Modelling The Water Quality Impacts Of Forest Roads At The Catchment Scale

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EXTENDED ABSTRACT

The aim of this study was to estimate the magnitude of the contribution of forest roads to catchment in-stream exports of sediment and nutrients in the context of natural background levels from forests in SE Australia.

The conceptual approach adopted in this study was to assume that the total load of sediment and nutrients from a forested catchment with roads can be apportioned to two sources; roads-related sources and non-roads related sources. The experimental approach to quantify these sources is shown in Figure 1.

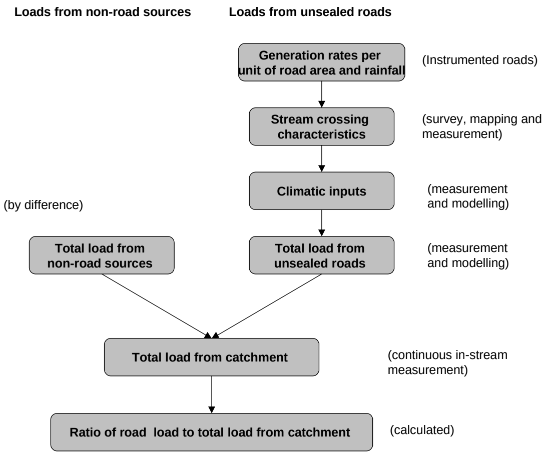

Figure 1. Flow diagram of the experimental approach to the estimation of the contribution of roads to the total loads of pollutants from forested catchments.

A 13,451 ha forested catchment in SE Australia was instrumented for one year to quantify total in-stream exports of total suspended sediment (TSS) and total phosphorus (TP). 101 road-stream crossings were mapped and characterised in detail within the catchment to identify the properties of these road sections that connect directly to the stream network. Sediment and nutrient generation rates from different forest road types were quantified using permanent instrumentation and rainfall simulation. Sediment and nutrient generation rates, mapped stream crossing information, annual rainfall and traffic data were used to estimate annual loads of TSS and TP from each stream crossing in the catchment. The annual sum of these loads was compared to the measured total catchment exports to determine the proportional contribution of roads within the catchment.

The results showed that the unsealed road network delivered an estimated 50 t of the 1449 t of TSS exported from the catchment, or about 3.5 % of the total sediment load from the forest. The unsealed road network delivered a maximum of 22 kg of the 1469 kg of TP from the catchment, or less than 1.5% of the total load from the forest. The lower proportional contribution of TP resulted from a low ratio of TP to TSS for the road-derived sediment. The contribution of unsealed roads to the export of total dissolved nitrogen (TDN) from the catchment could not be determined quantitatively, however the available data suggests roads are a minor source. The data indicate that in *this* catchment improvement of stream crossings will yield only small benefits in terms of net catchment exports of TSS and TP, and no benefit in terms of TDN.

These results are for a catchment with minimal roading-related mass movement, and extrapolation of these findings to the broader forested estate requires further research. It should also be noted that, even in the case where *catchment scale* impacts are minimal, pollutant impacts may still be substantial at the local scale of the individual *stream reach*, a scale of impact not addressed in this paper.

1. BACKGROUND

Unsealed roads have long been identified as a significant source of water pollution in forests (eg. Bilby 1989, Luce and Black 1999, Lane and Sheridan 2002, Sheridan and Noske *in press*) and several studies have indicated that the levels of sediment attributable to the forest road network are greater than the levels associated with timber harvest areas (Motha *et al.* 2003; Grayson *et al.* 1993; Cornish 2001). The proportional contribution of roads to catchment exports depends on the background loads from other sources, and the sediment generation rate from the road area that is connected to the stream network via overland flow pathways. The degree of the connection depends on the proximity of the road to the stream, the drainage of the road, and the nature of the overland flow pathway (Croke and Mockler 2001). The sediment delivery rate at a particular crossing is affected by factors such as the area and slope of the road (Sheridan *et al.* 2003), erodibility of the surface material (Grayson *et al.* 1993), and the level and type of traffic (Sheridan and Noske *in press*).

