A Catchment-Scale Model of Road Erosion and Sediment Delivery

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EXTENDED ABSTRACT

Unsealed roads and tracks are potentially significant sources of diffuse pollutants, particularly sediment. Identifying critical diffuse pollutant sources and their transport potential can greatly improve catchment-scale water quality management. This study describes the application and ongoing development of a road erosion and sediment transport model in the Moruya-Deua and Tuross River catchments of southeast Australia.

The prototype of an empirical model based on the Washington Road Surface Erosion Model (WARSEM) is applied. WARSEM estimates the volume of annual average road-derived sediment delivered to streams. The model takes account of both road surface erosion rates and the extent of road-to-stream connectivity. Several factors such as geology, rainfall, traffic, road physical characteristics, and the distance of the road drain outlet from streams are considered. The factors from WARSEM are modified to suit data availability for the study catchments

The outputs of the model show estimated annual sediment yields from roads, and predict the impacts of road management on sediment yields. The results suggest that annually, approximately 13 kt and 20 kt of sediment are produced from road erosion in the Moruya-Deua and Tuross River catchments, respectively, but less than 8% of the sediment is delivered to streams. Surprisingly, about half of the delivered sediment is derived from only 2% of the total road segments. These segments are referred to as critical road segments and are suggested as a focus for management effort.

Three management scenarios are run for the identified critical road segments, focusing on changes on road surface condition, road traffic and contributing area proportions. The results show that the most effective management option is changing surface materials. Re-gravelling the identified critical roads can reduce the total sediment delivery in the catchment by 35 – 50 %. These results do, however, need to be considered in terms of the costs and confidence in the model outputs before more definite conclusions can be reached.

Several suggestions for model improvement are discussed here. One significant limitation on model improvement is a lack of basic road measurement data such as road segment length, width, and slope. It is strongly recommended that efforts to gather such data be increased. Sediment load data are also essential for model testing. In a comparison with sediment load data collected in 2005 (Drewry, unpublished), road-derived sediment accounts for 26 % and 57 % of the total sediment loads in the Moruya-Deua and Tuross River catchment, respectively.

Sediment delivery is of fundamental interest to road management. The distance between the road drain outlet and the streams was used to estimate the sediment delivery ratio (SDR) in the model. However, it is recognised that the road surface area is also important, especially when the road-to-stream distances are high. A conceptual framework for modelling SDR is recommended here, but the conceptualisation, implementation and testing of the model requires further research.

Two approaches on model testing are recommended for future research: using published road sediment data of other catchments and using sediment tracing techniques. This reconnaissance project demonstrates the significance of diffuse sources from roads. This paper also shows a modelling approach to identify critical road sediment sources using mostly available data across southeast Australia.

1. INTRODUCTION

The significance of unsealed roads to off-site water quality decline is well recognised, especially in forested catchments (Grayson *et al.*, 1993; Anderson and Macdonald, 1998; Croke *et al.*, 1999; Motha *et al.*, 2004; Forsyth *et al.*, 2006; Ramos-Scharrón and MacDonald, 2007). For example, erosion rates from unsealed roads have been shown to be four and six orders of magnitude higher than undisturbed hillslope areas in the US Virgin Islands (Ramos-Scharrón and MacDonald, 2007) and coastal southeast Australia (Croke *et al.*, 1999), respectively. It is therefore critical to understand the road erosion and sediment delivery processes, and to quantify road-derived sediment contributions at catchment scales.

Techniques for quantifying erosion from roads include the use of road side and stream monitoring, sediment tracing and modelling. They are generally most effective when they are combined but difficulties are present. Sediment traps are inefficient for estimating the contribution of fine sediment (Ramos-Scharrón and MacDonald, 2007). It is difficult to distinguish road-derived sediment from other sources using stream monitoring techniques. Environmental tracing results are affected by stream water geochemistry, organic matter and particle size sorting (Foster and Lees, 2000), and the interpretation of tracing results can hence be difficult (Fu *et al.*, 2006). Environmental models have the advantages of catchment-scale application and prediction beyond current conditions, but without sufficient data, model calibration and testing are difficult.

Road erosion models are relatively less developed than hillslope and other types of water quality models which have been applied over the last half century. A review of road erosion models has been completed by Fu and Newham (submitted). The findings of the review are summarised below:

1) Many road models adapt theories of hillslope erosion processes, and the inherent limitations of the 'parent' models are transferred.
2) The data required to drive many road models are seldom routinely collected.
3) In most road models, there is a significant bias towards simulating erosion process, with much less consideration given to delivery process.
4) For management application, simpler models are potentially more directly useful.
5) Model testing and uncertainty analysis is seldom reported, but is required to advance capability in road erosion modelling.

