A Monte Carlo Analysis of Sediment Load from Unsealed Forest Road Crossings

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EXTENDED ABSTRACT

Unsealed roads are one of the dominant sources of the sediment load in many forested Australian streams and are a significant management concern. Most of the road network is unsealed in the Otway basin of the Corangamite Catchment Management Authority (CCMA). Forest harvesting, planting and management activities are important in the catchment. A stochastic model is designed for assessing a long term annual sediment production from unsealed forest roads at the stream crossing scale using the understanding of the plot scale generation of the sediment from unsealed (forest) roads. A Monte Carlo simulation is used to propagate the input uncertainty to the model output uncertainty and to scale up to the stream crossing scale using the plot scale generation.

A series of statistical models were developed to predict the model inputs and their (co)variability. Likely inherent statistical error due to the limited observations was incorporated in the input models while cross-correlations were retained in the input generation models, where deemed necessary. The Monte Carlo technique was then applied to produce estimated output distributions. Figure 1 shows several examples of the estimated distribution of the total sediment load at road or track crossings of streams.

Sensitivity analyses (rank order correlation analysis and scenario analysis) were carried out to identify the more important variables controlling sediment production from unsealed forest roads in the catchment. This suggested that four key characteristics govern the behaviour of this particular model. The runoff coefficient and rainfall are both important due to their influence on surface runoff production. The road geometry, including the longitudinal road slope and particularly the runoff producing road width are also important. The erodibility of the road material of the road catchment and the traffic volume (number of logging truck) are also significant in the sediment production from the unsealed forest road drainage area. The sensitivity analysis indicates that good knowledge of these variables is important for realistic model predictions.

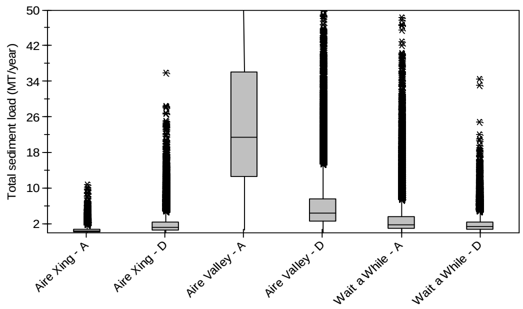

Figure 1. Truncated box plot of the simulated total sediment load at stream crossings by roads. Note A and D denote approach and depart roads respectively.

1. INTRODUCTION

Sediment and nutrient loads in a stream network are a resource management problem of global significance. Unsealed roads are the predominant source of sediment in many forested drainage basins (e.g. Fransen et al 2001, Luce and Wemple 2001, MacDonald et al 2001). It is also a dominant source of sediment in Australian forest catchments (e.g. Grayson et al. 1993, Motha et al. 2003).

Several mechanisms and factors affect the rate of erosion from the road catchment and their delivery to a stream e.g. landslide; gully erosion; surface erosion from the road surface, batter, and sidecast and fill materials; type and use of vehicle, kinetic energy of rainfall, shear stress of the overland flow, road slope, road catchment area, erodibility of the material of the road catchment, proximity of roads to a stream, connectivity between the drainage and stream. The relative significance of these mechanisms varies considerably between sites and with trigger factors (e.g. Reid & Dunne, 1984; Cocker et al., 1993). For example, land slides/mass movement (Hicks and Harmsworth, 1989) and debris flows are the principal mechanisms mobilizing road sediment in New Zealand (e.g. Cooker and Fahey 1993). Surface erosion from the road surface, batter, and sidecast and fill materials is the predominant mechanism generating sediment from roads in the USA (e.g. Reid & Dunne, 1984; Bilby et al., 1989), while surface erosion from the road surface, rill and inter-rill erosion and ruts are the main mechanisms of generating the road sediment in Australia (e.g. Sheridan and Noske, 2005). Gully erosion is another important mechanism driving forest road erosion in New Zealand (e.g. Hicks and Harmsworth, 1989).

Field observations suggest that rill and inter-rill erosion, overland flow erosion, and ruts are the principle mechanisms of the road erosion in the pilot sub-catchments modelled in this study. (section 4). Erosion of the table drain and mass movement/land slide of the batter is rare.

In this paper a methodology is presented to scale up the plot scale understanding of sediment generation from unsealed forest roads to the stream crossing scale. Key variables that are important in predicting the sediment loads into a stream from the unsealed forest roads are identified and the uncertainty in the model due to the variability of the input variables is quantified. This will assist in reliably predicting the sediment load into a stream system from the unsealed forest road network at the catchment scale.

