18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Integration of a road erosion model, WARSEM, with a catchment sediment delivery model, CatchMODS

Fu, B. [1], **L.T.H. Newham** [1] **and J. Field** [2]

[1] *Integrated Catchment Assessment and Management (iCAM) Centre, The Fenner School of Environment and Society, The Australian National University, Australian Capital Territoy, 2600*
[2] *The Fenner School of Environment and Society, The Australian National University, Australian Capital Territory, 2600*
Email: baihua.fu@anu.edu.au

Abstract: Road surface erosion is increasingly recognised as a potentially important source of suspended sediment delivered to streams and other water bodies, particularly in forested catchments. As a result, several models have been developed to estimate erosion rates and sediment delivery from unsealed roads. However, few studies have integrated such models or their outputs into catchment-scale sediment models so that a more complete simulation of sediment yields from a catchment can be achieved.

This paper describes the integration of a road erosion model, WARSEM, into a catchment-scale sediment delivery model, CatchMODS, using two coastal catchments in southeastern Australia as case studies. The integration process involved the testing of the comparability of sediment delivery rates predicted by the WARSEM and CatchMODS models using geochemical sediment tracing techniques, and the incorporation of the WARSEM outputs into the CatchMODS framework. This study provides comprehensive information on the sources of suspended sediment in the Moruya-Deua and Tuross River catchments, and also, and more importantly, describes a method that can be applied to similar studies that aim at integrating road erosion modelling for the purpose of catchment-scale erosion and sediment delivery assessment.

The annual erosion and sediment delivery rates from unsealed roads in the study catchments were modelled using WARSEM, and the sediment yields from hillslope, gully and streambank erosion were estimated using CatchMODS. Geochemical sediment tracing was employed to test the comparability of CatchMODS and WARSEM using the Goodenough Gully subcatchment as a case study. The results suggest that the level of agreement between the modelling and tracing results is 97% and that the models are comparable. Subsequently, the WARSEM outputs were directly integrated into the sediment routing equation in CatchMODS without modification.

The results of the integrated sediment model suggested that road erosion accounts for 9% and 10% of the total sediment yields in the Moruya-Deua and Tuross River catchments, respectively. The integration of WARSEM and CatchMODS can be a useful tool for catchment managers to investigate the potential impacts of comprehensive management options including road, landuse and riparian management on sediment yields at a catchment scale.

Keywords: *Road erosion modelling, sediment, catchment modelling, sediment tracing, water quality*

1. INTRODUCTION

The significance of unsealed roads to off-site water quality decline is widely acknowledged, especially in forested catchments (Motha *et al.*, 2004; Forsyth *et al.*, 2006; Ramos-Scharrón and MacDonald, 2007). Erosion rates from unsealed roads have been shown to be much greater than in adjacent undisturbed hillslope areas. For example, Croke *et al*. (1999) observed that road erosion rates are six and two orders of magnitude higher than undisturbed hillslope and general harvesting areas respectively in coastal southeastern Australia.

Several road erosion models have been developed to estimate sediment yields from the erosion of unsealed roads and the delivery of the sediment to stream networks (Fu *et al*., Accepted). However, a road erosion model alone cannot provide information such as the importance of road erosion in a catchment compared to other sediment sources such as gully and streambank erosion. On the other hand, catchment scale sediment budget models such as SedNet (Prosser *et al*., 2001) and CatchMODS (Newham *et al*., 2004) have been developed in Australia for hillslope, gully and streambank erosion, but road erosion has not been included in these models. As a result, the sediment budgets estimated from these models may be unreliable for catchments where road erosion is a significant sediment source. The purpose of this paper is to provide an example of integrating a road model with a sediment budget model.

2. STUDY CATCHMENTS

The study sites used for testing the integration of the models are the Moruya-Deua and Tuross River catchments, located along the southeast coast of Australia (Figure 1). The annual average rainfall ranges from approximately 700 mm to 1100 mm declining from east to west. The Moruya-Deua River drains a catchment of approximately 1500 km^2. The Tuross River Catchment is located to the south and adjacent to the Moruya-Deua catchment. It has a total area of approximately 2100 km^2. Both catchments are dominated by managed native eucalypt forests with metasedimentary lithologies.

