

Sources of uncertainty in estimating suspended sediment load

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Abstract An important task in the assessment of suspended sediment load estimates is to qualify and (where appropriate) quantify the uncertainty associated with that estimate. A sediment rating curve is a relationship between suspended sediment concentration and flow used in the calculation of a load estimate. However, this method assumes particular characteristics in the input data. It was found that historical data for the Murrumbidgee River catchment, Australia, did not possess all these assumed characteristics because of variations in suspended sediment sampling methods, a lack of metadata, and a lack of a sufficient number of samples covering the range of flow conditions. These factors inhibited the use of sediment rating curves for developing an appropriate suspended sediment load estimate and its associated uncertainty.

Key words Murrumbidgee River catchment, Australia; suspended sediment; uncertainty

INTRODUCTION

Suspended sediment (SS) concentrations and loads in streams often are estimated for management reasons, or used to calibrate process models for predicting erosion and sediment transport (e.g. Merritt *et al.*, 2003). In order to estimate the load over some period, an accurate determination of the mean concentration as a function of flow is needed at an appropriate temporal scale (Horowitz, 2003). Sources of uncertainty are present throughout the process of estimating loads, from the collection and determination of the SS concentrations, to the calculation of load estimates (Littlewood, 1995). For example, Olive & Rieger (1988) considered the occurrence of uncertainty in the data obtained from automatic sampling devices due to the misconception that flow and concentration peaks occur together. Other studies examined the influence of different sampling strategies on load estimates e.g. Robertson & Roerish (1999). Parker (1988) found that variations in SS concentration and flow contributed to the uncertainty in subsequent load estimates. Several authors have considered the uncertainty associated with the methods used to establish a relationship between flow and SS concentration (e.g. Walling & Webb, 1981; Crawford, 1991; Asselman, 2000). Most of these papers used regression analysis to establish this relationship. The uncertainty associated with the methods used, and data inconsistencies relative to the statistical assumptions needed to develop load estimates using regression, also have been considered (e.g. Clarke, 1990; Cohn, 1995). This paper seeks to examine systematically, the main sources of uncertainty associated with empirically-based load estimates. In the second

section of the paper, the factors that can inhibit the quantification of this uncertainty are examined, using an Australian case study.

Main sources of uncertainty

There are a number of sources of uncertainty that need to be considered in the estimation of SS loads (Fig. 1). The goal considered here is the estimation of sediment load over some period of time, usually considerably longer than the SS concentration sampling period. A sediment rating curve is a relationship between flow and SS concentration, (commonly a power law relationship) (Horowitz, 2003). The regression of SS concentration and flow permits the interpolation and extrapolation of SS concentration.

The factors that contribute to the uncertainty in load estimates are: (a) the uncertainty in the rating curve (both functional form and its parameter values); (b) the population mismatch between sampling and estimation periods; and (c) a lack of sufficient sampling for the flow conditions extant. The uncertainty in the sample population can be influenced by errors in the data (both SS concentration and flow), though uncertainty is highest when a small number of samples are used to represent a population that has considerable scatter, as well as data that typically are clumped towards low flows.

Uncertainty in data sources

A major contributor to data uncertainty is associated with collecting a sample that accurately reflects conditions in the stream, which refers to the top half of Fig 1. The amount of uncertainty can be substantially reduced if appropriate sampling methods are used, if the site is well-mixed, and if contemporaneous flow data are collected at

