Predicting Suspended Sediment Loads At A Catchment Scale: A Comparison Between Models

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Keywords: *Suspended sediment load; Model prediction; Murrumbidgee River catchment; Uncertainty.*

EXTENDED ABSTRACT

Owing to financial and other constraints on natural resource management, comprehensive data on the physical processes that determine in-stream water quality are rare. Consequently, managers are looking to models as decision-making tools. One important application is to identify areas in greatest need of erosion management. There are many ways that suspended sediment loads can be assessed. The main constraints in the determination of loads are the data available and the scale at which this information can be applied. This study has used two models to estimate the suspended sediment load in a number of catchments in the mid-region of the Murrumbidgee River catchment. The load derived using an empirical estimation technique is compared to the load predicted from a semi-distributed, lumped conceptual model (SedNet). Both these models can predict suspended sediment loads at a catchment scale with minimal data requirements compared to more complex physics-based models. Even so, it is important to recognise that these models predict loads at different time scales and include different assumptions, which can result in significant differences in the derived suspended sediment load. Nevertheless, managers rely on such models because of the reduction in available data to directly measure suspended sediment load and the increasing pressure for effective resource allocation. Hence, it is necessary to ensure consistency in the models used to assess water quality.

Three sub-catchments in the Mid-Murrumbidgee River catchment - Tarcutta, Muttama and Jugiong creek catchments - were used for the suspended sediment load comparison. The comparison presented in Table 1 indicates that the long-term steady-state prediction from SedNet is within the statistical uncertainty for two of the catchments (Muttama and Tarcutta creek catchments) on a per area basis. However, it seems that there is a large discrepancy between the empirical model estimate and SedNet prediction for the Jugiong creek catchment.

Table 1: Comparison of suspended sediment load estimates/prediction from two models

Site	Area (km^2)	Load t/ha/y	Upper limit t/ha/y	Lower limit t/ha/y	SedNet Load t/ha/y
Jugiong	2127	0.116	0.276	0.049	0.374
Muttama	1059	0.135	0.259	0.071	0.252
Tarcutta	1637	0.217	0.488	0.097	0.354

The large discrepancy for Jugiong Creek may indicate that there are serious inaccuracies in the models used to predict suspended sediment load. Possible reasons may include the limitation that suspended sediment concentration (SSC) measurements used to estimate the load for the Jugiong creek catchment are not necessarily representative of the long term load. Another possibility considered is that SedNet may over-predict the amount of suspended sediment from its sediment sources. Supporting this theory is the high gully erosion density in Jugiong compared to the other two catchments. An over-prediction in suspended sediment from gully erosion may explain the contradiction between modelled load estimates for Jugiong. Owing to the uncertainty in both models, it is unlikely that either is correct.

The use of these models as a tool to support policy and management prioritization is jeopardized when differences in model outputs contradict the ranking of catchments. Tarcutta creek catchment is the highest contributor of suspended sediment to the Murrumbidgee River using the empirical sediment rating curve model but the Jugiong creek catchment is highest when using the SedNet model. This research illustrates that differences between models will greatly affect the types of decisions that can be made based on the output of these models. It is clear that for effective natural resource management, a better understanding of the uncertainty and limitations of such models is needed.

1. INTRODUCTION

Suspended sediment loads in rivers are an indicator of river health. Yet, the direct measurement of suspended sediment load is difficult. Therefore most assessments of suspended sediment loads are either estimated from relationships between suspended sediment concentration and flow or predicted from source inputs. The models used to estimate or predict suspended sediment loads can assist to target allocation of resources to areas that are potentially the main sources of sediment to rivers.

The use of models to assess suspended sediment load also brings in the problem of uncertainty. Newham *et al.* (2003b) compared SedNet to empirical sediment loads as well as other methods of suspended sediment prediction for the upper Murrumbidgee River catchment. It was concluded that, while SedNet compared well to these other techniques to estimate suspended sediment loads, area of the catchment, temporal resolution and method uncertainty resulted in the possible over-estimation of load by SedNet.