Of the studies cited above, only the work by Motha *et al.* (2003) has *directly* attempted to quantify the contribution of forest roads to total catchment loads of TSS in a rigorous way for the forest and geomorphology of SE Australia. None of the studies have attempted to quantify nutrient loads from unsealed roads. Knowledge of the pollutant contribution of roads is valuable because roads are an identifiable and manageable point source of pollutants within catchments, and therefore the scope for successful remediation is considerable.

2. EXPERIMENTAL METHODS

2.1. Overview

The conceptual approach adopted in this study is to assume that the total load of sediment and nutrients from a forested catchment with roads can be apportioned to two sources; roads-related sources and non-roads related sources (Figure 1). Non-roads related sources in the context of this study can be considered to include background levels due to natural hillslope erosion, bank erosion, scouring of the stream bed, and also human induced sources such as from logging areas. Isolating these various non-road sources is difficult. However, isolating *roads* as a source of sediment and nutrients is more easily achievable because of the easy access to undertake surveys and experimentation, and the relatively well defined drainage pattern and therefore easily determined catchment area of roads. The proportional contribution S_{rp} (%) of road-derived TSS load S_r (t) to the net load of TSS exported from the catchment S_t (t) is given by;

$$S_{rp} = \frac{S_r}{S_t} \times 100 \qquad 1$$

This approach is conservative from an environmental perspective because it assumes that loads generated from roads are *all* delivered from the catchment outlet ie. there is assumed to be no in-stream deposition of this road derived material. The net load of in-stream TSS exported from the catchment S_t can be approximated by the equation;

$$S_t = \sum_{i=1}^{i=\frac{T}{15}} C_i Q_i \qquad 2$$

where C and Q are the instantaneous sediment concentration and discharge volume respectively, T is the period over which the load is calculated and i is the interval number. Measurement intervals were of 15 min duration. Methods for the estimation of C_i and Q_i are given in section 2.6. The road-derived TSS load for the catchment, S_r, was calculated from;

$$S_r = \sum_{j=1}^{j=n} S_{rj} \qquad 3$$

where S_{rj} is the TSS load from j^{th} road crossing of the total n road crossings in the catchment for the period T. Methods for the estimation of S_{rj} are given in the section 2.5.

2.2. Study site description

The study was undertaken in the upper Tyers River catchment, a 13,451 ha catchment extending across the southern face of Mt Baw Baw, Victoria, Australia. Soils are commonly strongly aggregated clay loams with high infiltration capacity. Almost all of the catchment is *Eucalyptus* forest. Annual rainfall and erosivity is in the range 800-1800 mm.y^{-1}, and 1500-2000 MJ.mm ha^{-1}h^{-1}y^{-1} respectively (Sheridan and Rosewell 2003). The drainage density of the catchment is 2.14 km.km^{-2}. The total road length in the catchment is 185 km, or 1.4 km.km^{-2} , and the number of stream crossings based on intersection of the available GIS stream and roads layers, is 106, (0.79 crossings km^{-2}).

2.3. Road generation rates

Ten experimental road segments are identified in this paper by the codes R1, R2,…R10. The instrumented road segments were used to determine the generation rates of runoff, sediment and nutrients from a range of road types under a range of rainfall and traffic conditions (Table 1). Measurement methods and detailed site descriptions for the instrumented sites are provided in Sheridan *et al.* (*in press*) and Sheridan and Noske (*in press).* Briefly, road runoff was delivered to a metal roadside bedload trap to trap coarse material, and then flowed to a logged tipping-bucket for runoff measurement. Runoff was proportionately sub-sampled and analyzed gravimetrically to determine the suspended sediment concentration of the runoff. Rainfall and traffic was logged continuously and instrumentation was serviced every 2-3 weeks (referred to herein as a "data interval") for one year.

Rainfall simulation was used to quantify a number of key erosion related parameters of road surfaces and batter surfaces under controlled conditions, such as infiltration rate, TSS, TP, and TDN generation rate. Parameter values determined from rainfall simulation were used to assist in the allocation of sediment generation rates for different road-surface types. Rainfall was applied to bordered plots for 30 min at 100 mm.h^{-1} to plots 1.5 m wide and 2 m long set up on typical sections of the road or batter surface. Runoff was collected for runoff measurement and measurement of sediment concentration.