2. THE ROAD EROSION MODEL

We have developed a stochastic model for predicting at a stream crossing scale a long term average sediment production from the unsealed forest road catchment based on the plot scale understanding of the sediment generation from the unsealed forest roads. The model inherits largely from Sheridan and Noske (2005) and incorporates the importance of the surface runoff (Kinnell, 2005) in the model in understanding that the shear stress of the overland flow overrides the rainfall kinetic energy once a sheet runoff layer has formed on the eroding surface (Moss & Green, 1983). The model is

$$TSL = 0.001 * Q * A * K * S \quad (1)$$

$$Q = i * C \quad (2)$$

$$A = L * W \quad (3)$$

where

TSL is the total sediment load (MT/year)

Q is the surface runoff (mm/year)

A is the road catchment area (m^2)

K is the sediment generation rate (Kg/m^2/mmrunoff)

i is the rainfall (mm/year)

C is the runoff coefficient (mm/mm)

L is the length of the road (m)

W is the runoff producing width of the road (m)

S is the slope factor adjusted for the effect of inter rill erosion (dimensionless) and is estimated as (Sheridan et al, 2004)

$$S = -1.5 + \frac{6.51}{1 + e^{0.94 - 5.3 \sin\theta}} \quad (4)$$

where

θ is the longitudinal slope of the road (degree)

3. MONTE CARLO SIMULATION

Road catchments are highly variable, and therefore, the spatial variability of the model inputs was incorporated into the analysis by using the Monte Carlo simulation technique. This was done using the @RISK 4.5 software (Palisade 2004) in three steps. First, the plot scale model was developed (equation 1). Second, various statistical input models (regression, parametric and nonparametric distributions) were constructed. Any cross correlation between and among the variables and parameter was maintained. Third, a Monte Carlo simulation was run.

For each Monte Carlo simulation 65,000 sets of input variables were stochastically generated. The sediment load model was run for each of these sets and a long term sediment load at the stream crossing and the variability of the plot scale rate of the sediment load was simulated (Figure 1).

4. STUDY SITE

The Aire and Ford river catchments of the Otway basin were selected as pilot catchments for the study. The catchments are heavily forested with pine plantation. They are logged and clear-felled areas exist in abundance. The geology is predominantly comprised of fluvial, volcanolithic sandstone, siltstone, mudstone and mud-cast conglomerate. Soil types vary from brown earth, black sands, mottled earth, brown duplex soil to yellow earth. Table 1 shows roads and tracks selected for the study, including their any interconnected roads/tracks. At main stream crossing of these roads and tracks, the road/track is identified as approach and depart from their nearest local road divide. In situations, these roads and tracks cross one or more waterways and were considered as part of the sediment load of the stream crossings.

5. PARAMETERISING THE MODEL

Longitudinal length of depart and approach roads/tracks was measured using a vehicle odometer or, where this was not possible, by pacing and is considered well known. The remainder of the model variables are estimated from the field and secondary information. They are considered poorly known and their spatial variabilities were simulated stochastically.

Random field samples of the longitudinal slope (θ) and width of the runoff producing area (W) of roads and tracks were collected by clinometer and measuring tape respectively. Any section of the road catchment from where generated sediment appear to be delivered to the downslope hillslope rather than the stream at the crossing or the waterways running across the roads and tracks was discounted while gathering random samples of W. To decide which distribution to use to simulate the spatial variability of θ and W, the fit of over thirty different distributions to the sample data was examined and the best distribution was selected based on the Kolmogorov-Smirinov goodness of fit criterion. Note that inherent statistical uncertainty in the location of θ and W due to finite sample sizes was incorporated by using the standard error of estimate of the mean and a normal distribution. Except for θ for the approach road of # 9 ridge track that fitted to the triangular distribution, θ and W of all of the roads and tracks fitted to parametric distributions, though inconsistently. For example, θ fitted to Logistic, Weibull, BetaGeneral, Normal, Exponential, Loglogistic and Inverse Gaussian distributions while W Logistic, Loglogistic, BetaGeneral, Inverse Gaussian, Normal, Weibull, and Pearson5 distributions. However, both θ and W fit to Loglogistic as the single most fit. These different distributions in approach and depart roads and tracks clearly show that there is significant uncertainty in which distribution is appropriate to use to simulate.