This current study compares the output of two models in determining the suspended sediment load of three catchments in the Mid-Murrumbidgee River catchment. An empirical model using a sediment rating curve to determine a suspended sediment load over a 17-year period is compared to the load predicted from a semi distributed, lumped conceptual model (SedNet) that estimates annual average loads over a 100-year period. Both these models can predict suspended sediment loads at a catchment scale with minimal data requirements, when compared to other physics-based models. The uncertainty and assumptions in both models will be discussed as well as the implication of the model outputs for management of water quality.

2. STUDY CATCHMENTS

This research is focused in the Mid-Murrumbidgee River catchment. This focus is motivated by the findings of Olive *et al.* (1994) where it was found that the peak of suspended sediment load for the Murrumbidgee River is found at Wagga Wagga, NSW. The three catchments that are used in this comparison are Jugiong, Muttama and Tarcutta creek catchments, (see Figure 1) which are located between Burrinjuck Dam and Wagga Wagga. Burrinjuck Dam is assumed to trap all sediment mobilized in the upper Murrumbidgee catchment and so all catchments west of the dam are considered to be the sources of sediment observed at Wagga Wagga.

The Mid-Murrumbidgee is dominated by a humid climate with average annual rainfall of 600 to 800mm/yr which is winter-spring dominated; in this region occasional summer storms also occur. Those catchments that are likely to contribute the greater volume of sediment to the Murrumbidgee River occur in the southern slopes owing to the presence of 20 to 25% slopes in combination with a predominantly cleared landscape used for grazing, with Muttama and Jugiong catchments examples of southern slope like catchments (Lucas, 1997).

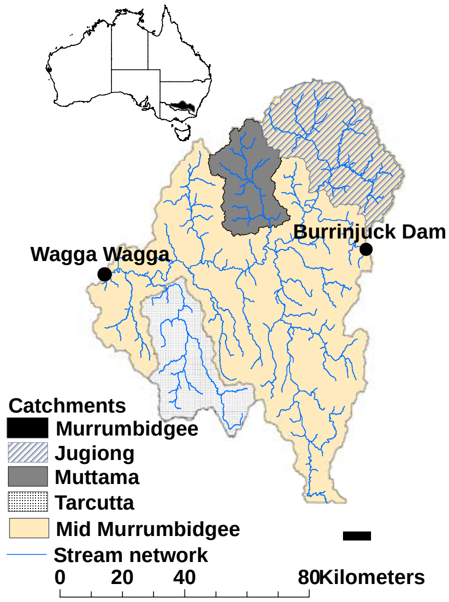

Figure1: Study area location and distribution of stream network.

3. EMPIRICAL MODEL

The empirical model employed in this study uses measured suspended sediment concentrations (SSC) at particular flows to infer a relationship between sediment concentration and flow. This relationship is used to both interpolate between measurements and in some cases extrapolate beyond the measurements, which increases the uncertainty in the load estimate. The model allows SSC to be predicted for all flows over a particular time period. To obtain a load from these predictions, the predicted SSC and flow are multiplied and then summed to produce a load over a specified flow time period. In this example the time period spans from 1/1/1981 to 1/1/1998. It is acknowledged that using a different flow period to the concentration collection period may increase the uncertainty in the load estimate. Nevertheless, the uncertainty was thought to be greater if the flow record contained gaps. To ensure a continuous flow record the date of the flow differs from the concentration collection period.

The SSC data were collected by the NSW Department of Infrastructure Planning and Natural Resources (DIPNR) for all three catchments from November 1992 to February 2003. Flow data used were from instantaneous stream height gauges, also recorded by DIPNR. The suspended sediment data were from combined event and regular (fortnightly) sampling. A power law relationship was found to best represent the relationship between flow and SSC for all three catchments (Walling, 1978).

$$C_{ss} = aQ^b \qquad (1)$$

Equation 1 allows the calculation of SSC (C_{ss}) to be predicted from flow (Q) at a 5 minutely time step given the relationship found in the collected data; parameters a and b were determined through linear regression. Using the predictions of SSC from the rating curve, these were then multiplied by the corresponding flow to produce a load estimate over a 17-year period.