2.4. Road crossing survey

The area of runoff-producing road-surface discharging in close proximity to streams was mapped throughout the upper Tyers catchment by manual survey in the field. The assessment of stream crossings for sediment delivery involved considering each crossing as consisting of a series of small road-related "flowlines" with various attributes (eg. slope, area, soil type, geology, soil colour) that affect the generation of runoff water and sediment.

2.5. Road-derived load calculations

The TSS load for the j^{th} crossing, is the sum of the TSS load (S_f) from each of the m flowlines contributing to the stream at the crossing;

$$S_{rj} = \sum_{k=1}^{k=m} S_{fk} \qquad 4$$

S_{fk}, the TSS load from the k^{th} flowline for the period T is a function of the sediment generation rate K of the surface (mg.mm$_{rain}^{-1}$ m^{-2}), the rainfall depth P (mm) for the period T, the surveyed catchment area A (m) generating the flowline, and the measured slope of the surface;

$$S_{fk} = K\,P\,A\,S_a \qquad 5$$

where S_a is a slope adjustment factor to account for variation in erosion rates due to the slope of the flowline using the interill slope adjustment equation proposed by Sheridan *et al.* (2003). The sediment generation rate K for a particular surface type category, was determined from data from instrumented road sections and rainfall simulation experiments reported in Sheridan and Noske (*in press*) and Sheridan and Noske (2005). For native soil track surfaces, K values were assigned on the basis of surveyed geology and soil color, and on the expected level of light vehicle traffic. For gravel surfaced roads, K values have been assigned from the annual aggregated erosion data (Sheridan and Noske, *in press*) and from equations relating sediment delivery rates to truck-traffic levels (Sheridan and Noske, *in press*).

Spatial patterns of annual precipitation depth (derived from a fitted rainfall surface) were used to assign a value of P to each of the crossings in the catchment for the period T. The TP load for the k^{th} flowline, P_{fk}, was calculated as a function of the corresponding TSS load;

$$P_{fk} = a \, . \, S_{fk} \qquad 6$$

where a is a regression coefficient determined from least squares linear regression of the TSS and TP concentration (mg L^{-1}) of runoff samples from the instrumented road sites and the rainfall simulation experiments. The TP load for the k^{th} crossing was then calculated as for S_r, assuming the majority of TP was transported adsorbed to suspended sediments.

2.6. Net catchment exports

The upper Tyers catchment was instrumented at its outlet to quantify the discharge and export of sediment and nutrients from the catchment. Nephelometric turbidity, U, (NTU) was measured as a surrogate for TSS and the sediment concentration C_i at the i^{th} interval was subsequently estimated from;

$$C_i = b\,U_i \qquad 7$$

where U_i is the in-stream turbidity for the i^{th} interval and b is a regression coefficient determined from least squares regression of the turbidity (NTU) and TSS concentration (mg L^{-1}) of auto-sampled water samples from the stream. Discharge Q_i at the i^{th} time interval was calculated from measurements of water depth using stilling well mounted pressure transducers logged at 15 min intervals and known stage-discharge relationships. Equation 2 was used to estimate TSS loads exported from the catchment, S_t, for the study period T (31/07/03 – 01/08/04). TP loads P_{ti} were estimated as a function of the corresponding TSS load;

$$P_{ti} = c \,.\, S_{ti} \qquad 8$$

where c is a regression coefficient determined from least squares linear regression of the TSS and TP concentration (mg/L) of water samples collected using the auto-sampler described above.

