Uncertainty of Parameter Values in a Gully Erosion Model

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EXTENDED ABSTRACT

The assessment of parameter value uncertainty is an important aspect of model evaluation. For gully erosion many of the underlying processes are largely unknown or have been found to be heterogeneous at a catchment scale. Therefore it is important to assess the spatial and temporal variation of parameter values of a gully erosion model at this scale to improve erosion and water quality management in catchments.

An exploration was undertaken of the spatial and temporal variability of parameter values for gully erosion modelling using field measurements and aerial photograph interpretation of gullies in the Jugiong Creek catchment. This study considered gully erosion at an individual gully scale and assesses how the measured model inputs will affect the model prediction of suspended sediment from a single gully. The analysis of uncertainty and use of probabilities as model outputs, as opposed to single value predictions, will allow management to better understand the uncertainties associated with modelling suspended sediment from gullies. Doing so will provide better information to assist the decision making process for efficient resource targeting.

The gully model used in this study was adapted from the gully sub-model used in the Sediment River Network model (SedNet) (Prosser *et al.*, 2001, Wilkinson *et al.* 2004). The model developed for this study uses Equation 1 to estimate suspended sediment from a gully over a long-term average. The model parameters are a gully erosion rate (m/yr); cross-sectional area (m^2); proportion of soil eroded from a gully potentially contributing to the suspended load in the stream network; and dry soil bulk density of the soil within the gully headcut and sidewalls (t/m^3).

The impact the 33 observed range of values have on the four parameters contained within the model was assessed using a Monte Carlo simulation to establish an estimate of a gully's contribution of suspended load to catchment streams. This range was found to be large, as indicated by the considerably high standard deviation value relative to the mean. The mean for the first erosion period (1944 to 1979 or 1983) was 30 ± 140 t/yr and for the second erosion period (1979 or 1983 to 1998) was 60 ± 230 t/yr. The use of annual rates took account of the variations in aerial photographs time periods. Ideally, these variations in aerial photo periods should be avoided; however, no consistent aerial photographs are available for the catchment.

Considering this large variation in possible model predictions it was important to consider the relative contribution of uncertainty from each variable for an improvement in model prediction. Most of the uncertainty in the gully erosion model was found to be from the gully erosion rate variable (70% for the first period and 68% in the second period). The other large contributor to the model uncertainty was found to be from the gully cross-sectional area parameter (40%). Both dry soil bulk density (1%) and proportion of soil eroded potentially contributing to the suspended load in streams from a gully (2%) contributed very little to the uncertainty in the gully erosion model. This study has major implications for gully erosion modelling and has highlighted the need for better process understanding of gully erosion in catchments. Also, there is a need to further reduce parameter uncertainty by establishing estimates for particular regions deemed to have high gully erosion.

1.1. INTRODUCTION

The history of the apparent rapid increase of erosion and the subsequent decline in water quality in Australia over the last 150 years is thought to be related to the expansion of European style agriculture that occurred in the nineteenth century (Scott, 2001). One of the main contributors is the increased occurrence of gullies in south-eastern Australia (Eyles, 1977; Scott, 2001). Current estimates regarding the large proportion of erosion from gully erosion are supported by tracing studies (e.g. Wallbrink *et al.*, 1996). However more recent studies suggest that gully erosion in particular has had a reduced impact on river sediments in south-eastern Australia in the last 20 years as indicated by optical dating techniques (Rustomji and Peitsch, in press). Nevertheless, gully erosion and its contribution to rivers in south-eastern Australia is still a concern to local communities, catchment managers and governments. Owing to this concern there is a need to assess the amount of current suspended sediment contributing from gully erosion, its spatial and temporal variation. This will allow focused management to ensure efficient reduction of the impacts of gully erosion on water quality.

One method of performing this assessment is to model gully erosion, in combination with other sources of suspended sediment (hillslope and streambank erosion), to allow the targeting of areas that contribute most to the suspended sediment load of a basin or catchment. A number of these models have been identified by Merritt *et al.* (2003) to be appropriate for catchment scale modelling and to consider gully erosion as an input. The SedNet model was selected as the best type of gully erosion modelling approach for this particular study because it was developed in the region of south-eastern Australia. The main aim of this paper is to assess the effect of using single number (or average) parameters to determine highly spatially variable gully dimensions when the statistical distribution of these variables are unknown; and to consider the contribution of uncertainty from each parameter value to enable future modelling improvements.

2. MODEL DESCRIPTION

The model used in this analysis is a simple conceptualisation designed to predict the long-term amount of suspended sediment from gullies, see Equation 1.

$$G_x = r\alpha\rho P_{ss} \qquad (1)$$

Here G_x (t/yr) is the amount of suspended sediment removed from a gully, r is the rate of erosion (m/yr) measured from the headcut retreat rates estimated from aerial photograph interpretation (API); P_{ss} represents the proportion of soil eroded from a gully that potentially contributes to the suspended sediment load in the stream network; ρ is the dry soil bulk density (t/m^3) of the soil within the gully headcut and sidewalls; and α is the cross sectional area (m^2) of a gully. The values of the last 3 variables are based on the distributions found during field measurements.