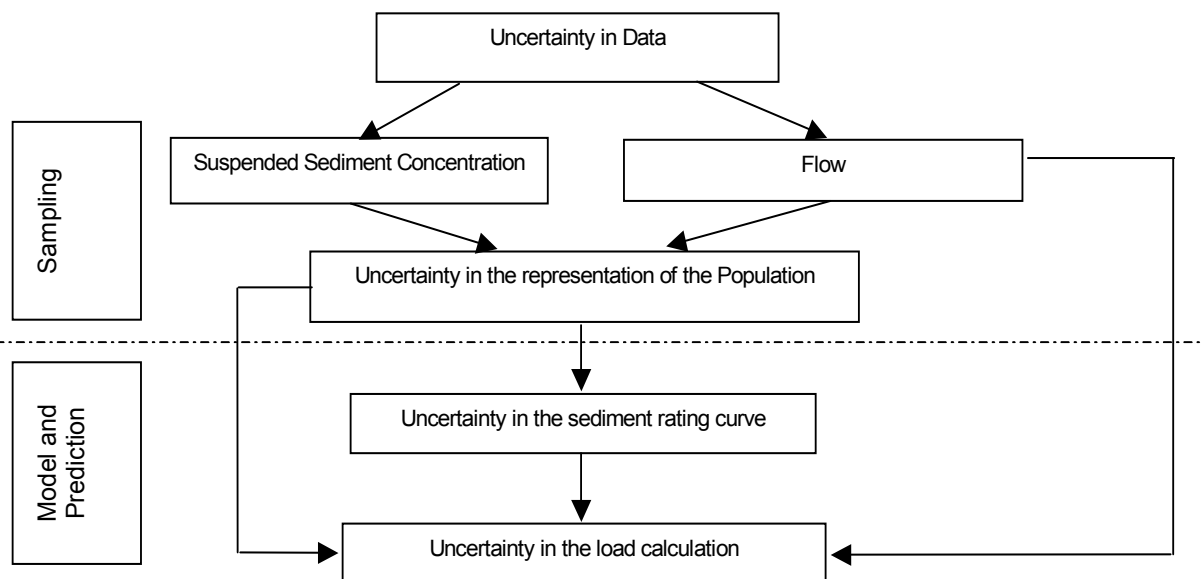


Fig. 1 An illustration of the main sources of uncertainty, and how they propagate through the estimation of SS load.

or very near the sampling site. This method of collection may provide an SS sample that most closely reflects the concentration occurring at that time. However, if the SS samples were collected from a stream edge, the uncertainty between the true composite concentration in the stream, and what actually has been collected is likely to be greater. Using replicates and depth-integrated sampling will reduce this source of uncertainty if the corresponding flow is measured to the same degree of accuracy.

Another significant source of uncertainty in flow measurements occurs when gauge height is converted to a discharge estimate (Clarke *et al.*, 2000). This primarily is due to uncertainty in the discharge rating curve (relationship between river level and flow volume), which depends on the stability of the stream profile at the gauge site (particularly problematic for gauges that rely on the natural channel profile, and streams with a very high bed load). Additionally, extrapolation beyond the measured gauge height-discharge relationship causes greater uncertainty in flow estimates made during extreme events. In comparison, uncertainty associated with gauge height measurements is typically small.

Uncertainty in population estimates

The main concern with sampled SS concentrations and flow data are how representative they are of the actual population. This depends on both the number and distribution of points that have been sampled, which will greatly affect the modelling and prediction of loads, illustrated in Fig. 1. Often the selection of samples taken is calendar-based (e.g. routine collection of fortnightly samples) rather than flow-based. As a result, the data tend to be clustered near the mode of the flows, which corresponds to low, or at best, medium flow values. The majority of sediment often is transported during high flows. For example, Olive *et al.* (1995) found that 35% of the sediment transport in the Murrumbidgee River occurred during only 10% of the time, using 50 years of sediment data. Due to the highly variable nature of many Australian catchments (see Croke & Jakeman, 2001), routine monthly or fortnightly sampling programs (even in long-term studies) may be insufficient to capture enough information with respect to extreme flows.

Event sampling attempts to overcome this, usually through the intense sampling of a small number of events. However, this can cause serial correlation within the data. Serial correlation refers to the non-uniform distribution of residuals along the horizontal axis, and usually occurs because flow and SS concentration data points are not truly independent; a requirement for regression modelling (Helsel & Hirsch, 1992). In addition, there is always the question of how well the distribution of actual samples represents the true distribution of events (range in rainfall intensity, antecedent conditions, event duration, etc.). This suggests that a flow-based (both on the rise and falling limb) sampling strategy may be more effective in defining the relationship between flow and SS concentration.

