

## Predicting road erosion rates in selectively logged tropical rain forests

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**Abstract** The main sediment sources created by selective harvesting of tropical rain forests come from building access roads and log haulage tracks that often extend the drainage network and deliver large quantities of sediment to channels. When unchecked, these tracks develop into gullies that continue to erode long after logging. Several years after harvesting, hollow log culverts beneath access roads can fail during exceptional storms sending surges of sediment into the drainage system. Predicting the erosion so caused involves calculating rates of erosion per unit length and width of road, estimating total road length within the catchment area, making allowances for road gradient and substrate, and calculating the potential sediment yield. Remote sensing of roads and tracks under a regenerating forest canopy requires considerable ground-truthing. Estimates derived for disturbed catchments compare favourably with measured rates in small catchments. However, episodic large sediment fluxes caused by road collapse are difficult to predict.

**Key words** erosion; roads; stream sediment; timber harvesting; tropical rain forest

### INTRODUCTION

Ninety percent or more of the soil erosion resulting from timber harvesting in the tropics comes from roads (FAO, 1977; Dykstra & Heinrich, 1992). Roads play a major role in altering near-surface conditions in disturbed forests and in the supply of sediment to streams (Bruijnzeel & Critchley, 1994; Ziegler & Giambelluca, 1997; Ziegler *et al.*, 2000). Hursh (1935) recognized the need to use mulches to prevent erosion of forest access roads. Later, Le Ray (1963) noted the role of extreme events, commenting that visiting sites immediately after heavy rain to examine erosion mitigation systems was important.

Mechanical logging and road construction in tropical hilly areas have led to much soil compaction and erosion (Burgess, 1971; Kamaruzaman, 1988; Jungerius *et al.*, 2002), leaving 25 to 30% of the ground bare and damaged in East Kalimantan and Sabah, Borneo (Abdulhadi *et al.*, 1981; Malmer & Grip, 1990). The disproportionate contributions of tropical forest roads to sediment yields have been noted in East Java (Rijsdijk & Bruijnzeel, 1991), northern Thailand (Ziegler *et al.*, 2000), and the Virgin Islands (MacDonald *et al.*, 2001). The reduction in infiltration caused increases runoff and soil erosion, particularly by Horton overland flow (HOF) (Ziegler *et al.*, 2001a). Actual rates for unsealed forest road surfaces range from 6500–8000 t km<sup>-2</sup> year<sup>-1</sup> in northern Thailand (Ziegler *et al.*, 2000), to 9000–15000 t km<sup>-2</sup> year<sup>-1</sup> in the Virgin Islands (MacDonald *et al.*, 2001). Prediction of erosion from logging disturbance in ungauged catchments still often relies on applying soil erosion equations, such as the USLE, in GIS applications (Lai, 2002). However, even when more appropriate soil

surface erosion equations such as KINEROS2 are used, problems may arise (Ziegler *et al.*, 2001b, 2002). The dominant variable may vary from catchment to catchment. The most important single variable associated with sediment yield in the Mae Taeng catchment, northern Thailand, was road length (Pransutjarit, 1983). Few studies, save in Puerto Rico (Larsen *et al.*, 1999), pay attention to increased erosion as a result of landslides along forest roads.

Providing the estimates of erosion that managers need in ungauged logging areas of 100 to 1000 km<sup>2</sup>, which is larger than usually studied in field hydrology, initially involves recognizing the bare areas, and determining their interconnectivity, gradient and length. A second task is to examine the recovery of the road or track after disturbance, taking note of vegetation regrowth and rill or gully development. A third is to find appropriate estimates of erosion rates for each state or condition of road. This paper examines the feasibility of doing so, using data from projects in Malaysian Borneo.

