Comparing TSS Loads from a Catchment Model, Two Rating Curves and a Ratio Method Without True Values: The Challenge

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Abstract: Due to lack of adequate observed suspended sediment concentration (SSC) data, sediment-rating curves and ratio methods have been commonly used to calculate suspended sediment loads. However, measurements of suspended sediment load concentration and flow and the subsequent use of rating curves or ratio methods to calculate suspended sediment loads alone would not answer many spatial and temporal scale related questions with regard to management decisions to improve water quality. These questions are better addressed using catchment scale water quality models. The SedNet (Sediment River Network) model is a sediment generation and transport model to estimate long-term mean annual end-of-valley and in-stream sediment loads. Due to lack of appropriate data, very little work has been done to test the accuracy of outputs SedNet in Queensland catchments.

The objective of this study is to compare mean annual total suspended sediment (TSS) load data estimated from two rating curve methods, and the Beale ratio method with outputs of SedNet at six sites in the Burnett catchment in Queensland, Australia. SedNet consistently estimated much higher sediment loads than the other three methods. The power function method consistently predicted the lowest total load. The ratio (highest/lowest) in predicted TSS loads for the six sites varied from 16 to 36. Hence there is poor agreement across all four methods on the annual TSS load both at a site and across several sites. Possible reasons for the discrepancy between the estimates are discussed. This study has shown the challenge in choosing a relatively more accurate method of load estimation in the absence of actual suspended sediment load values against which estimates from the different methods are to be compared. Hence, it is suggested that a similar study be conducted on a site with a very high frequency data set, so that the comparison can be presented as deviation from a known true value and the results can be used to truly quantify error in the methods.

Keywords: Water quality, Rating curves, Beale ratio, Sediment Delivery Ratio

1. INTRODUCTION

The quantification of suspended sediment load is needed in order to determine its effect on water quality trends, reservoir sedimentation, channel and harbour silting, soil erosion and loss, as well as ecological and recreational values.

Whilst monitoring is a very important component of water quality protection plans and management support tools, it is not possible to answer all temporal and spatial questions using monitoring alone. Modelling can be a very useful tool that can complement monitoring to assist managers. It is recognised that it is logistically very difficult and costly to evaluate the effectiveness of management actions without simulating them by modelling, which is a cost effective tool over large geographic areas.

Suspended sediment rating curves have been widely used to estimate suspended sediment when and where measured data are not available (Asselman, 2000; Horowitz, 2003). More recently a catchment-scale sediment generation and transport model referred to as SedNet (Wilkinson *et al.,* 2004) has been developed and used at the continental scale (Prosser *et al.,* 2001) and across a number of catchments in Australia (Bartley *et al*., 2003; Bartley *et al*., 2004; DeRose *et al.,* 2002; DeRose *et al.,* 2003; Dougall *et al.,* 2005; Fentie *et al.,* 2005a, Hateley *et al.,* 2005; McKergow *et al.,* 2005; Prosser *et al.,* 2002; Prosser *et al.,* 2003). However, with the exception of two similar studies in the Mary catchment (DeRose *et al.,* 2002) and the Fitzroy catchment (Fentie *et al*., 2005), very little work has been done to test the accuracy of the SedNet model in catchments in Queensland. As part of a qualitative test, this study compares estimates of a ratio method and two sediment rating curve methods with estimates of suspended load from the SedNet model in the Burnett catchment.

The ratio methods are a group of methods used to estimate loads. The flow weighted Beal ratio method (Beale, 1962) is one of these approaches and is the most commonly used.

It is recognised that the sediment rating curve method tends to under-predict high, and over-predict low suspended sediment concentrations (Horowitz, 2003). Moreover, the range of errors associated with the corresponding flux estimates for relatively short time-frames (e.g. daily, weekly) are likely to be substantially larger than those associated with longer time-frames (e.g. quarterly, annually). This is because, in short time-frames, the over-predictions and under-predictions do not have sufficient time to balance each other (Horowitz, 2003).

The purpose of this study is to discuss the discrepancy between total suspended sediment loads estimated by the Beale ratio, rating curve and SedNet modelling methods by highlighting the possible reasons for the discrepancies so that improvements in these techniques can be targeted towards addressing these issues.

