, the amount of soil loss from the undisturbed forest, skid trail and logging road were 281.2, 2111.3 and 3416.7 kg ha^{-1} respectively. These values correspond to about 8 and 11 times that of the undisturbed area. During the first year these values were 22 and 30 times respectively. The reduction of soil loss was due to re-establishment of ground cover on the skid trail and logging road and might also be due to an extensive washing activity during the first year. The magnitude of soil loss depends primarily on the proportion of soil surface protected from the direct impact of rainfall by plant and litter (Meeuwig 1970). Rapid re-establishment of ground cover and the emergence of pioneering trees in one year after logging is a common sight in Malaysia (Zulkifli 1990).

The higher amount of eroded particles from the skid trail and logging road may be associated with the high bulk density. Bulk density influences erosion because porosity is inversely related to bulk density. Soils of high porosity have good infiltration characteristics and consequently produce less surface runoff and erosion. Under undisturbed forest, not only has the soil a higher total porosity but most of the pores are elongated in nature and are of bigger sizes (Baharuddin 1992).

Table 2. Annual rainfall and runoff characteristics of the undisturbed forest, skid trail and logging road

Period		Slope		
		10%	20%	30%
		Undisturbed forest		
First year	P(mm)	3084.0	3084.0	3084.0
	Q(mm)	66.8	71.0	83.3
	Q/P(%)	2.2 a*	2.3 a	2.7 a
Second year	P(mm)	2308.0	2308.0	2308.0
	Q(mm)	46.7	48.8	59.4
	Q/P(%)	2.0 a	2.1 a	2.5 a
		Skid trail		
First year	P(mm)	3084.0	3084.0	3084.0
	Q(mm)	314.1	462.9	629.8
	Q/P(%)	10.1 b	15.0 d	20.4 fg
Second year	P(mm)	2308.0	2308.0	2308.0
	Q(mm)	222.1	294.2	425.1
	Q/P(%)	9.6 b	12.7 c	18.4 d
		Logging road		
First year	P(mm)	3084.0	3084.0	3084.0
	Q(mm)	565.4	565.8	683.1
	Q/P(%)	18.3 ef	18.3 ef	22.1 g
Second year	P(mm)	2308.0	2308.0	2308.0
	Q(mm)	448.9	456.2	551.6
	Q/P(%)	19.4 e	19.7 e	23.8 g

P = Precipitation, Q = Surface runoff
* Means in each row followed by the same letters are not significantly different at $p<0.05$ as determined by Scheffe's multiple range test.

Table 3. Annual soil losses from the control and treatment plots of the Jengka Experimental Basin ($kg\ ha^{-1} y^{-1}$)

Site	1st year	2nd year
Undisturbed forest	453.7 a*	281.2 a
Skid trail	10 069.7 b	2 111.3 b
Logging road	13 340.7 b	3 416.7 b

* Means in each column followed by the same latter are not significantly different at $p<0.05$ as determined by Scheffe's multiple range test.

Generally, soil loss is highest during the first few months after road construction and drops rapidly in subsequent months (Leaf 1974, Ruslan & Manan 1980, Swift 1984, Fahey & Coker 1988). Leaf (1974) also concluded that in mountain watersheds most of the erosion occurred within a few years after disturbances. This time factor should be considered in land use planning and development in order to minimize soil erosion and water quality degradation. A similar pattern of soil loss reduction with time was also observed in this study for the skid trail and logging road.

The annual variations of monthly soil loss from the undisturbed forest, skid trail and logging road are illustrated in Figure 4. If the reduction in soil loss continues in subsequent years, the amount of soil loss from these logging tracks may be back to pre-logging conditions after three to four years. In Colorado, United States, it took six years for the sediment yield to approach the preharvest level (Leaf 1974).

Apparently, the study indicates that the logging road and skid trail were the main point sources of sediment yield in the logged-over forest particularly during the first year after logging operations. Thus it is suggested that in logging operations, logging roads and skid trails should occupy the smallest possible area in order to reduce soil erosion.