Figure 3 shows an example of a sediment rating curve for one of the study catchments (Jugiong). There is considerable scatter along the regression curve which is another source of uncertainty in the load prediction; note that the data are plotted on a logarithmic scale. A bias correction factor was applied to the predicted SSC, however this only attempts to correct for the errors associated with the use of log transformation of the data.

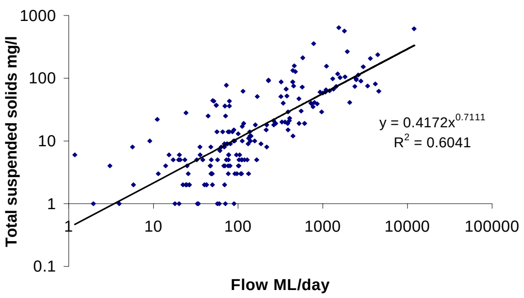

Figure 3: Sediment rating curve for Jugiong Creek Catchment.

There are a number of sources of uncertainty in a suspended sediment load estimate from a sediment rating curve (Smith and Croke, 2005; Walling, 1978). The evaluation of the uncertainty within the load estimate is limited to qualified caveats related to the known limitation of the data. The quantification of the uncertainty within this model is limited to the statistical evaluation of the difference between the measured and predicted suspended sediment values. The results for the suspended sediment load estimates per unit catchment area over the 17 years for the three study catchments are in Table 1, which also indicate the upper and lower statistical limits. These limits were calculated by taking two standard deviations from the mean of each parameter value giving the worst case scenario in the load uncertainty over the 17-year period. These error bars represent the assumption that the error in the fitted values is dominated by systematic error (see Figure 4).

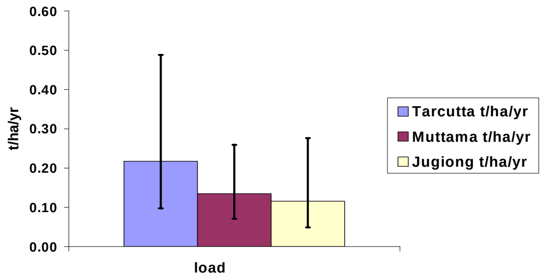

Figure 4: Load estimates from an empirical model dominated by the systematic error in the mean of the parameter values over the total 17 years.

If the uncertainty is assumed to be dominated by random errors it is reduced considerably, as seen in Figure 5. The most representative statistical uncertainty within the load estimates would probably be somewhere between these two extremes.

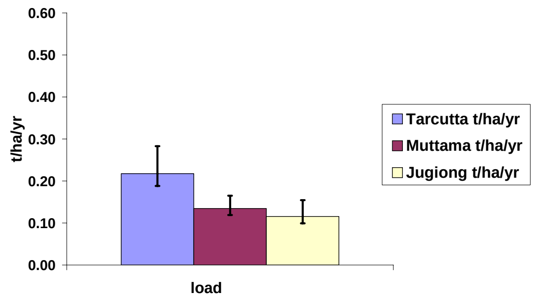

Figure 5: Load estimates from an empirical model dominated by the random error in the mean of the parameter values on a yearly basis.

The difference in the quantifiable uncertainty for the load estimate between Figure 4 and 5 using the empirical model indicates how variable the estimates could be. This uncertainty is only a small fraction that could exist in these results given the inadequate data that were available to use.

To compare the results from this empirical model to another model using a different approach, given this uncertainty, is difficult. Nevertheless, owing to the fact that there is very little data to predict suspended sediment loads these methods are two of the few options available.