Uncertainty in the sediment rating curve

Sampling and measurement uncertainties, as well as issues associated with adequate coverage of the variety of flow conditions, will affect the uncertainty that exists in the

development and analysis of sediment rating curves (Fig. 1). Much of the uncertainty that affects the rating curve itself stems from the unwarranted assumption that SS concentration is solely flow-limited (Crawford, 1991; Asselman, 2000). Hence, the positive results obtained using rating curves should not be viewed as proof of a cause-and-effect relationship. In spite of these limitations, comparisons of annual rating curves can be used to estimate the degree of variability in the sediment transport occurring in a catchment, and help relate it to such factors as land-use changes.

The traditional assumptions associated with using linear regressions for establishing an empirical discharge-SS concentration relationship can be stringent. For example, these can include not only the usual assumptions that the model form is correct, given the available data, and that the data used in the model are representative of the population; but that the variance of the residuals are constant, and usually that the residuals are independent and normally distributed (Helsel & Hirsch, 1992). The uncertainty in the predicted values will increase if the assumptions in the functional form of the regression are invalid, while not adhering to the assumptions regarding residuals will impinge on any analysis of the uncertainty in both the parameters and the predicted values. Checking residuals for these characteristics should be a routine step in the calculation of load estimates; however, this is not always the case.

Another statistical consideration is that environmental data are rarely normally distributed; however, parametric regression analyses assume normally distributed data. To eliminate this problem in developing rating curves, the data often are log-transformed. Subsequent conversion of the fitted, log-transformed SS concentration data back into arithmetic space can produce a bias (Ferguson, 1986). Several methods have been devised to correct for this inherent bias (Ferguson, 1986; Cohn, 1995). However, using a correction factor to remove bias may actually generate additional uncertainty that combines with what is already inherent in the data used to develop the rating curve itself.

Uncertainty in load calculations

The uncertainty in the predicted values of mean SS concentration for a particular flow, using a sediment rating curve, obviously will affect load estimates. Additional uncertainty associated with estimating SS concentrations using rating curves can occur when there is a disparity between the period covered by the samples and measurements used to generate the rating curve, and the period when the rating curve is applied. Also, the flow time series used to derive load estimates from the predicted concentration will impact on the uncertainty in the load estimate, as seen in Fig 1. This uncertainty may include: gaps in the flow time series data; differences in temporal resolution between the data used to generate the curve *vs* the estimation period (e.g. daily flow data used in the sediment curve *vs* hourly load predictions); and the length of time covered by the load estimates (e.g. annual estimates compared with total load estimates over 10 years). The uncertainty present in gauge height measurements, as well as that associated with the conversion of gauge height to discharge will also impact load calculations. When flow data is absent, a rainfall-runoff model can be used to estimate flow; however, this is likely to engender a corresponding increase in the uncertainty associated with the resulting load estimates.

Case study analysis for the Murrumbidgee River catchment

The previous sections have described the main sources of uncertainty in the estimation of SS loads, highlighting a number of potential factors that will affect load uncertainty. The next section is an outline of some of the problems found in attempting to determine loads, and its uncertainty, for three tributaries of the Murrumbidgee River catchment, Australia. At present, accurate estimates of SS load cannot be calculated due to the paucity of available historical data.

Data

In this case study, historical SS concentration data were used to establish a rating curve to estimate loads for three catchments. These data contained very little to no information regarding the sampling techniques used, the laboratory analysis undertaken, nor the reason(s) for sampling. During a preliminary data analysis, it was apparent that there were a number of sampling strategies used to compile the available SS concentration data set. The exact purpose, or methods used to collect SS concentration data are unknown; this lack of information has the potential to increase the uncertainty in the subsequent SS load estimate.