Whilst the role of the SedNet model is in getting relativities right so that dominant processes and geographical areas that contribute the majority of the load are identified. Confidence in the use of SedNet is expected to improve if it can be shown that the model gives reasonable estimates of loads at the end of the catchment or at a point of interest. However, in comparing the difference between TSS estimates from these independent methods, it is important to bear in mind the error and uncertainty involved in each method.

Both rating curve and ratio methods of load estimation have been widely documented (e.g., Degens and Donohue, 2002; Horowitz, 2003) and are not described in great detail in this document.

2. THE BURNETT CATCHMENT

The Burnett catchment is the third largest river basin draining to the Queensland coast, Australia, and is located south of the Tropic of Capricorn. The climate of the catchment is characterized by variable distribution of rainfall and subtropical weather patterns. Table 1 shows climatic data of the Burnett catchment.

Table 1. Climatic data at four locations in the Burnett catchment (P_a = Mean annual rainfall, E_a = Mean annual evapotranspiration, and T_a = Mean annual temperature). Source: Van Manen (1999).

Location	P_a (mm)	E_a (mm)	T_a (°C) (min-max)
Bundaberg	1123	1823	16.8-26.6
Gayndah	774	2020	14.2-28
Monto	723	1866	12.8-27.2
Kingaroy	778	1601	11.4-24.7

Figure 1. The Burnett catchment

Grazing is the dominant land use within the catchment covering about 26500 km^2 (67%) of the 39500 km^2 catchment.

Six (five unregulated and one regulated) gauging stations were chosen based on the quality of flow data, concentration-flow relationship, and length of record (McNeil, personal communication). Table 2 shows details of the six gauging stations.

Table 2. Stream length (L), area (A), period of flow record, total number of TSS datum (N_{DS}), % of flows with TSS datum in the bottom 10 percentile, and % of flows with TSS datum in the top 10 percentile

Gauge	L (km)	A (km^2)	Period of flow record	N_{DS}	Bottom 10%	Top 10%
136006A	39	251	1/10/1965 - 25/01/2005	63	6	13
136101C	276	1598	1/10/1964 - 9/12/2004	79	24	20
136304A	247	1593	1/10/1965 - 8/03/2005	82	9	16
136305A	812	5286	1/10/1965 - 1/02/2005	60	17	23
136207A	907	5540	1/10/1966 - 12/11/2004	107	2	22
136208A	211	1441	11/06/1968 - 8/02/2005	86	14	15

The last two columns in Table 2 show that flows with TSS data are biased towards the bottom 10 percentile of flows at gauging stations 136101C, 136305A, and 136208A; and towards the top 10 percentile of flows at all gauging stations. Whilst these biases indicate that the flow dataset with TSS is not a representative sample of the full flow record, it is not possible to ascertain whether or not this results in under or overestimation of suspended loads calculated by either the rating curves or Beal ratio method.

3. THE TWO RATING CURVE METHODS AND THE BEALE RATIO

The two rating curves used in this study are given by equations 1 and 2.

$$SSC = aQ^b \quad (1)$$

$$SSC = c + dQ^e \quad (2)$$

where SSC and Q are suspended sediment concentration and discharge respectively, and a, b, c, d, and e are regression coefficients.

The Beale ratio (Beale, 1962), which is implemented in a software tool called the Loads Tool (Marsh *et al*., 2006), is given by

$$Load = Q_a \frac{\bar{l}}{\bar{q}} \left(\frac{1 + \frac{1}{N}\frac{\mathrm{cov}(l,q)}{\bar{l}\bar{q}}}{1 + \frac{1}{N}\frac{\mathrm{var}(q)}{\bar{q}^2}} \right) \quad (3)$$

Where Q_a = annual flow, load = annual load, $\bar{l}$ = average load for times when samples were collected, $\bar{q}$ = average flow for times when samples were collected, N = number of samples collected, cov(l,q) = co-variance between sampled loads and flow at time of sampling, and var(q) = variance of the flows at the time of sampling.

4. THE SedNet MODEL

The SedNet model is a sediment generation and transport model for predicting long-term annual average end-of-valley and in stream

The SedNet model is based on a node-link configuration generated from a digital elevation model (DEM) of a catchment. The suspended load budget for a link is computed as a mass balance of inputs and outputs as shown in the conceptual model depicted in Figure 2.