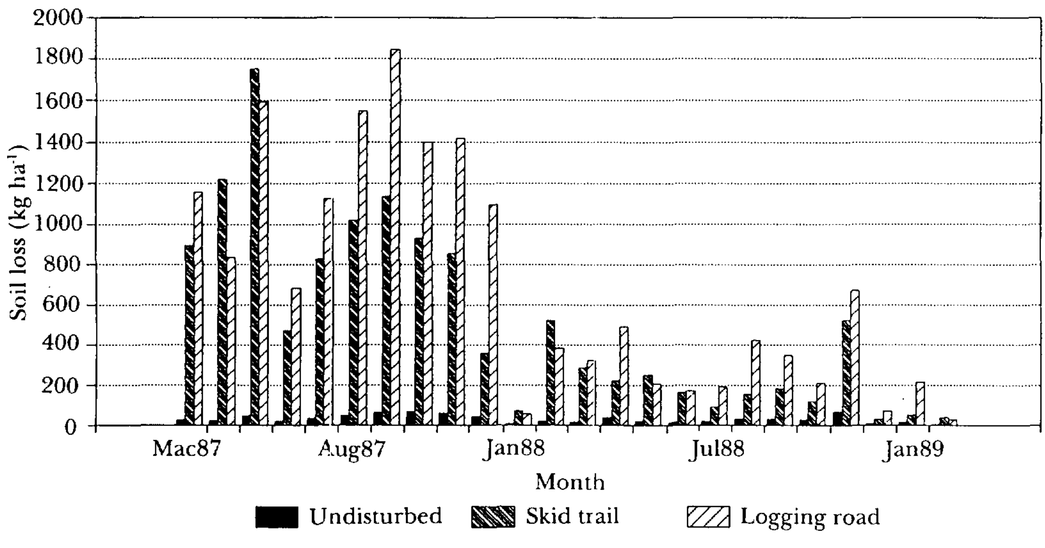

Figure 4. Monthly soil loss from the undisturbed forest, skid trail and logging road of the Jengka Experimental Basin

The annual soil losses from the plots for the different slopes of undisturbed forest, skid trail and logging road are shown in Tables 4, 5 and 6 respectively. As expected the sediment yield increased as the slope increased.

Table 4. Annual soil losses from the undisturbed forest on different slopes at the Jengka Experimental Basin (kg $ha^{-1} y^{-1}$)

Slope (%)	1st year	2nd year
10	435.1 a*	187.3 a*
20	432.4 a	270.9 a
30	493.6 a	385.4 a

* Means in each column followed by the same letters are not significantly different at p<0.05 as determined by Scheffe's multiple range test.

Table 5. Annual soil losses from the skid trail on different slopes at the Jengka Experimental Basin (kg $ha^{-1} y^{-1}$)

Slope (%)	1st year	2nd year
10	6 848.5 bc	1 116.7 a
20	3 881.3 ab	1 086.1 a
30	19 479.2 d	4 131.1 ab

* Means in each column followed by the same letters are not significantly different at p<0.05 as determined by Scheffe's multiple range test.

Table 6. Annual soil losses from the logging road on different slopes at the Jengka Experimental Basin (kg $ha^{-1} y^{-1}$)

Slope (%)	1st year	2nd year
10	6 624.7 ab	2 017.2 a
20	9 452.7 b	3 803.0 a
30	23 944.6 c	3 619.9 a

* Means in each column followed by the same letters are not significantly different at p<0.05 as determined by Scheffe's multiple range test.

For the skid trail, the soil losses from the 10 and 30 % slopes were 6848.5 and 19 479.2 kg $ha^{-1} y^{1}$ respectively (Table 5). In the first year, a significant difference ($p<0.05$) was observed between the 10 and 30% slope classes but there was no significant difference between the 10 and 20% slope classes. In the second year, there was no significant difference among all three slope classes. The same trend was observed in the logging road (Table 6).

The amounts of soil loss from the skid trail and logging road constructed on 30% slopes were significantly higher than from the road at 10 and 20% slopes. This phenomenon happened only in the first year after logging operations, but not in the second year. In addition slope angle did not influence the rate of surface erosion in the undisturbed forest. It shows that the plant and litter covers were the greatest deterrent to surface erosion. Similar findings were reported by Heede (1984) and Peh (1978).

The soil losses in the logging road and skid trail increased up to 20% steepness. Above 20% there was a sudden rapid increase in soil loss. Therefore, it is suggested that skid trails and logging roads should not be constructed on slopes exceeding 20%.

Conclusion

The reduction of soil loss may be due to soil stability and re-establishment of ground cover. It can be concluded that after forest harvesting operations higher soil loss is detected in the first year only and decreases in the subsequent years. Disturbed soils on the logging road and skid trail surfaces are the major sources of sediment yield in the area.

These unfavorable effects of forest harvesting could be minimized or reduced by proper design and construction of the logging roads. It is recommended that the skid trails and logging roads should not be constructed on slopes exceeding 20% and should occupy the smallest possible area. Logging operations should be avoided during the wet or rainy season. It is also suggested that control measures such as cross drains should be constructed on the logging road and skid trail immediately upon completion of forest harvesting to reduce erosion. A buffer zone along the streams should be also established. In addition, enforcement should be carried out during logging operations to ensure that the logging specifications are being followed to reduce the damaging environmental effects from the logging activities. If this practice is implemented during logging operations, a large amount of soil loss from logging roads can be prevented, particularly in the first year after forest harvesting.

Acknowledgements

This study was part of the first author's Master thesis at the Universiti Pertanian Malaysia, Serdang. We wish to thank the staff of the Hydrology Unit for their technical assistance. Thanks are also due to Abdul Rahim Nik and Wan Razali Wan Mohd for their invaluable comments on the manuscript.

References

ABDUL RAHIM, N., BAHARUDDIN, K. & AZMAN, H. 1986. Soil temperature regimes under mixed dipterocarp forest of Peninsular Malaysia. *Pertanika* 9(3) : 277 - 284.