## FOREST ROAD CONSTRUCTION AND MAINTENANCE

Three types of road are built for selective logging in Borneo: (a) major access roads to be used for 10 or more years for trucks carrying logs to ports or sawmills; (b) temporary local roads into individual logging areas; and (c) skid trails made by bulldozers dragging logs to truck loading areas. The first two types usually have a gravel surface protection, while the latter are simply loose soil and weathered rock. Breaking up the surface of skid trails and local roads after logging ceases and construction of simple barriers to surface runoff (water bars) reduces subsequent sediment yields. High soil losses also occur on the log loading zones and the places where high lead-cable winching operations took place. Much of the material so removed is trapped by vegetation downslope of the site, but some escapes to streams down gullied skid trails. However, at the head of the Baru catchment in the Danum Valley research area (Fig. 1),

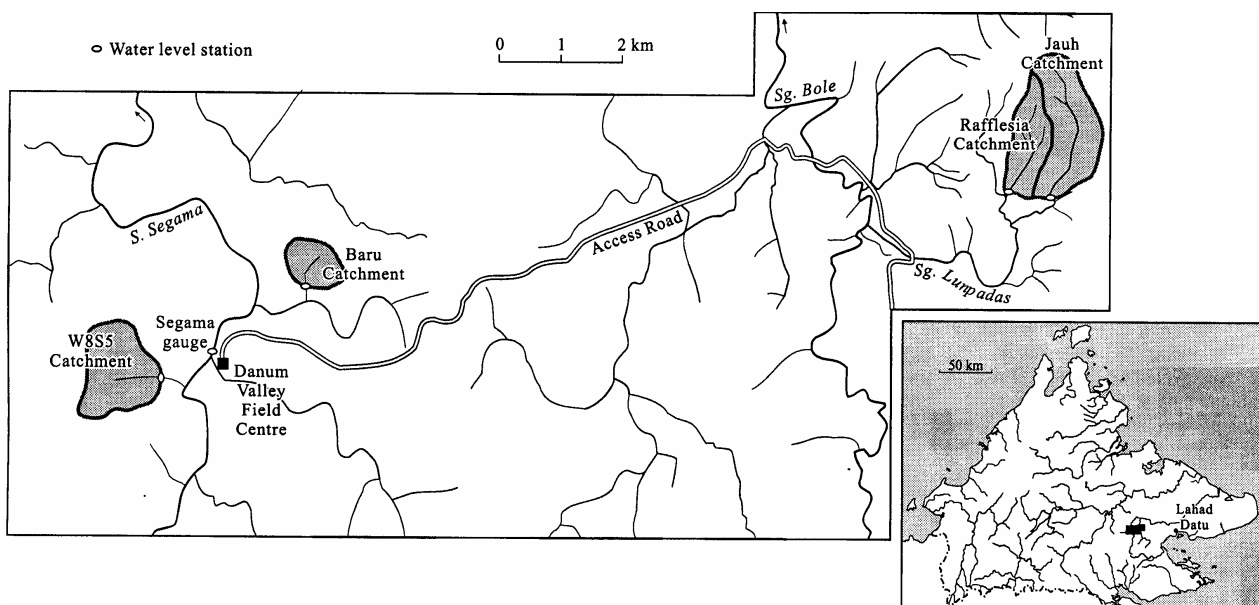


Fig. 1 Location of the study catchments at Danum Valley, Sabah.

earth barriers downslope of a former high lead area trapped much of the eroded sediment, much of the area becoming covered with ground level creeper a few months after abandonment, so reducing raindrop splash and overland flow. Reduction of rain splash by vegetation regrowth leads to decrease in soil loss (Anderton, 1990). Nevertheless, later erosion of the earth barriers allowed sediment accumulated in the first few months after logging to reach the stream channel. These temporary storages thus introduce another element of nonlinearity into the hydraulics of sediment transport in these disturbed tropical rainforests.

### **ESTABLISHING EROSION RATES ON FOREST ROADS AND TRACKS**

In the 0.54 km<sup>2</sup> Baru catchment, a short-term investigation in July 1989 established two small 1 m × 5 m bounded runoff plot experiments on skid trails taken out of use a few weeks previously, and another on a trail abandoned a year earlier. One plot allowed uninterrupted runoff downslope, while the other had a 2 m high earth barrier at its upper end blocking runoff from upslope. The one year abandoned track yielded 0.53 t ha<sup>-1</sup>, little more than the 0.38 t ha<sup>-1</sup> from the adjacent primary forest plot. Differences between the plots were far greater in terms of soil loss than in runoff.