3. EXPERIMENTAL RESULTS

3.1. Road generation rates

TSS generation rates from the instrumented road sites (adjusted for slope) are reported in detail in Sheridan and Noske (*in press*) and reproduced briefly in Table 1. The value of the coefficient a in Equation 6 is shown in Figure 2

Figure 2 shows that there is a 44 fold variation in the relationship between TSS and TP for the different road sites. The highest ratios of TP to TSS are from the gravel-surfaced roads receiving heavy truck traffic (eg. South Face Road, Feglins and Tanjil Bren Roads). The tracks constructed on natural surface soils (eg. 4WD Track and Firebreak Track) illustrate a similar medium ratio of TP to TSS, while the track constructed on an erodible silty subsoil (Delpretes Track) showed the lowest ratio of TP to TSS. The South Face Road site with a large unstable granitic batter showed a low ratio of TP to TSS reflecting the large contribution of coarse sediment to the TSS load at this site (R3). The low ratio at Delpretes Track may also be due to the large contribution of silt and fine sand to TSS at this site. Computed TP loads based on the application of Eq 8 to the instrumented road data are given in Table 1.

The mean value for TDN for all the samples from all the instrumented road sites (n=66) was 0.08 mg L^{-1} (SD of 0.06). The mean Total Nitrogen (TN) of the road surface material (ie. from soil sampling) from each site was 0.02% N, (SD 0.03%), close to the instruments lower detection limits.

3.2. Road crossing survey

A total of 101 crossings and 192 flowlines were identified and mapped during the field survey in the upper Tyers catchment, yielding a stream-crossing density of 0.75 crossings per km^2.

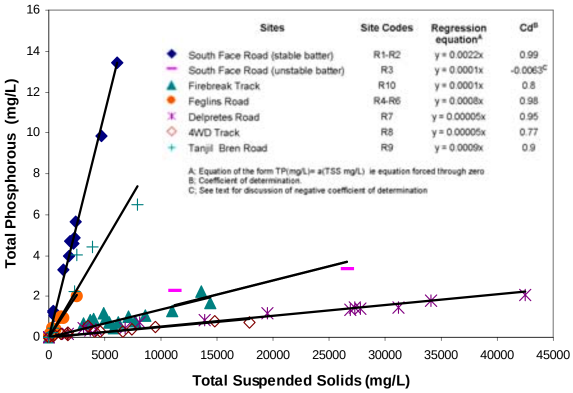

Figure 2. The relationship between TSS and TP concentrations for road-runoff from different road types.

As noted in the methods section, a sediment and nutrient generation rate (Table 2) was assigned to every individual crossing in the catchment based on data from the instrumented road segments and the mapped information for each crossing. Representative sediment generation rates are reported for a 9% slope using a slope adjustment equation proposed by Sheridan *et. al.* (2003). TSS generation values were transformed to TP generation values using Equation 6.

3.3. Catchment exports

Continuous in-situ turbidity measurement was used as a surrogate for measurement of TSS and TP concentrations so as to estimate the total loads of TSS and TP exported from the catchment. The value of the coefficient b in Equation 7 for the relationship between NTU and TSS (mg/L) was determined by regression to be 2.56 (r^2 = 0.55). The value of the coefficient c in Equation 8 for the relationship between TSS (mg/L) and TP (mg/L) was found to be 0.001 (r^2 = 0.90). Using these relationships, and the measured discharge and turbidity, the TSS load from the catchment S_t was estimated at 1449 t.y^{-1} for the period 31/07/03 – 01/08/04.

Using the methods described previously, the quantity S_r of road derived sediment was estimated at 63 t for the 1 year period T (31/07/03 – 01/08/04) during which catchment exports were monitored at the instrumented stream sites. Of this road-generated sediment, 39 t was discharged directly into streams from 109 flowlines.

Table 1. Summary of precipitation, discharge, total loads and mean concentrations of TSS and TP for each of the instrumented road sites for a 1 year period.

Site Code	Total Precip (mm)	Total Runoff (mm)	Total Runoff (L)	Total Traffic^A	Mean Sediment conc (mg/L)	Total Sediment (kg)	Mean P Conc (mg/L)	Total P (g)
R1	1517	1535	938536	T1685	750	698	0.990	929
R2	1270	987	640756	T389	380	246	0.395	253
R3	1385	587	364397	T0	730	265	0.025	9
R4	1173	594	357084	T1020	1050	376	0.692	247
R5	1413	511	207691	T727	730	154	0.481	100
R6	1523	481	422796	T129	690	290	0.509	215
R7	723	574	343159	L1319	6820	2322	0.192	66
R8	892	649	362389	L54	1450	525	0.083	30
R9	855	482	294472	T3369	3090	854	1.229	362
R10	1161	543	225796	L51	3800	868	0.270	61

A; return passes of vehicles L= light vehicle, T= truck. Sediment concentrations are the mean of data interval values for each site. Sediment and nutrient loads and concentrations reported for 9% slope.