AMIR HUSNI, M. S. 1989. Site fertility and carrying capacity in two Malaysian tropical forest reserves. Ph.D. thesis, University of Aberdeen, United Kingdom.

ANDERSON, B. & POTTS, F. 1987. Suspended sediment and turbidity following road construction and logging in Eastern Montana. *Water Resources Bulletin* 23(4): 681- 690.

BAHARUDDIN, K. 1988. Effects of logging on sediment yield in a hill dipterocarp forest in Peninsular Malaysia. *Journal of Tropical Forest Science* 1(1) : 56 - 66.

BAHARUDDIN, K. 1992. Effects of logging operations on soil erosion and soil physical properties in a hill dipterocarp forest of Peninsular Malaysia. M. Sc. thesis, Universiti Pertanian Malaysia, Serdang.

DALE, W.L. 1959. Rainfall of Malaya - Part I. *Journal of Tropical Geography* 27 : 1 -18.

DOUGLAS, I., SPENCER, T. , GREW, T., KAWI, B., WAIDI, S. & WONG, K. M. 1992. The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama Rainforest, Sabah, Malaysia. *Philosophical Transactions of the Royal Society* B 335 : 397 - 406.

FAHEY, B. D. & COKER, R. J. 1988. *Erosion and Sediment Production from Forest Roads in South-West Nelson.* What's New in Forest Research, No. 168. Forest Research Institute, New Zealand.

HEEDE, B.H. 1984. Sediment source area related to timber harvesting on selected Arizona watersheds. Pp. 123 - 130 in O'Loughlin, C.L. & Pearce, A.J. (Eds.) *Proceedings of the Symposium on Effects of Forest Land Use on Erosion and Slope Stability* . 7-11 May 1984. East-West Center, Honolulu, Hawai.

LAI, F. S. & RENTAP, S. 1986. Sediment concentration from two logged-over watersheds. Pp. 321-334 in Yusof, H. (Ed.) *Proceedings of the Workshop on Impact of Man's activities on Tropical Upland Forest Ecosystems.* 3 - 6 February 1986. Faculty of Forestry, Universiti Pertanian Malaysia, Serdang, Selangor.

LEAF, C. F. 1974. *A Model for Predicting Erosion and Sediment Yield from Secondary Forest Road Construction.* Research Note RM-274. United States Department of Agriculture, Fort Collins, Colorado.

MEEUWIG, R.O. 1970. *Sheet Erosion on Intermountain Summer Ranges.* USDA Forest Service Research Paper INT-85. Utah, USA.

MEGAHAN, W.F. 1972. Logging, erosion, sedimentation - Are they dirty words? *Journal of Forestry* 70 : 403 - 407.

MEGAHAN, W.F. & KIDD, W.J. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terain. *Journal of Forestry* 70(3): 136 -141.

MEGAHAN, W.F. & KING, P.N. 1975. Identification of critical areas on forest lands for control of nonpoint sources of pollution. *Environmental Management* 9(1) : 7 - 18.

PEH, C.H. 1978. *Rates of Sediment Transport by Surface Wash in Three Forested Areas of Peninsular Malaysia.* Occasional Paper No. 3. University Malaya, Kuala Lumpur.

PHANG, C.M.S. 1986. Comparative erosional losses in primary forest and forest logged 10 years previously in Niah Forest Reserve, Sarawak. Unpublished Report. Soil Research Unit, Forest Department, Sarawak.

PONNADURAI, D.K. 1982. Effect of selective felling on the hydrological parameters of a wet zone forest catchment. *Sri Lanka Forester* 15(3): 139 - 153.

RUSLAN, M. & MANAN, S. 1980. The effect of skidding road on soil erosion and runoff in the forest concession of Pulau Laut, South Kalimantan, Indonesia. Paper presented at the Seminar on Hydrology in Watershed Management, Surakarta.

SALLEH, M. N., ABDUL RAHIM, N. & MUSHRIFAH, I. 1981. Logging and water quality. A Malaysian experience. Paper presented in the International MAB Symposium on Man's Impact on Ecosystem Dynamics - with emphasis on Influences on Environmental Pollution. Tokyo, Japan.

SWIFT, JR. L.W. 1984. Gravel and grass surfacing reduces soil loss from mountain roads. *Forest Science* 30 : 657 - 670.

WENDT, R.C., ALBERTS, E.F. & HJELMFELT, JR. A.T. 1986. Variability of runoff and soil loss from fallow experimental plots. *Soil Science Society of America Journal* 50 : 730 - 736.

WYATT-SMITH, J. 1963. *Manual of Malaysian Silviculture for Inland Forest.* Volume II. Malayan Forest Records No. 23, Forest Research Institute Malaysia.

ZULKIFLI, Y. 1990. Effects of logging on stream water quality and solute input-output budgets in small watershed in Peninsular Malaysia. M.Sc. thesis, University Pertanian Malaysia, Serdang, Malaysia.