4. SEMI DISTRIBUTED LUMPED CONCEPTUAL MODEL

The Sediment River Network Model (SedNet) (Prosser *et al*. 2001) uses sediment inputs, from hillslope, gully and streambank sources, to predict a sediment load (both suspended and bed load) at a catchment scale. SedNet uses a combination of both empirical and conceptual models to quantify sediment erosion, transport and deposition occurring in a stream network. Increasingly, simple models (i.e. few parameters) such as SedNet are required by managers to be developed for smaller scales to prioritise management. The SedNet model can be used to some extent to predict suspended sediment loads at a catchment scale.

Outputs from SedNet for the three catchments are shown in Table 1. This is based on the output of the 2005 version of SedNet with inputs from a 25m DEM and gully and stream bank erosion from aerial photo analysis completed in 1998 by DIPNR.

5. MODEL COMPARISON

The agreement between SedNet and empirical predictions is close, especially given the different approaches used to determine suspended sediment load. Table 1 indicates that the Tarcutta and Muttama creek catchment loads predicted by SedNet are within the statistical uncertainty (systematic dominated error) found in the empirical load estimates using measured data. This suggests that SedNet can be used to give reasonable suspended sediment predictions for some catchments. However, the Jugiong Creek suspended sediment prediction from SedNet is considerably greater than the upper limit of the statistical uncertainty bounds of the suspended sediment load estimate from the empirical model.

As previously mentioned SedNet predicts the long term load while the empirical model uses known SSC data and considers only the load over the last 17 years. Another consideration is that the estimates produced by the empirical model contain greater uncertainty at high flows owing to the lack of measured concentration data for these flows. These aspects may explain the under-prediction of the suspended sediment load by the empirical model.

The results from the other two catchments show reasonable similarities between the two model predictions and suggest that there are some problems with the modelling of the suspended sediment load which is particular to the Jugiong creek catchment. The SSC data collected for all three catchments were similar because the catchments were usually sampled at the same time each fortnight. The event data that could be used for the load estimates were also collected simultaneously. The flow regimes for the three catchments, however, were different due to their catchment characteristics.

These catchment characteristics (see Table 2) are predominantly derived from a 25m DEM; the gully and streambank density is obtained from erosion mapping for the Murrumbidgee River Catchment (DLWC, 1998); flow characteristics are from Pinneena flow data base 2001 (DIPNR, 2001); and rainfall data is from regionalized rainfall data over a 5km grid for all of Australia (Jeffery *et al*. 2001). The dominant geology and soils is sourced from a 1:250,000 mapping project (MDBC, 1999).

Although these characteristics are spatially crude they do provide a useful tool to explore possible reasons for the discrepancies and similarities between the load predictions for the three catchments. In other words, some of the discrepancy found in the comparison with the model outputs may be explained by catchment characteristics. This influence will only be apparent if the catchment characteristic is used in the model.

The maximum flow for the last 20 years was recorded in Jugiong Creek. This influences the estimation of suspended sediment load by the rating curve method, owing to the use of the flow record as an input. The prediction of the SSC, from the empirical model, will be influenced by the lack of data that is available for these extreme flows compared to the greater amount of data available for low to medium flows. The absence of data for these extreme flows and the subsequent use of these high flows to produce the load estimate will cause an increased uncertainty in the total load when using a sediment rating curve.

In the estimation of mean annual flow (MAF) from the flow record, Tarcutta creek has the highest average. Supporting this is a greater relief and mean slope as well as higher rainfall in the catchment. Both relief and slope characteristics are used in the estimation of hillslope erosion within SedNet. Yet, it is unlikely that this has influenced the predicted load for the Tarcutta creek catchment by SedNet owing to the small predicted contribution of suspended sediment sourced from hillslope erosion in this catchment, see Table 3.

A combination of area, average rainfall and the runoff coefficient are used to estimate MAF in SedNet. The Jugiong creek catchment has a larger area than Tarcutta with the Muttama creek catchment the smallest. Average rainfall was very similar for Jugiong and Muttama but higher in the

Tarcutta catchment and so will influence both the runoff coefficient and MAF present in the model. MAF used in SedNet affects the prediction of suspended sediment load contribution from streambank erosion. Bankfull discharge and median overbank flows use MAF to estimate the amount of deposition on floodplains that occur in a catchment. It is difficult to ascertain the parameters in the model that are most influential, given these catchment characteristics, which impact on SedNet's suspended sediment load prediction.