Table 2. Representative sediment generation rates* for a range of unsealed forest roads.

Description	Typical Site	Traffic Level^B	K (mg $mm_{rain}^{-1}.m^{-2}$)
Gravel: 2WD Traffic only	R3	T0	150-200
Gravel: Occasional use by trucks	R6, R2	T100-400	200-300
Gravel: Moderate usage by trucks	R1, R4	T1000-1700	500-750
Gravel: Heavily used logging roads	R9	T3400	1700
Gravel: Very Heavily used log road	Lit.^{A}	T3400-16000	1,700-10,000
Soil: Yellow/White Sub clay	R8	L54	1000
Soil: Red Earth A horiz	R10	L51	1800
Subsoil: Sedimentry/White Silty	R7	L50	4500
Subsoil: Sedimentry/White Silty	R7	L500	5000
Subsoil: Sedimentry/White Silty	R7	L1319	5500

A; Bilby et al. (1989) Sheridan & Noske (*in press* a) B; return passes of vehicles, T=Trucks, L = Light vehicles
*Generation rates are given for 9% slope.

Another 16 t was discharged into near stream vegetated buffers with an average interception length of 19m (38 flowlines), with the remaining 8 t (50 flowlines) discharged into structures such as filter fences, sediment ponds, or combinations of these and buffers. The average capacity of sediment ponds, when present, was 1.2 m^3.

These values indicate that the true value of S_r lies somewhere between 39 t and 63t, depending on the effectiveness of interception areas. This suggests that the value of S_{rp} lies between 2.7% and 4.3%. Numerous authors have shown that vegetated buffers in forests are very effective in infiltrating concentrated runoff water (Lane *et al.*, *in press*, Sheridan and Noske 2005) and trapping sediment (Loch *et al.* 1999, Hairsine *et al.* 2002). Small sediment ponds have been shown to be relatively ineffective for *operational* roads (Bilby *et al.* 1989. Considering these results, the net TSS load from the catchment due to roads is estimated at 50 t ± 10 t.

Using the methods described earlier, the TP load from all of the crossings in the upper Tyers catchment for the year was 22 kg. Expressed as a spatial load per unit of near-stream road-surface the value is 7 kg ha^{-1} y^{-1}, and on a per total catchment area basis it is 0.0016 kg $ha^{-1}y^{-1}$.

The mean TP load per crossing per year was 0.22 kg y^{-1} (SD 0.30). The considerable variability in rainfall, slope, area, sediment generation rate, and nutrient generation rate (per unit of sediment) at each of the stream crossings resulted in a range in TP loads from individual crossings, from 0.001 kg y^{-1} to 1.7 kg y^{-1}. As was the case for sediment, the highest yielding 10% of crossings deliver about 50% of the total TP load from roads.

4. DISCUSSION

4.1. Background loads from forests

The total suspended sediment load measured from the upper Tyers catchment of 0.11 t $ha^{-1}y^{-1}$ is similar in magnitude to loads reported by other authors in similar landscapes and climates. Grayson *et al.* (1993) instrumented logged and unlogged catchments. The unlogged catchment produced an average suspended load of 0.052 t $ha^{-1}y^{-1}$ while the logged catchment (*without* roads intersecting runoff areas) recorded 0.076 t $ha^{-1}.y^{-1}$. Hartland *et al.* (1990) report suspended load values that average 0.228 and 0.236 t $ha^{-1}.y^{-1}$ for two catchments. The TP load measured of 110 g $ha^{-1}y^{-1}$ agrees well with loads reported in the literature for SE Australian forests. For example, Young *et al.* (1996) reviewed Australian literature on nutrient export rates and estimates TP loads at 30 to 100 g $ha^{-1}y^{-1-}$ for SE Australian Forests.