Another, longer-term experiment had a 1 m × 5 m plot, open at its upper end to allow free run-on of flow from upslope, on an abandoned skid trail and a fully bounded skid trail plot which only trapped water falling within its boundary wall (Sinun *et al.*, 1992). The unprotected plot became subject to severe gullying, whereas the one protected by the soil barrier was quickly colonized by grasses and herbaceous material. In the unprotected plot, disturbed, loose soil was quickly evacuated, but such losses declined rapidly in the protected plot as vegetation grew. On the unprotected track, soil losses continued to rise for the first few months after road use ceased (Sinun, 1991). In July 1989, the unprotected skid trail plot had a sediment yield of 190.5 t ha<sup>-1</sup>, compared to 10.5 t ha<sup>-1</sup> from the trail with the earth barrier. By July 1990 the unprotected plot was covered with vegetation and yielded only 10.5 t ha<sup>-1</sup>. Yields in any individual time period reflect the prevailing hydrometeorological events as well as the progress of post-logging recovery. Compaction of the soil surface on tracks greatly reduces infiltration so that 52% of the incident rainfall would run off the surface of the bounded plot on the abandoned track, compared to only 3% in nearby primary forest (Sinun, 1991).

### **OBSERVATIONS ON THE VULNERABILITY OF FOREST ROADS TO EXTREME EVENTS**

Practical guidelines on timber harvesting emphasize the need to have contingency plans for severe storms and other extreme events (Dykstra & Heinrich, 1992). Road cuts and embankments often fail during heavy rain. Unusually high streamflows can break decayed hollow log culverts beneath access roads, releasing large volumes of sediment to streams. At Danum Valley, on 19 January 1996, 167 mm of rain, the highest daily fall in the period 1988–1996, activated several landslips, so producing new primary sediment sources (Chappell *et al.*, 1998). Two hollow log culverts collapsed, feeding masses of cut-and-fill road material into adjacent first and second

order tributaries. In this event, 33 t of sediment—almost 50% of the total annual load—were delivered to the gauging station of the 2-East tributary of the Baru catchment, largely from the remobilization of sediment from a road culvert collapse on 4 December 1994 and new culvert collapse (Chappell *et al.*, 1998). Such new sources introduce elements of nonlinearity and nonstationarity into the sediment supply system.

The gradual decay of the hollow logs used for culverts also influences their collapse out side extreme storm events. The collapse and landslide in the Baru catchment on 4 December 1994 was associated with a rainfall of only 15.2 mm in a relatively dry period. It is important to include propensity to mass movement in any programme of erosion prediction for forest roads, and perhaps to give more attention to the engineered access roads than to the skid trails in promoting more sustainable timber harvesting (Chappell *et al.*, 1998).

### **SIMPLE ROAD EROSION PREDICTION**

Reservoir planning often requires estimation of potential siltation rates. The Bakun dam site in the headwaters of the Rajang River, Sarawak, Malaysian Borneo, lies in an area of tightly folded Tertiary sedimentary bedrock, with an abundance of weak mudrocks and a few beds of more resistant sandstones. One question raised in preparing the environmental impact statement for the reservoir was how the removal of trees from the area to be drowned would affect siltation of the gradually filling reservoir. Timber harvesting after 1980 created a network of roads and skid trails throughout the catchment, many of which had become severely gullied, with much erosion of roadside drains and siltation of small streams. Prediction of future erosion had to take account of present and future roads as the dominant sediment source.