Table 2: Catchment characteristics for the three study catchments

Site	Jugiong	Muttama	Tarcutta
Area(km^2)	2127.4	1058.6	1636.5
Mean elevation (m)	478.9	403.0	433.4
Relief (m)	589.3	486.3	871.5
Mean slope(deg)	4.6	5.4	7.9
Drainage density (km/km^2)	0.9	0.9	0.9
Mean Annual Flow(MAF) (ML/day)	113 800	58 419	187 000
Maximum Flow ML/day (1980 to 2000)	57 379	32 752	34 641
Average annual rainfall across catchment (mm)	694	652	797
Gully density (m/km2)	391	189	180
Streambank density (m/km2)	65	130	84
Dominant Geology	Silurian - Devonian S-type granodiorites/Silurian volcanics	Devonian /Cambrian volcanics	Ordovician metasediments
Dominant soil	Yellow Podzolic/Red Brown earth	Soloth (Sodic Red Podzolic)/Yellow Earth	Red Duplex/Red Earth

A sensitivity analysis of the SedNet model by Newham *et al.* (2003a) found that the hydrological parameters in SedNet, such as MAF, were the most sensitive. Perturbations to the hydrological parameters had the greatest effect on both suspended and bedload predictions. The Jugiong creek catchment has the greater area while Tarcutta has the greater average rainfall. These differences between the catchments do not explain the possible over-prediction in suspended sediment load in Jugiong and the close agreement between the two model outputs for the Tarcutta creek catchment. Also, considering the small difference in both average rainfall and area between the catchments it is unlikely that these differences can explain the discrepancy found between the load predictions.

The one aspect of this catchment characteristic comparison which may explain the discrepancy seen between the two models for the Jugiong catchment is the higher density in gully erosion. Gully erosion density is almost double in Jugiong than for the other two catchments. Gully erosion is a major source of suspended sediment to rivers and it is a significant input in the SedNet model to predict suspended sediment load.

SedNet predicts the amount of erosion from gullies (G_x) for each subcatchment using a log-linear equation (see Equation 2).

$$G_x = \frac{1000\ A_x \alpha P_x \rho}{\tau} \qquad (2)$$

A_x (typically 50km^2) is the area of the subcatchment, α is the mean cross-sectional area of a gully (set at 10m^2), P_x is the gully density of the subcatchment (km/km^2), ρ is the bulk density of the eroded sediment (set at 1.5 t/m^3) and τ is the age of the gully, assumed to be 100 years.

Given the steady state assumptions in the gully erosion model and the high gully density in Jugiong creek catchment, the discrepancy between the two model predictions may be due to the over-estimation of the suspended sediment contribution from gully erosion as determined by SedNet. This may be the result of assuming that the observed gullies all initiated within the last 100 years. Alternatively, there may be an error in the estimated gully density. The dominant sediment sources in SedNet for each catchment, as seen in Table 3, shows that for Jugiong both hillslope and gully erosion are equally important. Tarcutta Creek is dominated by streambank erosion which is supported by the catchment characteristics (e.g. streambank erosion density) as seen in Table 2. Muttama creek catchment has a high amount of hillslope erosion that greatly contributes to the suspended sediment load predicted by SedNet.

Table 3: The amount of erosion predicted by SedNet, separated into the three dominant sources for the three study catchments.

Catchment	Gully erosion (%)	Streambank erosion (%)	Hillslope erosion (%)
Jugiong	40	19	41
Tarcutta	22	54	24
Muttama	23	29	48

The evidence suggests that gully erosion may be a cause for SedNet comparatively over-predicting the suspended sediment load for Jugiong which is due to the high numbers of gullies in the catchment. Although hillslope erosion attributes the same amount of suspended sediment as gully erosion in Jugiong, Muttama creek catchment is also dominated by hillslope erosion, however the model outputs for this catchment are similar for both approaches. This suggests that hillslope erosion is not over-predicted in SedNet.