The Moruya-Deua and Tuross River catchments have road lengths of 1120 km and 2090 km, respectively, with approximately 89% and 97% of the roads unsealed. Most of the roads are located in the lower parts of the catchments and have highest densities in forested areas (Figure 1). Roads in these areas are constructed for access for forest harvesting and associated activities and for fire suppression. The proportions of the roads that are within 100 m to the stream network in the Moruya-Deua and Tuross River catchments are 23% and 20%, respectively.

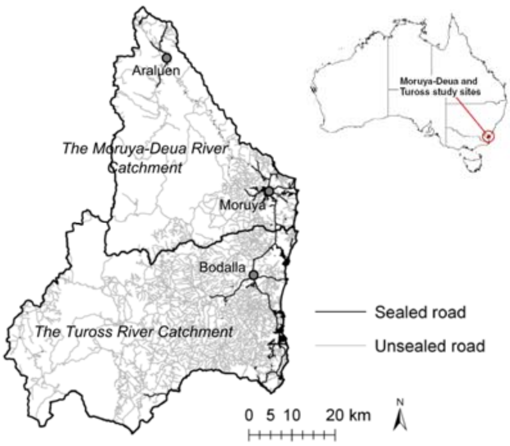

Figure 1. The location of study catchments and the distribution of road network in the study catchments.

The Moruya-Deua and Tuross River catchments provide drinking water supplies for nearby towns including Batemans Bay, Moruya, Bodalla and Narooma. Therefore, water quality is of high concern. The ecological importance of maintaining good water quality in these catchments is also high due to the estuaries and marine habitats they support.

3. BACKGROUND TO MODELS

3.1. 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 is spatially-distributed by road segment. It can be applied at large catchment scale and the effects of a variety of best management practices can be simulated to aid catchment decision making.

WARSEM considers sediment sources from multiple features, including the road surface, the table drain, and cutslope. A base erosion rate is estimated as a function of average annual rainfall. This rate is multiplied by a series of factors that act to increase or decrease the base erosion rate. The delivery of road-derived sediment to a stream is modelled using a sediment delivery ratio based on the distance between road drain outlets to the stream (Megahan and Ketcheson, 1996). The factors are derived from literature on the effects of changes in road characteristics on road erosion and sediment delivery (Dubé *et al*., 2004). A maximum of 15 data inputs are required but these vary according to the intended purpose of the modelling (Dubé *et al*., 2004). These inputs include annual average rainfall, road surface materials, vegetation cover, slope, traffic and maintenance, and the contributing area for the road surface, cutslope and table drain. The factor-based approach used in WARSEM has many similarities to the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). The factors of WARSEM are directly related to road surface erosion while those of the USLE are estimated for agriculture lands.

A number of road erosion models have been developed for different environmental settings (Fu *et al.*, Accepted). WARSEM was selected for this case study mainly because it can be applied at catchment scales, it has the flexibility to be modified and applied in different environmental settings, and most data required for the model are available or can be routinely collected in the field. The structure and applications of WARSEM in the Moruya-Deua and Tuross River catchments is published in Fu *et al*. (In press).

3.2. CatchMODS

CatchMODS is a model framework for simulating water quality conditions and the effects of management on water quality at a catchment scale (Newham *et al.*, 2004). CatchMODS contains hydrology, sediment and nutrient submodels, and a simple economic component to simulate the trade-off between investment in remediation and water quality improvement. Outputs from CatchMODS include streamflow, annual average suspended sediment (SS) yields, total nitrogen and phosphorus yields, and the costs for management scenarios. Detailed descriptions on CatchMODS can be found in (Newham *et al*., 2008), and the applications of CatchMODS on the Moruya-Deua and Tuross River catchments are described in Fu (2008).

4. COMPARABILITY BETWEEN WARSEM AND CATCHMODS

Testing of the WARSEM model based on sediment load data for the study catchments suggests that it is likely to overestimate the sediment yields from roads (Fu *et al.*, In press). If identifying critical road segments is the purpose of the study, overestimation of the total sediment yield is not so important, as long as the relative level of road erosion and sediment delivery within the catchments is accurate. However, when integrating the results of WARSEM with CatchMODS, the relative accuracy of sediment yields estimated between CatchMODS and WARSEM is vital. As a result, the first step towards model integration is to test the comparability of model outputs from CatchMODS and WARSEM.