This study applies and modifies a road erosion and sediment delivery model to assess road erosion in the Moruya-Deua and Tuross River catchment of southeast Australia. The next section introduces the selection of a model and its structure. The physical characteristics of case study catchments are described in Section 3. Application of the model, including the description of the special data processing, is described in Section 4. A summary of key model results is then presented. In Section 6, several improvement options for the model are discussed.

2. MODEL STRUCTURE

2.1. Model Selection

The scope of this study requires the road model to estimate contributions of road sediment at a catchment scale, be relatively simple, have modest data requirements, and be testable. The Washington Road Surface Erosion Model (WARSEM) was selected as a basis for the road model for the following reasons:

- It can be applied at catchment scales;
- It incorporates most of the major factors thought to control rates of road erosion;
- It can be used for management-oriented applications;
- Its structure is easy to implement in a GIS application;
- It has flexibility to be modified and applied in different environmental settings; and
- Most data required for the model are either available, or can be easily collected in the field.

2.2. WARSEM

WARSEM is an empirical model used to estimate long term average sediment delivery from roads to streams. It was developed by the Washington State Department of Natural Resources (Dubé *et al.*, 2004). WARSEM considers sediment sources from multiple features, including the road surface, the ditch, and cutslope. Cutslopes are not considered in this study because their stability was assessed as moderately high by inspection.

A base erosion rate is estimated on the basis of average annual rainfall. This rate is multiplied by a series of factors that act to increase or decrease the base erosion rate. These factors are derived from the literature on the effects of changes in road characteristics affecting road erosion and sediment delivery (Dubé *et al.*, 2004).

2.3. Road Model Structure

The road model modified from WARSEM (Dubé *et al.*, 2004) is described below:

$$E = RE \times CAP \times SDR \quad (1)$$

$$RE = BE \times G \times SF \times S \times T \times CA \quad (2)$$

$$BE = 3 \times 10^{-5} \times R^{1.5} \quad (3)$$

$$CA = L \times W \quad (4)$$

$$SDR = \max(0, \frac{103.62 \times e^{-D/32.88} - 4.95}{100}) \quad (5)$$

Here E is total sediment delivered to a stream from each road segment (kg yr^{-1}); RE is road surface sediment yield from each road segment (kg yr^{-1}); CAP is the contributing area proportion (percentage); SDR is the sediment delivery ratio (percentage); BE (kg m^{-2} yr^{-1}) is an erosion rate based on average annual rainfall (R, in mm yr^{-1}); G is a geologic erosion factor (dimensionless); SF is a road surfacing factor (dimensionless); S is a road slope factor (dimensionless); T is a traffic factor (dimensionless); CA is contributing road area (m^2), calculated by multiplying the segment length (L, in meters) and road width (W, in meters); and D is the distance between road drain outlet and streams (meters).

The factor values are based on those of WARSEM (Dubé *et al.*, 2004), with modifications corresponding to available data on the catchment geology, surface, and traffic. The values utilised are listed in Table 1.

Table 1: Factor values for input parameters

Factor	Value	Factor value
Geology (G)	Metasediment	4
	Granite	4
	Others	1
Surface (SF)	Sealed	0
	Unsealed (worn gravel)	0.6
Road slope (S)	< 5 %	0.2
	5 – 10 %	1
	> 10 %	2.5
Traffic (T) (values are based on road function classification)	Arterial roads	8
	Subarterial roads	8
	Local roads	2
	Track vehicular	1
	Path	0
Contributing area proportion (CAP)	-	0.8

Field investigation of the study area suggests that the distinctions of different road configurations (i.e. insloped, outsloped and crown) are not simple. Most often, a road segment is a combination of different configurations. Thus, instead of using road configuration to estimate road surface contributing area (as in WARSEM), a contributing area proportion (CAP) factor is used. The CAP is the percentage of road surface that has effective runoff delivered to the drain outlet. The remaining road surface delivers diffuse runoff to the lower hillslope from the road side. Considering the low energy in diffuse roadside runoff, this proportion of the road surface is assumed to have no effect on sediment delivery to the streams.