It was also determined that there were potential inaccuracies in the recorded dates and times for SS sampling. This represents a problem because, in the absence of corresponding flow data, the SS sampling dates and times were used to obtain flow data from archived records. These inaccuracies in record-keeping resulted in making some SS concentration data unusable; further, this lack of information (metadata) prevented an analysis of expected errors that might be present in the original data. Reducing the number of data points also affected how representative the data are compared to the unknown true population.

Population

Often, water-quality data do not extend to high flows. The lack of concentration data for the higher flows is very apparent in Muttama Creek (flow gauge location 148°09'E, 34°55'S) (Fig. 2). The period of flow that is available to estimate the long term load contains a significant number of events where the measured flows are higher than the maximum flow sampled for SS, thus requiring an extrapolation of the rating curve (Fig. 2). The lack of historical high-flow SS sampling, and the need to extrapolate the rating curve is, potentially, the single greatest source of uncertainty in load estimations using this technique. Very few long-term sampling studies generate SS concentration data at maximum flow; even so, the extent of the difference between the highest sampled flow, and the highest recorded flow in the Muttama Creek, is extreme. The other two tributaries: Jugiong (flow gauge location 148°22'E, 34°47'S) and Tarcutta Creek (flow gauge location 147°39'E, 35°10'S), show similar representative plots. The spread of concentration values among the flows that do have concentration measurements are limited. This is due to the sampling frequency wherein manual samples were collected on a fortnightly basis, and event sampling, when it was undertaken, did not correspond to large events.

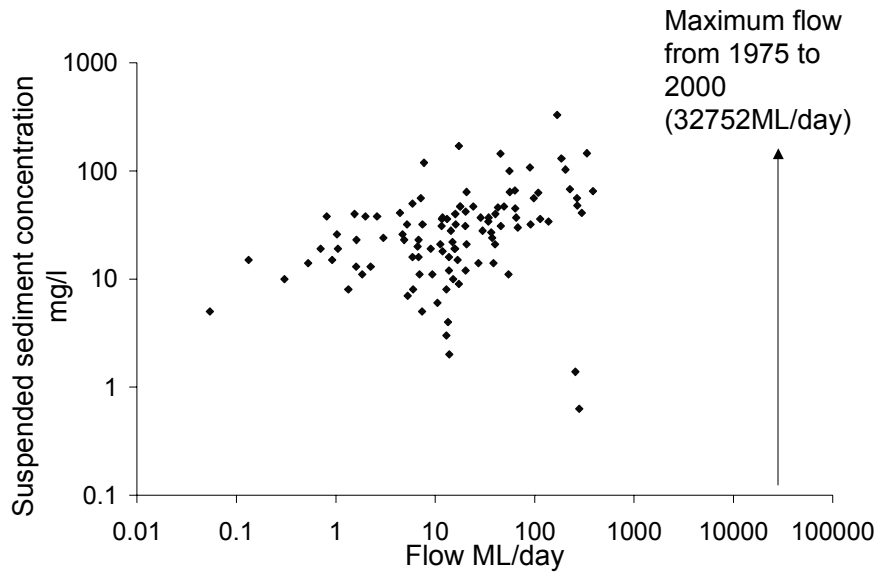


Fig. 2 Examples of flow–SS concentration data from Muttama Creek, 1995–2001. The arrow represents maximum flow recorded from the gauge between 1975 and 2000.

Rating curves

Scatter in the relationship between SS concentration and flow can be high (Fig. 3). The spread of data for Tarcutta Creek is variable along the line of fit. Amongst the data, there was an extreme outlier, a very high SS concentration taken at very low flow. This outlier may be present due to poor sampling (e.g. the sampler hit the riverbed), or the time recorded for sample collection was inaccurate; however, this point may represent an SS concentration/flow relationship not captured by the sampling regime. This outlier also might represent a “first flush” phenomena after a long antecedent dry period. Regardless, the inclusion of this point would substantially alter the fit, and hence the concentration estimates, from this rating curve (Fig. 3). The sensitivity of rating curves to outliers, as well as the impact of removing such points, needs to be considered relative to the effect it would have on concentration estimates and their associated uncertainty.