4.1. Methods

Geochemical sediment tracing was employed to test the comparability of CatchMODS and WARSEM using the Goodenough Gully subcatchment (Figure 2). The Goodenough Gully subcatchment, located in the midstream section of the Moruya-Deua River, is approximately 3.7 km^2 in area and is dominated by native forests. Approximately 700 m of the Araluen Road cuts through the lower subcatchment. No gully or streambank erosion was observed in the subcatchment, hence hillslope and road erosion were identified as the dominant SS sources in the subcatchment.

Sediment tracing was used to estimate the relative contribution of the hillslope and road sources to the downstream sediment mixture. Hereto, three and seven topsoil samples were collected from the road and hillslopes, respectively, in the Goodenough Gully subcatchment, together with three deposited sediment samples from the Goodenough Gully at a point 150 meters downstream of the road-

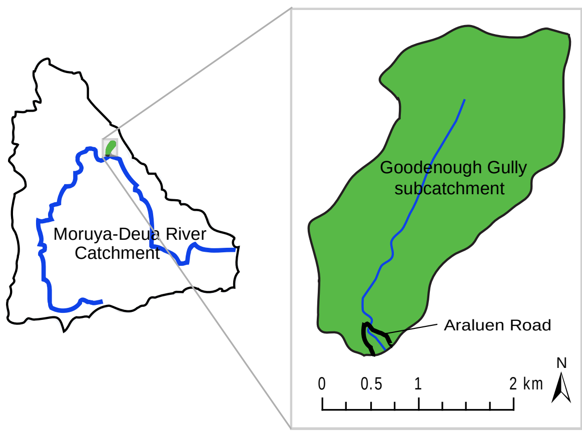

Figure 2. The Goodenough Gully subcatchment showing its location in the Moruya-Deua River catchment and the positions of the stream and road.

stream crossing.

The less than 63 µm fraction samples were used for geochemical analysis by Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES). The resulting SS geochemistry was used to identify the proportional contribution of SS from hillslope and road. The multivariate mixing model for SS source discrimination is described below (Collins *et al.*, 1998):

$$\text{Minimize } \sum_{i=1}^{n}((C_i - E_i)/C_i)^2) \qquad (1)$$

Where $E_i = R_i x + H_i y$, constrained by: $x + y = 1$, and $0 \le x \le 1$.

Here C_i is the median concentration of tracer i in the downstream sample; E_i is the estimated concentration of tracer i in the downstream sample; R_i and H_i are the median concentrations of tracer i in road and hillslope samples, respectively; x and y are the percentage contributions from road and hillslope, respectively.

The tracers were selected based on two criteria: (i) the element concentrations of samples from road and hillslope were required to be significantly different and (ii) the element concentrations of samples from downstream lie between those from the road and hillslope. As such it was found that the most suitable tracers were Fe and Pr.

The estimated contributions of road and hillslope sources to the suspended sediment yield were subsequently compared to the suspended sediment yields from roads and hillslopes modelled by WARSEM and CatchMODS respectively. The comparability is tested based on the level of agreement between the outputs of modelling and tracing, as calculated using the formula expressed below. It is assumed that when the agreement level is greater than 90%, then CatchMODS and WARSEM results are comparable and the two models can be integrated directly. The formula is:

$$a = 1 - (y_m - y_t)/y_t \qquad (2)$$

Here a is the agreement level between the models and tracing; y_m is the estimated SS contribution from modelling; and y_t is the mean estimated SS contribution from sediment tracing.

4.2. Results

Sediment tracing results show that the proportional SS contributions from road and hillslope to the downstream Goodenough Gully are 96.3% and 3.7%, respectively, with a variance of 5.1%.

The SS yield from hillslopes of the Goodenough Gully subcatchment, estimated by CatchMODS, is approximately 0.4 t yr^{-1}. The sediment delivery from roads in the subcatchment to stream is estimated to be 47.0 t yr^{-1}, using WARSEM. The road sediment delivery is high because most of the road segments are close to the stream. Assuming the road and hillslope are the only sources of SS to the downstream sediment, the proportional contributions of road and hillslope erosion to downstream SS are 99.1% and 0.9%, respectively.

The agreement level between the modelling and tracing results is 97% and in fact, the results from modelling are completely within the ranges of SS contributions suggested by the geochemical sediment tracing. Therefore, the sediment yields predicted by the models are comparable and no modification is needed when integrating WARSEM with CatchMODS.