The over-prediction of gully erosion by SedNet is further supported by DeRose *et al.* (2003) who compared SedNet with suspended sediment loads derived from a sediment rating curve for the Goulburn-Broken River Catchments in Victoria. This study found that the SedNet results were within 50% of the load estimated from the rating curve. Given the assumed uncertainty in the both models these two predictions were considered quite close. However, all measured loads were below the SedNet prediction. DeRose *et al.* (2003) proposed that the systematic over-prediction was due to either the modelling in all three sediment sources or insufficient floodplain deposition. This study also mentioned that the largest differences between measured and SedNet predicted loads were from sub-catchments that were dominated by gully erosion. To combat this over-prediction, DeRose *et al.* (2003) recommended that the rate of erosion for gullies be lengthened from 100 to 150 years in an attempt to reduce the suspended sediment load predicted by SedNet from gully erosion. While this solution may decrease the amount of sediment predicted from gully erosion by SedNet, improved understanding of gully erosion and its variability in a catchment is needed to provide further insight into targeting and managing suspended sediment contributions from this erosion source.

In contrast, Newham *et al*. (2003a) also considered gully erosion parameters and found that perturbations of 10% did not radically affect the suspended sediment predictions. As indicated in this study, over-estimation of suspended sediment load, due to inaccuracies in the gully erosion model, seems only likely when gully erosion is a dominant source of suspended sediment in the catchment.

Although any model has uncertainty associated with it, the prioritisation of management and resources to those areas that produce the most suspended sediment should be able to be identified with a high degree of accuracy. Whereas, in this comparison between an empirical model and SedNet, it was found that there was a difference in the ranking of catchments. SedNet predicted that Jugiong creek catchment is the highest contributor of suspended sediment to the Murrumbidgee River compared to Tarcutta and Muttama creek catchments (see Table 1). In contrast, the suspended sediment estimate from the empirical model found that Tarcutta creek contributed more to the Murrumbidgee River suspended sediment load. This difference in the ranking of suspended sediment contribution between the two models will greatly influence the prioritisation of management in the region, resulting in possible mismanagement and inefficient use of resources. Not only would the wrong catchment be targeted but the incorrect dominant source of erosion may also be identified based on either result.

6. CONCLUSIONS

The comparison of the predicted suspended sediment load from two models for three catchments in the Mid-Murrumbidgee River catchment has revealed some discrepancies between the load estimates. Two out of the three catchments contained suspended sediment predictions that compared well between the two models. One of the catchments, Jugiong, did not yield a similar load estimate between the two models. The suspended sediment load predicted for Jugiong by SedNet was considerably higher than the empirical load estimate. While it is recognized that there is a high uncertainty associated with both model predictions, this large discrepancy between the model outputs for Jugiong indicate that there is a possible over-prediction of suspended sediment by SedNet for this catchment. The comparison of catchment characteristics seem to suggest that a high estimation of suspended sediment from gully erosion is the cause of this over-prediction.

Further compounding the problem of the over-prediction of suspended sediment loads in gully dominated catchments is the change in rank this over-prediction could cause. SedNet has been designed to predict loads to enable catchments to be ranked according to their output, which allows land managers and policy makers to target resources to those catchments that are at greater risk of producing high sediment loads. The discrepancy found between the SedNet and the sediment rating curve load estimates questions the reliability of SedNet for use in management decision making. It is suggested that the inaccuracy, not only in the load, but the ranking of catchments by their predicted suspended sediment load contribution could lead to ineffective management and resource allocation inefficiencies, both within catchments and between catchments. Further research into the variability in sub-model parameters, especially for gully erosion, may improve SedNet predictions of load for gully dominated catchments such as Jugiong.

7. ACKNOWLEDGMENTS

The authors would like to thank the NSW Department of Infrastructure, Planning and Natural Resources for their assistance in data collection and record keeping. Funding from CSIRO Land and Water, Canberra for fieldwork was also greatly appreciated.

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