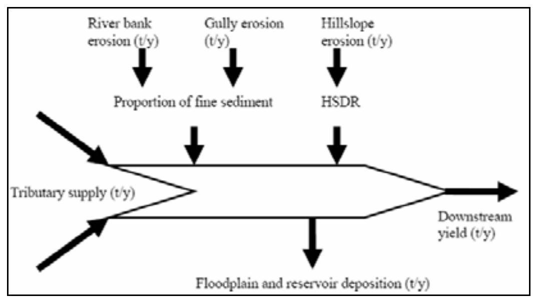

Figure 2. Components of the river link suspended load budget. After: Wilkinson *et al.* (2004).

5. RESULTS AND DISCUSSION

The Disaggregation Tool in the current version of SedNet (Wilkinson *et al.,* 2004) was used to apply the methods described by Equations 1 and 2 by fitting a power function (with and without a constant) to flow and TSS data. This power function (or rating curve) was then used to predict daily TSS values based on a time series of mean daily flow at each of the six gauging stations for the period of record at the gauge. Table 3 shows the model efficiency (E) values, with values close to unity indicating a high level of agreement between measured and values by the two rating curves. There is a marginal improvement in values of E when Equation 2 is used instead of Equation 1 at all of the six sites. The highest E values were achieved at gauging stations 136006A and 136207A while the lowest E values (the lowest agreement between measured and calculated values) were found at gauging stations 136101C and 136305A. The negative value of E at gauging station 136101C indicates that the relationship is not better than using the average as a load estimator. Values of E that are greater than 0.5 are commonly regarded as acceptable, indicating that the rating curve methods are only suitable for gauging stations 136006A and 136207A (see Table 4).

Table 3. Model efficiency (E) values for the two rating curve methods

Gauge	E (Eq. 1)	E (Eq. 2)
136006A	0.83	0.83
136101C	-0.07	0.05
136304A	0.31	0.32
136305A	0.11	0.12
136207A	0.80	0.88
136208A	0.45	0.48

The mean annual TSS load was then calculated from the TSS time series and is presented in Table 4. The Beal ratio method (Equation 3) was applied using the Load Tool (Marsh *et al.,* 2006) to the flow and concentration data to generate annual TSS loads which were then used to calculate an annual average load (Table 4). Table 4 shows measured and modelled mean annual flows as well as mean annual suspended sediment loads estimated by the four methods. SedNet resulted in higher estimates of suspended sediment at all gauging stations than the other three methods that rely more heavily on measured suspended sediment concentration data. The quantities r1, and r2 and r3 in Table 4 are ratios of suspended load estimated by the SedNet model to the other three methods. These ratios indicate that the highest discrepancies between SedNet estimates and those of the other methods are the highest at gauging station 136101C where SedNet estimates are about 27, 28, and 30 times the estimates by Eq. 1, Eq. 2 and Eq. 3, respectively.

As shown in Table 4, the two rating curve methods and the Beal Ratio method, all being based on TSS data, resulted in similar load estimates. However, agreement between these estimates is not an indication of the accuracy of these methods over SedNet. An Assessment of the accuracy of a method of load estimation can only be carried out if there are "true load values" to compare these estimates against. Unfortunately, enough data to determine these "true load values" are not easy to obtain, as is the case in this study.

As shown by Fentie *et al. (*2005b), SedNet is highly sensitive to the hillslope sediment delivery ratio (HSDR) parameter value. We back-calculated the necessary HSDR values required to achieve the sediment yield values predicted using the other methods. The largest predicted HSDR value from the back calculation process was 0.03, and in most cases was negative. Prosser *et al. (*2001) recommends a HDSR value of 0.1, hence a reduction of this parameter value by 70% in one case, and zero in most cases seems unreasonable, implying that the discrepancy in SedNet yield calculations is not simply an over estimation of the HSDR parameter value.

Figure 3 shows the suspended sediment contributions (t/ha/y) of areas draining to each of the six gauging stations as determined by SedNet, from which the total suspended sediment was estimated by the model.