5. MODEL INTEGRATION

The road sediment delivery rates estimated by WARSEM were summarised for each subcatchment defined in CatchMODS. They were then integrated with the sediment yields from hillslopes, gullies and streambanks estimated by CatchMODS. The sediment routing from each subcatchment was then modified as below to include the SS yield from road erosion:

$$X_{out,i} = X_{out,j} + H_i + G_i + S_i + R_i - F_i \qquad (3)$$

Here $X_{out,i}$ is the sediment routing from subcatchment i; $X_{out,j}$ is the sediment routing from the upper subcatchment j; H_i, G_i, S_i and R_i are the simulated SS yields from hillslope, gully, streambank and road erosion from subcatchment i; and F_i is the floodplain deposition in subcatchment i.

5.1. Modelling results

Using the integrated sediment model, total SS yields from the Moruya-Deua and Tuross River catchments are both estimated to be 13.7 kt yr^{-1}. Total floodplain deposition was estimated to be about 2 t yr^{-1} in each catchment. The spatial distribution of the estimated total SS yields, as well as the SS yields from hillslope, gully, streambank and road erosion are shown in Figure 3.

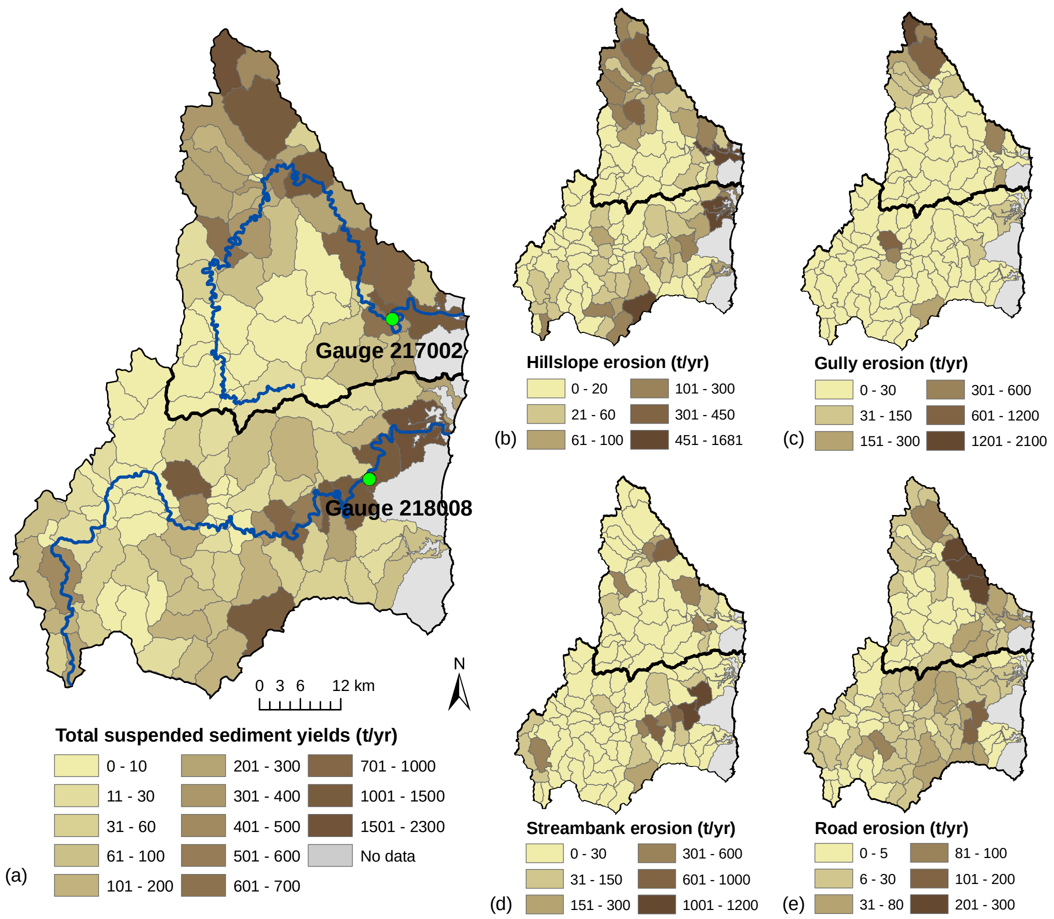

Figure 3. Estimated SS yields from the integrated sediment model, showing (a) total SS yields; (b) SS yields from hillslope erosion; (c) SS yields from gully erosion; (d) SS yields from streambank erosion; and (e) SS yields from road erosion.