Table 1. Roads and tracks by river catchment.

River catchment	Name of the roads and tracks	Remarks
Aire river sub-catchment	Aire crossing track Aire Valley road Congram Break road Congram Creek road Football Break road Horse Paddock road Youngs creek road	Incorporates old coach road
Ford river sub-catchment	# 9 ridge track Aire Settlement road Amiets track Wait a while road	

The 0.025x0.025 degree gridded average annual rainfall layer (http://www.bom.gov.au/climate/how newproducts/IDCraintempgrids.shtml) and the triangular probability distribution are used to approximate a long term rainfall (depth) variations along the road catchment. Spatial variation in the runoff coefficient is simulated using the Lognormal distribution based on the work of Sheridan and Noske (2005).

K is a function of soil type, surface material and geology of the road catchment, track type and traffic level and estimating it is a difficult task. There are no data on *K* in these or other similar catchments of the CCMA. However Sheridan and Noske (2005) found that truck traffic levels were the most important determinant of *K* and they developed a regression relating *K* to the truck traffic density. Data from Sheridan and Noske is used to develop a regression relationship between *K* and annual logging truck traffic. The uncertainty in this was incorporated by adding a normally distributed error term. For gravel surface forest roads, *K* is estimated as

$$K = 0.000276 + 5.167 * 10^{-8}\, Traffic \quad (5)$$

where

$Traffic$ is the volume of logging truck (number/year)

For dirt roads, the spatial variability of the *K* is simulated using the uniform distribution using the small amount of information available from the Gippsland Lakes' catchments (Sheridan and Noske, 2005) and heuristic consideration of the erodibility of field surface materials. There is also very little data on the volume of logging truck traffic in the pilot sub-catchments, which is used for predicting the variability in the logging truck through the uniform distribution.

6. RESULTS

The long term mean annual rate of sediment load (TSL, MT/year) was estimated at each of the selected stream crossings (Figure 2). Figure 1 shows the interquartile range, median and outliers of the simulated model results. The same plot also suggests the nature of the distribution e.g. longest whisker and largest box area above the median of Aire valley approach road dictate highly positive skewed distribution of the total sediment load from Aire Valley approach road. Figure 2 indicates that the Aire valley road generates the highest sediment load among the sampled roads.

7. SENSITIVITY OF THE MODEL

Sensitivity analysis of the model was carried out in order to infer which variables and the parameter are most important to the realistic prediction of the sediment load at a stream crossing. Two layers of sensitivity analyses are carried out for every road. Spearman rank order correlation sensitivity analysis suggests that except traffic load, all variables are key, well knowledge of which is indispensable for the reliability of the model.

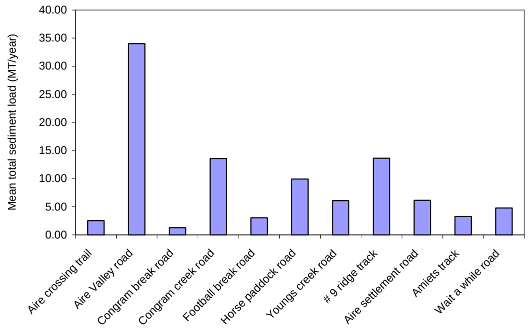

Figure 2. Mean total sediment load by roads and tracks.

However, not all of them are important for every road. Tornado plot (Figure 3) shows an example of the sensitivity of the variables and parameter. Note from Figure 3 the relative longer bars at the top show most significant variables and parameter while the shorter bars at the bottom the least.

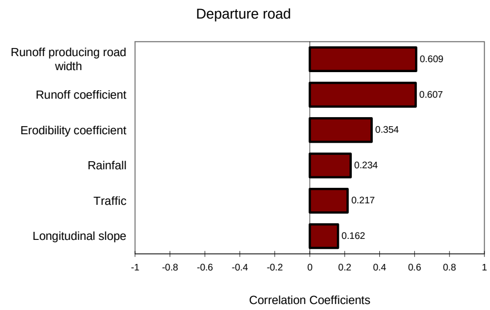

Figure 3. Sensitivity plot of the variables and parameter.