The road network was traced from a mosaic of Landsat images held by the State Forestry Department, and the total length and mean gradient of the roads was estimated. The potential annual soil loss per unit length of road was estimated using the long-term observations at Danum Valley, with an allowance for the high mean annual rainfall in the Upper Rajang and for the high proportion of highly erodible mudrocks in the catchment. The rate of sedimentation was then calculated assuming a minimal trapping of sediment in the stream channels, on the assumption that the material already in the channel would be washed further downstream by successive storm events and thus end up in the reservoir. This crude estimate did not allow for the variety of substrates, changes in road width and the presence of former log loading areas. A more rigorous method applicable at the management scale was needed.

### **ROAD EROSION PREDICTION USING IMAGE ANALYSIS AND GROUND TRUTHING**

In a major project relating detailed erosion measurements to remotely sensed data in Southeast Asia (Cheesman *et al.*, 2000; Cutler *et al.*, 2000; Foody *et al.*, 2001), road erosion was assessed by repeated cross sectional surveys using an erosion bridge (Shakesby *et al.*, 1991; Walsh & Bidin, 1995; Douglas *et al.*, 1999) as well as with the detailed long-term data from Danum Valley (Chappell *et al.*, 1998). The areas likely to

be most eroded, roads and log loading areas, were described in terms of gaps in the forest. The forest canopy obscures part or all of many road segments and true road width (ground surface gap size) is difficult to detect by remote sensing. Disturbance maps were used to assess the degree to which the forest canopy is perforated by gaps of varying shape and size (termed “gappiness” by the project team). To estimate accurately the disturbance of the forest canopy by a road opening, the composition of the image pixels had to be unmixed into its road and forest components. A basic three layered neural network with a 6:8:1 architecture was constructed. This network was trained using “pure” pixels of undisturbed forest and of road, from large exposed areas such as log landing sites. The network outputs were softened to derive a fuzzy or soft classification in which the magnitude of the network outputs was hypothesized to be related to the road coverage. The relationship between actual road width and that hypothesized by the neural network was strong and significant ( $r = 0.64$ ). This technique provided a means of characterizing the roads in a way suitable for integration into a GIS for erosion modelling.

## EROSION RISK MODEL

To incorporate terrain data with the forest biomass and gappiness data, an erosion risk model (Fig. 2) was coded as a series of steps within the ArcView GIS package (Cheesman *et al.*, 2000). The first step of the model is to segment the gap and biomass images into the five terrain classes. By applying a biomass threshold below which significant erosion is likely to occur, a simple two-class biomass image of “susceptible to erosion” and “not susceptible to erosion” is produced. This is then combined with the gap image, which itself is a simple binary image indicating “gap” and “forest”. Once classified into one of the soil erodibility classes, a calculated erosion value, using ground data for specific road surfaces, derived from erosion bridge or other surface soil loss measurements, can be assigned to that class. Where representative ground data are not available, values derived from erodibility and erosivity determinations made locally may be used instead. A slope angle derived from the DEM, but checked locally for any short slopes ignored by the surveyed contour interval, is also allocated to each pixel. Erosion predictions in  $t\ year^{-1}$  can then be made for individual pixels, groups of pixels or whole catchment areas. The important element in this process is the use of locally derived measurements of erosion on representative ground and track surfaces. The experience of the Danum Valley project team suggests that there is so much variation due to parent material, rainfall regime, road dimension, method of construction and maintenance regime that theoretical soil loss values based on plot studies in different circumstances tend to obscure, rather than illuminate, what happens during and after timber harvesting.

The ability of the model to predict mean annual sediment loss at the outlet of the catchment was assessed by comparing the model output with measured suspended sediment flux data, using data from Baru catchment (Fig. 1). In the partially undisturbed western subcatchment, the predicted and actual fluxes of around 100 t differed by only 3 t. However, a difference of over 1000 t arose in the eastern subcatchment where landsliding and culvert collapse produced over 1500  $t\ year^{-1}$ . The pattern of irregular sediment source creation from collapsing roads needs to be built into this model.