The total SS yields for each subcatchment were calculated by subtracting the floodplain deposition from the SS yields from hillslope, gully, streambank and road erosion in each subcatchment, so that sediment routing from the upper subcatchment was excluded. The model results suggest that major SS sources include the subcatchments along the middle to lower Moruya-Deua River, the Araluen Creek, and the middle to lower Tuross River.

In the Moruya-Deua River catchment, hillslope, gully, streambank and road erosion contribute 32%, 33%, 26% and 9% of SS, respectively. In contrast, streambank erosion in the Tuross River catchment contributes nearly half of the SS. Road erosion is estimated to provide 10% of the total SS in the Tuross River catchment.

5.2. Model evaluation

The estimated SS yields from the areas upstream of gauges 217002 and 218008 (as shown in Figure 3a) calculated by the integrated sediment model were compared with the SS loads obtained from event-based SS monitoring in 2005 (Drewry *et al.*, 2005; Drewry *et al.*, 2009). The SS yields estimated by the integrated sediment model for the subcatchments upstream of the gauges are 10.7 and 10.4 kt yr^{-1}, respectively. This is approximately three and six times as high as the calculations made from event-based SS monitoring, respectively. These differences can be explained by the time periods over which each is estimated. The estimate from the integrated sediment model was for the last 20 years, whereas the SS load calculation made by Drewry *et al.* (2009) was only for 2005, which was one of the driest years within the last 20 year period. The annual discharges recorded at the two gauges are both 1.2×10^5 ML in 2005, which is equivalent to about 60% and 46% of the annual average discharge for the 1983–2008 period in the Moruya-Deua and Tuross River catchments, respectively. It is very likely that the lower discharge in 2005 has resulted in relatively low SS yields.

A second explanation for the differences between the monitored and modeled SS yield estimates is that the integrated sediment model may overestimate the SS yields owing to overestimation of erosion and/or underestimation of deposition. For example, the RUSLE model, as used for hillslope erosion estimation in CatchMODS, has been reported to overestimate SS yields for forest areas (Croke and Nethery, 2006). Consequently, both underestimation of SS yields by monitoring data and overestimation of SS yields by the integrated sediment model could cause the differences between integrated model outputs and SS loads estimation.

6. DISCUSSION AND CONCLUSIONS

When integrating two models, it is crucial to have output-comparable components in the integrated sediment model. This does not only apply to the comparability between WARSEM and CatchMODS, but also within CatchMODS to the modelling of hillslope, gully, and streambank erosion and floodplain deposition. This is because comparable, if not accurate, estimation of SS yields from hillslope, gully, streambank, road erosion and floodplain deposition, is an assumption that underlies the sediment routing algorithm (Equation 3). If the estimates of SS yields from the above five components are not comparable, then the outputs of the sediment routing algorithm are biased towards the components that are relatively overestimated. In this case, the sediment routing algorithm should be modified to include appropriate weight factors for the components.

In this study, only the hillslope erosion modelling in CatchMODS was tested against the WARSEM for one small subcatchment with forest as the only landuse type. The comparability between the hillslope, gully, streambank, and road erosion, and floodplain deposition should be further tested for subcatchments that involve a wider range of erosion and landuse types. Potential testing areas include the subcatchments in the Araluen and Belowra valleys where hillslope, gully, streambank and road erosion exists and a mixture of forest and pasture landuses are present.

Whilst not attempted in this research, inclusion of a road submodel such as WARSEM into the CatchMODS framework is needed. The integration will not only simplify the modelling processes, but will also allow CatchMODS users to simulate SS yields based on different road management scenarios. The integration can expand the modelling capacity of CatchMODS for road erosion and thus allow CatchMODS to provide a more complete simulation of a sediment budget.

For the inclusion of a road submodel, a minimum of two additional sets of data are needed as inputs to CatchMODS, and six additional parameters. The two input data sets are geology and road network, with the latter including information on the road position, surface, traffic, width and segment length. Other input data for the road submodel, such as the annual average rainfall and DEM, are already included in CatchMODS for hydrology and sediment submodels. Additional parameters include two rainfall parameters, a contribution area proportion, and three parameters for the calculation of the road to stream sediment delivery ratio. As previously mentioned, parameterisation of the road submodel from Australian data is needed for future model development.