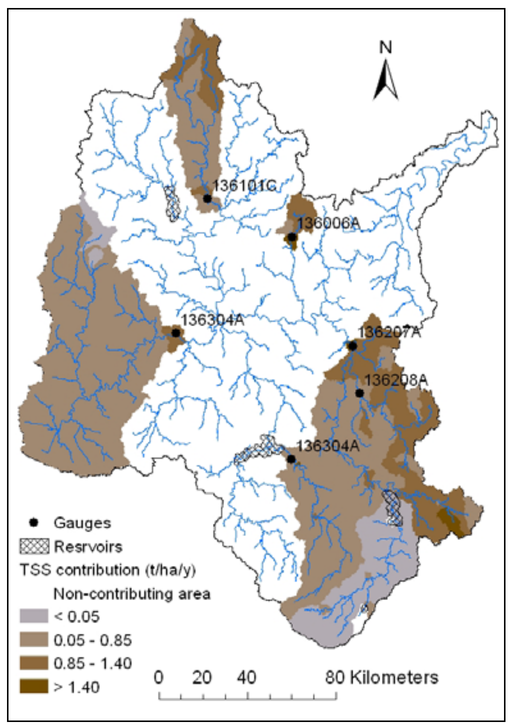

Figure 3. TSS contribution to the six gauging stations

Table 4. Measured mean annual flow (MAF_o) and modelled mean annual flow (MAF_m), TSS estimates (t/ha/y) by the four different methods and the ratio of SedNet estimates to estimates by Eq. 1 (r1), Eq. 2 (r2) and Eq. 3 (r3).

Gauge	MAF_o (Ml/y)	MAF_m (Ml/y)	SedNet	Rating Curve (Eq. 1)	Rating Curve (Eq. 2)	Beale Ratio (Eq. 3)	r1 (Eq. 1)	r2 (Eq. 2)	r3 (Eq. 3)
136006A	22,528	11,274	29,596	3,446	3,401	11,837	8.6	8.7	2.5
136101C	34,225	71,436	122,636	4,543	4,372	4,018	27.0	28.1	30.5
136304A	44,731	67,710	71,885	10,328	9,747	6,886	7.0	7.4	10.4
136305A	78,246	162,447	162,781	53,541	52,605	21,468	3.0	3.1	7.6
136207A	214,092	214,123	324,199	71,439	59,180	154,639	4.5	5.5	2.1
136208A	53,663	63,182	125,905	27,795	33,302	20,637	4.5	3.8	6.1

Previous studies have indicated that both rating curve methods and ratio methods of TSS load estimation are uncertain due to data quality and quantity issues in addition to the often weak relationship between suspended sediment concentration and discharge.

Too few TSS data were collected compared to flow data resulting in the possibility that some events with high TSS loads may not have been sampled. Moreover, uncertainty involved in estimating representative daily discharge and TSS concentration used in the study is likely to have added to the error in total load estimation using both the two rating curve methods and the Beale ratio method.

In regards to rating curves, Asselman (2000) notes that scatter about the regression line is, among other things, caused by factors not accounted for such as variations in sediment supply due to seasonal effects, antecedent conditions in the river basin, and differences in sediment availability at the beginning or the ending of a flood. Rating curves are also regarded as representative for a location under environmental and climatic conditions in which the relationship between discharge and suspended sediment concentration is consistent during the entire measurement period. Investigation of this is beyond the scope of this study, but is assumed to be a possible source of uncertainty and is a subject for further study.

A fundamental limitation of load estimation is the lack of near continuous time-series concentration data necessary to estimate true loads against which the effects of sampling and the different load calculation methods can be tested. Sampling variability, hysteresis, exhaustion processes and seasonal variability in flow-concentration relationships are expected to bring about scatter in rating curve relationships.

It is also possible that estimates of SedNet are overestimated as the result of uncertainties in input data and parameter values, including the hillslope sediment delivery ratio, used in the model.

6. CONCLUSIONS

In order to increase our confidence in the use of a suspended load estimation method, we need to compare its outputs with long-term measured suspended sediment load data. As long-term measured data are not available, estimates of a method may be compared with estimates from other independent methods. This study compared total suspended sediment outputs of the SedNet model with those estimated using two sediment rating curve methods and a ratio method at six gauging stations in the Burnett catchment.

The SedNet model, which does not use measured suspended sediment data as input, estimated more suspended sediment load at all six sites than the other three methods which are based on measured suspended sediment concentration data. However, due to uncertainties in estimated suspended loads by all methods arising from uncertainties in input data, model parameter values, sampling methods, and weak flow and concentration relationships, and the lack of long-term actual suspended sediment load values, it is not possible to determine which of the methods is more accurate than the others.

A long-term high frequency sampling program is needed so that we can assess the relative accuracy of the different load estimation techniques including SedNet. All we know, as the result of this study, is that SedNet estimates disagree with those of other methods for the data we have used.

7. ACKNOWLEDGEMENTS

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