4.2. Loads from roads

The annual loads from the forest road segments monitored in this study varied from 3.2-13.7 t $ha^{-1}.y^{-1}$ for gravel surfaced roads, to 8.4-39.2 t $ha^{-1}.y^{-1}$ for unsurfaced tracks (ie. per ha of road surface). Spatially, these values are in the order of 100 to 1000 times greater than the background rates from forests. For both the gravel roads and the native soil tracks, sediment generation rates were found to be within the range of values reported by other detailed quantitative field studies (Bilby *et al.* 1989, Grayson *et al.* 1993; Fransen *et al.* 2001). Detailed reviews are provided in Sheridan and Noske (*in press*). Literature values could not be found quantifying the nutrient (TP & TDN) generation rates from unsealed forest roads and the ratio of TSS to TP varies substantially between different roads (Figure 2). Interestingly, the gravel surfaced roads all show a much higher ratio of TP to TSS than the non-gravelled roads.

4.3. Catchment scale contribution of roads

The ratios of TP to TSS shown in Figure 2 are low compared to the TP/TSS relationship found for the in-stream sediment. The results show that unsealed roads contribute approximately 3.5% of the TSS load and 1.5% of the TP load from the upper Tyers catchment. In contrast, Motha *et al.* (2003) used a range of sediment tracing techniques in a similar catchment and estimated that between 18%-39% of the TSS load from a forested catchment was from unsealed roads. However, it should be noted that a much greater proportion of roads run parallel to the stream network in the study of Motha *et al.* (2003). This arrangement results in a greater level of connection between streams and roads. It should also be noted that the two studies use fundamentally different methods with which to estimate the contribution of loads. Underlying each method are a number of different assumptions, and it is unknown as to what extent the results from the two different methods can be compared. In another study, Croke & Mockler (2001) identify the active gullying of overland flow pathways at the road discharge point as a major source of road-derived sediment.

This variability observed in the literature raises the question as to how representative the experimental catchment is of SE Australian forested catchments in general. How reasonable is it to extend these results to other catchments? The two key factors to consider are the presence or absence of mass movement erosion processes associated with roads, and the extent of the road-stream network connection (indicated by the density of stream crossings and proximity of roads to streams).

The relatively small contribution of forest roads to the net exports of TSS (3.5%) and TP (1.5%) from the catchment should not be interpreted as implying that water pollution due to unsealed roads is insignificant from an environmental perspective. The calculation of net loads provides information about possible impacts at the *catchment* scale. A different measure is required to evaluate impacts on stream health at the scale of the individual *stream reach*. Sheridan and Noske (*in press*) showed that the temporal patterns of pollutant intensity downstream of road crossings in this catchment are commensurate with levels that have been shown to result in changes in in-stream macro invertebrate community structure.

Catchment scale contributions of unsealed roads to net exports of TDN were not able to be calculated directly because TDN could not be correlated with any of the other water quality parameters that were measured on a regular basis. However, the very low concentrations of TDN measured in the road runoff, and a very low percentage of TN (0.02% by mass) for the road surface material indicates that the road surfaces are likely to be a very minor source of nitrogen in stream water in forested catchments.

5. CONCLUSION

The major findings from this study are;

- The unsealed road network delivered an estimated 50 t of the 1449 t of TSS exported from the 13,451 ha catchment, or about 3.5 % of the total load from the forest.
- The unsealed road network delivered a maximum of 22 kg of the 1469 kg of TP from the catchment, or about 1.5 % of the total load of TP from the forest.
- Qualitative analysis of the data suggests that the TN contribution from unsealed roads is minor
- Variability between individual crossings was high with 50% of the TSS and TP load coming from the highest yielding 10% of crossings

- The ratio of TP to TSS was very high for gravel surfaced roads compared to soil roads, indicating that improved surfacing, while effective at reducing sediment loads, may not necessarily lead to reduced nutrient loads.
- These results are for a catchment with minimal road-related mass-movement, and extrapolation of these findings to the broader forested estate requires further research.

These findings suggest that unsealed forest roads contribute only a very small fraction of the TSS and TP *load* from this forested catchment. Road-derived pollutants are considered from a *river-health* perspective by Sheridan and Noske (*in press*).

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