To further explore the sensitivity, an analytical method called scenario analysis is used. Scenario analysis examines what input variable values are associated with particular ranges (subsets) of output values (eg. outputs in the fourth quartile). Unlike the general sensitivity analysis above, this identifies the key variable groups and their values associated with particular outcomes (e.g. high simulated sediment load). It calculated by taking the difference between the median of an input variable for the subset of realizations of interest and the median of the same input variable for all realisations. This difference is then divided by the standard deviation of that input variable (over all realizations) to obtain a sensitivity score (Jha et al, 2005). Three scenarios are considered for this analysis – the lower quartile, upper quartile, and the upper decile of simulated rates of the road sediment loads (Table 2). Table 2 gives the results for Aire Valley road as an example. Here the runoff coefficient and runoff producing road width are the most sensitive inputs, followed by the erodibility coefficient. The scenario analysis reconfirms the sensitivity results of the rank correlation sensitivity analysis and adds one variable to the sensitivity list– for the higher end of the sediment loads (≥ 90 %) the traffic volume is also among the most important variables but not in every road. Both sensitivity analyses suggest that runoff coefficient is almost always the single most important variable in this model. In terms of contributing to uncertainty rainfall and traffic volume are almost always unimportant.

Table 2. Scenario analysis of the total sediment load based on conditional median for Aire valley road.

Variables	Scenario	Approach road	Depart road
Runoff coefficient	≤ 25 %	-0.71	-0.65
	≥ 75 %	0.99	0.94
	≥ 90 %	1.4	1.36
Runoff producing road width	≤ 25 %	-0.75	-0.77
	≥ 75 %	0.90	0.89
	≥ 90 %	1.15	1.22
Erodibility coefficient	≤ 25 %	-0.60	-0.51
	≥ 75 %	--	--
	≥ 90 %	0.63	0.61
Longitudinal slope	≤ 25 %	--	--
	≥ 75 %	--	--
	≥ 90 %	0.62	--
Rainfall	≤ 25 %	--	--
	≥ 75 %	--	--
	≥ 90 %	--	0.58
Traffic	≤ 25 %	--	--
	≥ 75 %	--	--
	≥ 90 %	0.55	0.53

8. DISCUSSION

The Monte Carlo framework has allowed the analysis of model sensitivity to input uncertainty in predicting sediment loads from road crossings. This analysis will allow further targeting of data collection efforts by identifying the input variables that are more important in determining data related model uncertainty.

The model is built upon the widely used Universal Soil Loss Equation (Wischmeier and Smith, 1978) and it recognises the importance of the shear stress of the surface runoff (Kinnell 2005, Moss & Green, 1983) in generating and transporting the road sediment. However, the lack of testing data is an important limitation.

A strength is that the spatial variability of the input variables is rigorously incorporated in the analysis. In achieving this it should be recognised that some data is not of long duration e.g. heavy traffic volume (logging truck) and that there are limits to the current understanding of some inputs, for example the effect of light vehicle traffic is yet to be incorporated. Knowledge about the hydrologic connectivity between the road drainage and the stream, essential for the delivery of the road sediment to the stream, is another area which needs to be refined.

9. SUMMARY AND CONCLUSION

A stochastic model is developed for estimating the long term mean annual sediment load to a stream from unsealed forest roads at the stream crossing scale. It is based on the understanding of the plot scale erosion from the unsealed forest road and a stochastic upscaling. Because the variables and parameter of the model are highly spatially variable, a Monte Carlo simulation approach was used to both identify and estimate uncertainty in the plot scale model of road erosion and to scale the results up to the stream crossing scale. Except for the length of the road, all input variables and the parameter are considered poorly known and their spatial variabilities are stochastically simulated using either empirically based stochastic prediction models, fitted distributions or subjectively chosen probability distributions. A Monte Carlo framework is used to combine the input models and the road erosion model using the @RISK 4.5 software. This enabled estimates of the long term mean annual sediment load to a stream and also gave an estimate of the combination of the actual variability and input associated uncertainty of plot scale rates of sediment loads within the approach and departure roads at the stream crossings.

Two layers of sensitivity analysis were conducted so as to be able to find out which variables and the parameter govern the behaviour of the sediment production from the unsealed road catchment. The results suggested that all variables namely surface runoff through rainfall and runoff coefficient, slope, width, erodibility coefficient, and volume of logging trucks (not necessarily in order) can be important, though not all of them are important at any particular road crossing. The runoff coefficient is almost always the single most important variable followed by the bank angle. Good knowledge of these variables and the parameter is indispensable for reliably predicting a long term sediment load from the unsealed forest road at a stream crossing.

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