Further, there are statistical limitations to the estimation of uncertainty in the predicted values of a rating curve due to heteroscedasticity, and to serial correlation effects commonly found in water-quality data. Heteroscedasticity and serial correlation have similar consequences; the non-uniform distribution of residuals along the horizontal axis can affect estimation uncertainties. However, this usually is due to the uneven distribution of SS concentration data points along the flow axis. The use of weighting techniques may remove this statistical problem in assessing load uncertainty.

Load

Determination of the long-term loads for the Murrumbidgee River Catchment tributaries presents serious obstacles. So far, inadequate representation of the

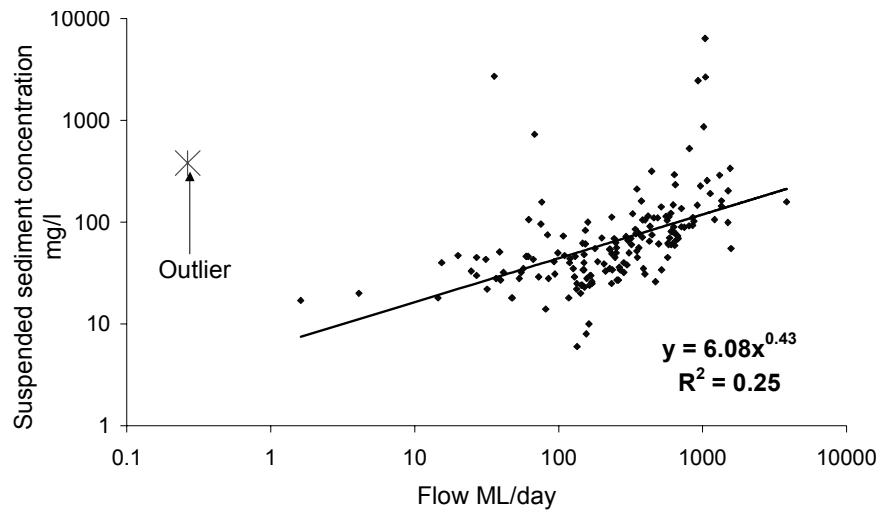


Fig. 3 Scatter plot with linear regression trend line and equation for Tarcutta Creek. Note the outlier present in the data; it was removed for the regression.

suspended sediment population from the samples available, the inadequate recording of information such as the time and date of collection, and heteroscedasticity in the residuals found in the rating curve analysis, have prevented an SS load estimate with a corresponding measure of uncertainty to be qualified.

CONCLUSIONS

The main problem in estimating loads highlighted in this paper, is that both flow and SS concentration data will greatly impact subsequent load estimates as well as the uncertainty in those estimates. The statistical inferences used in sediment rating curves assume that the data represent an independent subsample of the total SS concentration–flow population. During an attempt to use sediment rating curves as a method to develop load estimates for the Murrumbidgee River tributaries, and to quantify the uncertainty in those estimates, it was found that the available data were not compatible with these assumptions. The data, characterized by: inadequate metadata; variations in sampling methods; the presence of serial correlation (when event data were used); heteroscedasticity; and inadequate representation of the suspended sediment population from the samples available, is typical of most water-quality monitoring that occurs in Australia. The user of historical data needs to be diligent in ensuring that:

- (a) all information is gathered;
- (b) substantial amount of preliminary analysis into the flow–SS concentration relationship is undertaken;
- (c) use of the correct functional form in the model is assessed; and
- (d) the residual distribution of the regression will permit an uncertainty analysis.

It seems that if contributions of SS from tributaries (using historical data) are to be evaluated for management prioritization in Australian catchments, given the data available, other techniques need to be developed. These new techniques may require a

transition away from traditional empirical procedures in assessing load contributions, to more descriptive approaches.

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