After the inclusion of the road submodel in CatchMODS, management scenarios such as relocation of existing roads, positioning of new roads, changing surface conditions, changing drainage spacing, and traffic control can be included in the CatchMODS user interface. These management options, together with existing landuses and riparian management options in CatchMODS, provide useful tools for catchment managers to investigate potential best management practices.

ACKNOWLEDGMENTS

This research was undertaken with funding from the Australian Research Council and Eurobodalla Shire Councils as part of project LP0560439. Support from the Australian National University and the Department of Environment and Climate Change were also provided and are gratefully acknowledged.

REFERENCES

Collins, A.L., Walling, D.E. and Leeks, G.J.L. (1998), Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms,* 23: 31-52.

Croke, J., Hairsine, P. and Fogarty, P. (1999), Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. *Hydrological Processes,* 13: 2705-2720.

Croke, J. and Nethery, M. (2006), Modelling runoff and soil erosion in logged forests: scope and application of some existing models. *CATENA,* 67: 35-49.

Drewry, J.J., Greene, R.S.B., Newham, L.T. and Croke, B.F.W. (2005), The role of soil regolith properties, river suspended sediment and nutrient concentrations during storm events in the Moruya and Tuross catchments, NSW. In: *Regolith 2005 – Ten Years of CRC LEME*, Roach, I.C. (Ed.). Cooperative Research Centre for Landscape Environments and Mineral Exploration. Adelaide and Canberra. pp. 78-82.

Drewry, J.J., Newham, L.T.H. and Croke, B.F.W. (2009), Suspended sediment, nitrogen and phosphorus concentrations and exports during storm-events to the Tuross estuary, Australia. *Journal of Environmental Management*, 90(2): 879-887.

Dubé, K., Megahan, W. and Mccalmon, M. (2004), *Washington Road Surface Erosion Model (WARSEM) Manual*, State of Washington, Department of Natural Resources.

Forsyth, A.R., Bubb, K.A. and Cox, M.E. (2006), Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain Pinus plantation. *Forest Ecology and Management,* 221: 194-206.

Fu, B. (2008), An integrated catchment-scale approach to identifying suspended sediment sources. Unpublished PhD thesis. The Australian National University.

Fu, B., Newham, L.T.H. and Ramos-Scharrón, C.E. (Accepted), A review of surface erosion and sediment delivery models for unsealed roads, submitted to *Environmental modelling and software*.

Fu, B., Newham, L.T.H. and Field, J.B. (In press), Modelling erosion and sediment delivery from unsealed roads in southeast Australia. *Mathematics and Computers in Simulation*. doi:10.1016/j.matcom.2008.10.001.

Megahan,W.F., and Ketcheson, G.L. (1996), Predicting downslope travel of granitic sediments from forest roads in Idaho, *Journal of the American Water Resources Association*, 32, 371-382.

Motha, J.A., Wallbrink, P.J., Hairsine, P.B. and Grayson, R.B. (2004), Unsealed roads as suspended sediment sources in an agricultural catchment in south-eastern Australia. *Journal of Hydrology,* 286: 1-18.

Newham, L.T.H., Drewry, J.J. and Fu, B. (2008), Catchment-scale water quality modelling and integration of collateral information. In: *Integrating Sciences and Information Technology for Environmental Assessment and Decision Making, Proceedings of the 4th Biennial Meeting of the International Environmental Modelling and Software Society Vol. 1*, Sànchez-Marrè, M., Béjar, J., Comas, J., Rizzoli, A.E. and Guariso, G. (Eds.). International Environmental Modelling and Software Society, Barcelona. pp. 584-591.

Newham, L.T.H., Letcher, R.A., Jakeman, A.J. and Kobayashi, T. (2004), A framework for integrated hydrologic, sediment and nutrient export modelling for catchment-scale management. *Environmental Modelling & Software,* 19: 1029-1038.

Prosser, I., Rustomji, P., Young, B., Moran, C. and Hughes, A., 2001. *Constructing river basin sediment budgets for the National Land and Water Resources Audit.* CSIRO Technical Report 15/01. CSIRO Land and Water, Canberra.

Ramos-Scharrón, C.E. and MacDonald, L.H. (2007), Runoff and suspended sediment yields from an unpaved road segment, St John, US Virgin Islands. *Hydrological Processes*, 21:35-50.

Wischmeier, W.C. and Smith, D.D. (1978), Predicting rainfall erosion losses – a guide to conservation planning. *Agricultural Handbook Vol. 537*. U.S. Department of Agriculture, Washington, D.C..