3. DESCRIPTION OF CASE STUDY CATCHMENT

3.1. Catchment Characteristics

The Moruya-Deua and Tuross River catchments are located along the southeast coast of Australia (Figure 1). The annual average rainfall ranges from 700 mm to 1100 mm. The Moruya-Deua River drains a catchment of approximately 1420 km^2. The Tuross catchment is located to the south and adjacent to the Moruya-Deua catchment. It has a total area of approximately 1820 km^2. Both catchments are dominated by native eucalypt forests with metasedimentary lithologies.

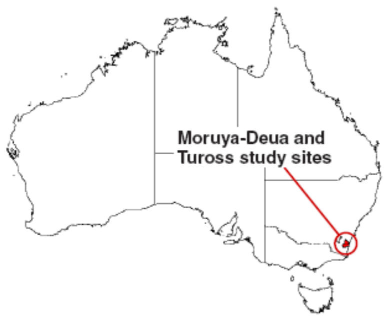

Figure 1: The location of study catchments.

The Moruya-Deua and Tuross River catchments have road lengths of 1120 km and 2090 km, respectively, with road densities of 0.78 km/km^2 for the Moruya-Deua River catchment, and 1.14 km/km^2 for the Tuross River catchment. Most of the roads are located in the lower parts of the catchments and are associated with forest access. Approximately 89% and 97% of the roads are unsealed in the Moruya-Deua and Tuross River catchments, respectively.

3.2. Data collection

The spatial data required for application of the model include: 25 m digital elevation (DEM), geology, and road network data. All data were obtained from NSW Government agencies. The road network data contain the classification of the roads based on function (primary, arterial, subarterial, local, track and path), and road surface (sealed or unsealed). These data are representative of what are available for the remainder of southeastern Australia.

Field data were also collected for selected road segments. The measurements include: location and type of drains, segment length, width, CAP, slope, and surface type. A road segment was identified as the length of a road that drains to the same drainage outlet. The ends of a road segment are a hilltop, or mitre, culvert, stream crossing, or the end of a road. Road drain outlets were located using GPS, and drainage types were recorded. The contributing area of the road surface proportion was recorded based on observation. A distance measuring wheel was used to measure the length of the road segment and a measuring tape was used to measure the width of a road segments (defined as the road surface area that bears traffic). The slope of a road segment was measured using a clinometer. The surface characteristics of the road were inspected and recorded

Four types of roads were sampled: arterial roads, subarterial roads, local roads, and tracks. The number of segments, range of slope, and the length and width of roads are summarised in Table 2.

Table 2: Summary of slope range, average length and average width of sampled roads

Road type	Arterial	Sub-arterial	Local	Track
Number of segments	25	12	20	20
Slope (degree)	0.1 - 6.0	1.0 - 6.0	0.1 - 6.3	1.2 - 9.0
Segment length (m)	50	100	70	55
Road width (m)	5.4	3.9	3.2	2.8

4. MODEL APPLICATION

The model application is divided into two steps. The first step involves using an Arc Macro Language (AML) script to generate spatial inputs for the model. This is followed by estimating sediment yields and delivery for each segment using Microsoft Access. The details of the approaches are described below.

4.1. Generating spatial data inputs

In WARSEM, all the roads need to be sampled so that the segment length and width, and road slopes are precisely known. However, these data are not available in the study area, and sampling all roads is not practicable. It was assumed that the segment length and width are the same for the roads with same function. The average segment length and width obtained from field measurements were used to divide roads into segments. The road slope was calculated using the elevation of the two ends of a road segment, and the length of the segment.

An annual average rainfall surface was produced by the Kriging method in ArcMap, using data from 83 rain gauges within and surrounding the catchments. The mean value of the two ends of a road segment was used for model input. The road-to-stream distance was calculated using the flow distance of the road end with lower elevation. The flow distance grid was obtained by using the flow length tool in ArcMap. Other model inputs were obtained directly from spatial data. The AML script was run to generate segments and their corresponding input values.

4.2. Estimating sediment yields and delivery

The input data were exported to Microsoft Access. The queries were built based on the model structure described in Section 2.3.

The impacts of road management options can be modelled, including the changes of road surface, traffic use, drain spacing and road contributing area proportion. Re-gravelling or sealing native dirt roads leads to a lower surface factor. Reducing traffic level results in lesser disturbance of the road surface, hence less erosion. Changing road configuration, increasing the proportion of outsloped surface of a road segment within safety standards can reduce the road contributing area proportion, hence reduce sediment delivery (but not erosion). Three scenarios were run for selected road segments:

- Re-gravelling the road surface, which reduces the surface factor from 0.6 to 0.2;
- Reduced traffic level, which reduced the traffic factor from 8 to 5; and
- Reduced road contributing area proportion, which reduced the CAP factor from 0.8 to 0.6.