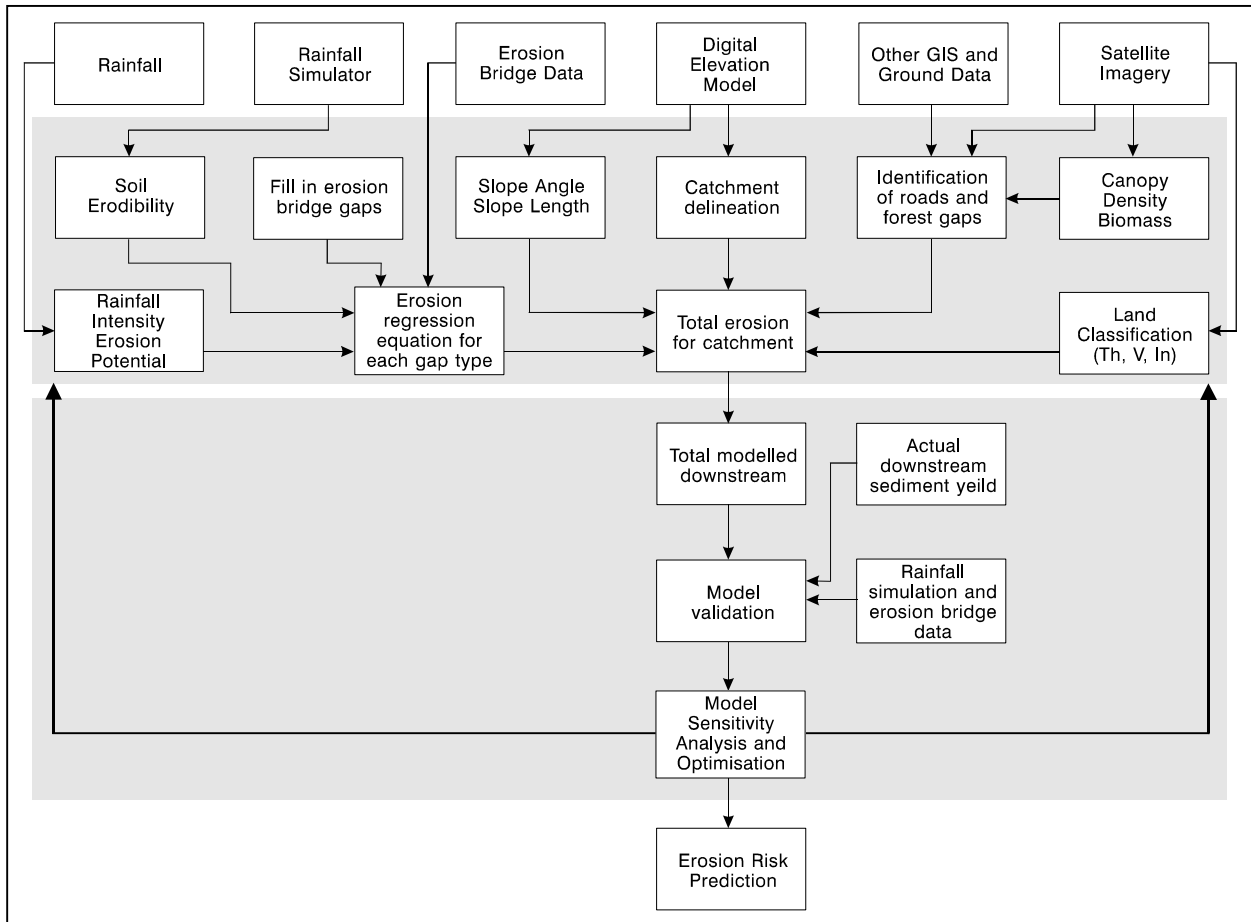


Fig. 2 Erosion risk model flow chart used at Danum Valley, Sabah.

## CONCLUSIONS

The predictions discussed here differ from more detailed approaches to soil detachment on road surfaces and those that examine road characteristics in great detail. At the time and space scales of timber harvesting in Borneo, rapid, accurate assessments are required. Some progress has been made, but at the management scale, of annual harvesting areas of 10 to 100 km<sup>2</sup>, the change in road surface erodibility with time after logging and the likelihood of mass movements need further attention.

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