5. RESULTS

5.1. Catchment-scale sediment yield and delivery

The overall modelled estimates of sediment yields from unsealed roads of the Moruya-Deua and Tuross River catchments are approximately 13 kt/yr and 20 kt/yr, respectively. About 8 % and 5 % of the sediment is delivered to the streams in the Moruya-Deua and Tuross River catchments, respectively. The roads that actively deliver sediment to stream network account for approximately 16 % and 14 % of the total road lengths. The distribution of sediment delivery in the Moruya-Deua and Tuross River catchments are shown in Figure 2.

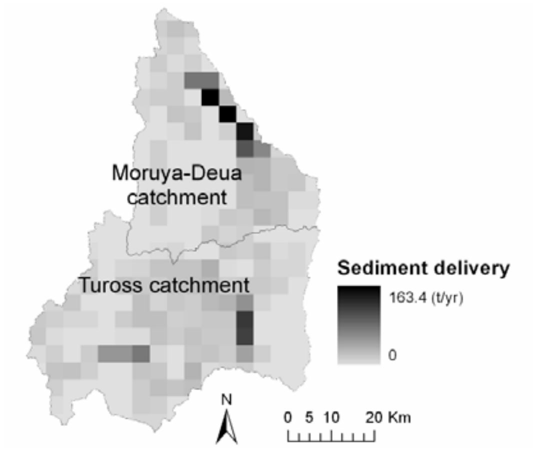

Figure 2: Sediment delivery in the Moruya-Deua and Tuross River catchments. Note that results are lumped at a 4 km^2 resolution for display purpose.

The annual average sediment delivery from roads is compared with event-based suspended sediment loads generated by Drewry (unpublished) (Table 3). The suspended sediment loads were estimated using a log discharge-concentration regression (Letcher *et al.*, 2002), with consideration of the time shift between the concentration and flow. The road-derived sediment accounts for 26 % and 57 % of the total sediment loads in the Moruya-Deua and Tuross River catchment, respectively.

Table 3: Comparing sediment delivery from roads, and whole catchment sediment loads in 2005 (Drewry, unpublished)

Catchment	**Road sediment (t/yr)**	**Total sediment (t/yr)**	**Road sediment proportion (%)**
Moruya-Deua	1011	3816	26
Tuross	1060	1703	57

5.2. Management

Three roads are identified as having high sediment delivery: the Araluen Road in the Moruya-Deua River catchment, and the Eurobodalla – Reedy Creek Road and the Bourkes – Wadbilliga Road in the Tuross River catchment. All of these roads are either arterial or subarterial roads, which have higher traffic levels and are wider. The Araluen Road is estimated to deliver approximately 730 t/yr of sediment to streams, equivalent to about 72 % of the total road-derived sediment in the Moruya River catchment (from 2.6 % of the total road length in the catchment). The road segments of the Eurobodalla – Reedy Creek Road and the Bourkes – Wadbilliga Road are only 1.4 % of the total length of road in the Tuross River catchment; but deliver 42 % of the total sediment. These results indicate that focussing management on these roads can be cost-effective.

The scenarios described in Section 4.2 are applied on four road sections, with a total management length of 60 km, equivalent to 1.8 % of the total road length. The results show that re-gravelling on these roads can reduce the sediment delivery by 35 – 50 % in both catchments (Figure 3). Nearly a third of sediment delivery can be reduced if the traffic levels are reduced. Reducing effective road contributing area by changing road surface configuration is least effective in reducing sediment delivery.

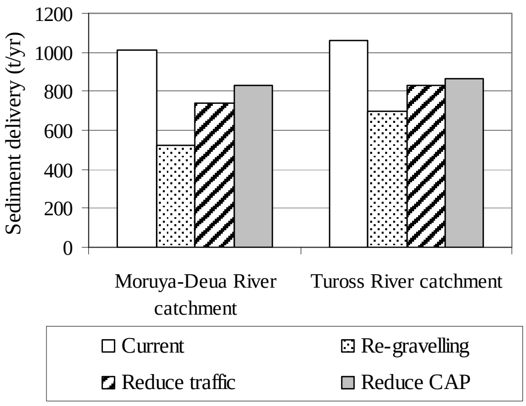

Figure 3: Sediment delivery under current conditions and for three different management options (re-gravelling, reduced traffic and reduced contributing road proportion) on critical road segments.

6. ONGOING WORK ON MODEL IMPROVEMENT

6.1. Monitoring data

The model application is largely based on widely available data in southeastern Australia, and some limited field measurements. However, monitoring data, such as the location of the drains (i.e. the segment length), road width, road slope, more detailed traffic levels and road surface conditions are lacking. As a result, uncertainty in model application on individual segments can be high. In this study, model inputs on segment length and width were based on a small subset of roads sampled. Steps should be taken to address this data gap.

Road monitoring programs are expensive. However, the results of this paper suggest that most of the sediment delivered to the streams is derived from a very small proportion of the roads. Hence improving road monitoring programs on the identified critical road erosion sections will improve confidence in model predictions. This approach can be applied to other catchments, to refine monitoring programs based on the results of preliminary modelling from generally available data, and then refine the model application by improving monitoring data.

6.2. Sediment delivery ratio

In WARSEM, the SDR is a function of the distance between the road drain outlet and streams. However, it is argued that the contributing road area is also an important factor affecting the volume of sediment delivered to streams (Croke and Mockler, 2001; Hairsine *et al.*, 2002). This is because larger contributing areas produce larger volumes of runoff, which have greater potential to reach the streams.

Hairsine *et al.* (2002) estimate the probability of road runoff reaching the streams based on both the distance between the road drainage outlet and streams, and the road contributing area. However, there has been no investigation to relate hydrological connectivity to SDR. A conceptual diagram based on a hydrological connectivity model (Hairsine *et al.*, 2002) has the broad behaviour expected for sediment and is shown in Figure 4. When the road drainage outlet is very close to the streams, the SDR is high regardless of the road contributing area. However, when the road-stream distance increases, the road contributing area becomes important. Large road contributing area keeps the SDR high, even the road to stream distance is large.

Data are needed to test this conceptual framework for sediment and generate an SDR model. If this relationship is identified, the impact of changing drainage spacing on sediment delivery can then be modelled, and greater confidence placed on the model outputs.

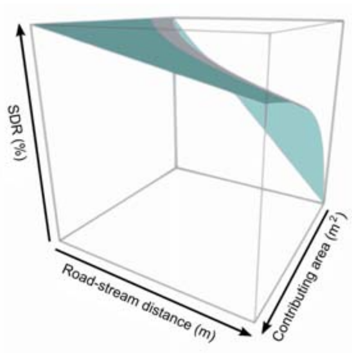

Figure 4: Conceptual diagram of the relationship between SDR and road to stream distance, and road contributing area, derived from a hydrological connectivity model (Hairsine *et al.*, 2002).

6.3. Model testing

Published sediment load monitoring data for unsealed road erosion are rare in Australia, which is a major constraint for model testing. There are a few studies conducted on forest roads in coastal lowlands of southeastern NSW (Croke *et al.*, 2006), and the Central Highlands of Victoria (Sheridan and Noske, 2007).

An alternate approach for model testing is to use sediment tracing techniques. Motha *et al.* (2003) used geochemical and radionuclide tracers in the West Tarago catchment of Victoria, and identified 18 – 39% of the sediment in the forest catchment are derived from unsealed roads. Using sediment tracing, in conjunction with total suspended sediment monitoring program, the volume of road-derived sediment can be estimated. This research is currently underway.

7. CONCLUSION

Unsealed roads in forest catchments are recognised as an important source of diffuse sediment. This study applied WARSEM to identify critical road segments for sediment delivery. WARSEM was modified according to data availability in the study catchments. These data are also generally available in southeast Australia, making it possible to apply a similar model in other areas.

More than half of the road sediment delivery is derived from only 2% of the roads in the Moruya-Deua and Tuross River catchments. Management on these critical road segments can potentially reduce sediment inputs relatively cost effectively. Sediment delivery was assessed under three management scenarios. Re-gravelling is the most effective management option in reducing sediment delivery.

Due to the limitation of the road measurement data, the uncertainty of the model may be high. Road monitoring programs on segment length, width, slope, and possibly road traffic level and surface condition are recommended for application of any road model to support catchment management.

With respect to model improvement, the SDR is identified as the most important area. A conceptual framework is suggested to estimate SDR as a function of both the distance between the road drain outlet and the steam, and the road contributing area. In addition, model testing using existing data from other studies, and sediment tracing techniques is recommended.

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