This model of gully erosion is adapted from SedNet gully sub-model. The main adaption is the substitution of an estimated gully erosion rate for the combined gully age and current length of actively eroding gullies. The erosion rates (r) were based on measured length changes (assumed to be headcut retreat rates) using API over a 54 year period (1944 to 1998). This enabled the spatial uncertainty in the parameter values to be explored. However, direct comparisons in the output predictions between the SedNet sub-model for Jugiong Creek catchment and the predictions made from Equation 1 can not be done without further analysis on the effects of varying sub-catchment areas on each of the parameters value distributions.

There are a number of assumptions in this model, including: most gullies are either connected to, or are close to, the stream network; sediment delivery of suspended sediment from gullies to the stream network is 100%; gullies erode at the same rate annually; and all erosion is occurring with the process of headcut retreat. From previous studies it is well known that gully erosion is highly episodic, that there are lags in delivery of sediment to the stream network and gully sidewalls and floor erode as well as the headcut resulting in increases in gully depth, width and length (e.g. Blong *et al.* 1982; Crouch 1987). The headcut retreat rate estimation is used to assume an erosion rate for the entire gully because, in this analysis, changes in gully width and depth are difficult to estimate using API.

3. STUDY CATCHMENT

The Jugiong Creek catchment is located in south-eastern Australia, within the Southern Tablelands of NSW. The catchment has an area of 2127 km^2 and a mean annual rainfall of approximately 700 mm/year. The Southern Tableland of NSW has been found to contain a high proportion of gullies and has been subject to a number of studies (e.g. Wasson *et al.*, 1998; Olley and Wasson, 2003, Eyles, 1977). The high amount of erosion found, in the Jugiong Creek catchment in particular, has also been researched in a number of previous studies (e.g Zierholz *et al.*, 2001).

The Jugiong Creek catchment has a considerable number of gullies (estimated at ~1560) and is of concern to local catchment managers in the region (Lucas, 1997; NSW Department of Infrastructure, Planning and Natural Resources (DIPNR) 1998). The dominant geology of the catchment is Silurian/Devonian granodiorites associated with Yellow Chromosol soil types in the western side of the catchment and Silurian undifferentiated rhyolitic-dacitic tuffs associated with Red Chromosol and Kandosol soil types in the eastern and more gullied side of the catchment (DIPNR, 1998; Murray Darling Basin Commission (MDBC), 1999). The main land uses are native and improved pasture (74%) and cropping (22%) (Scown 2001).

The distribution of the eight field sites (Figure 1), was based on the variation in geology type of the catchment and the availability of sequential aerial photos from 1944, 1979 or 1983 and 1998 that contained a gully in at least 1998. The influence of geology on gully presence, and more importantly absence, was identified in Smith *et al.* (2003) and therefore was used to ensure a reasonable distribution in the eight field sites.

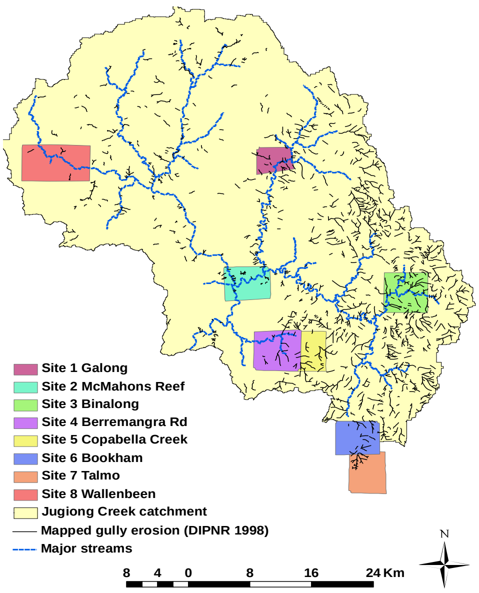

Figure 1. Location of field sites in Jugiong Creek catchment; also depicted is the current map of the gully distribution in the catchment by DIPNR (1998).

4. METHODS

The methods for the analysis of the uncertainty in gully erosion model parameter values involved two distinct parts: the collection of gully measurements in the Jugiong Creek catchment and analysis of the gully length changes over time using API; and the assessment on how the predicted contribution of suspended sediment for an individual gully may vary over the catchment.

4.1. Aerial Photograph Interpretation

To estimate the rate of erosion, lengths of the gullies were compared over the two time periods; 1944 to 1979 or 1983 and 1979 or 1983 to 1998. Photos were available for 1979 in the western side of the catchment and 1983 in the eastern side. Therefore, there is some variation in the gully sequence across the catchment. However this was taken in to account by normalising all measurements on an annual basis.

To quantify some of the uncertainty with the interpretation of gully length, a detection limit was identified for each sequence. This limit was determined by measuring the distance between two relatively stable objects which were common in all three images, usually trees or dams (this was repeated 10 times per photo). A pessimistic 20 metres was chosen as a detection threshold to encompass all the various detection limits between sites. Therefore any change in gully length of 20 metres or less, over the two time periods, was considered to have no notable change in gully length between the aerial photo sequences (Betts and De Rose 1999).

This method assumes that the 1998 image shows the full extent of all gullies, which was not always valid. In some cases, the detectable gully length decreased over time. While it is unusual for a gully headcut to fill in over a time period of 39 years (the maximum time between pairs of photos used in this study), an apparent reduction in gully length over time has been found in a number of other studies (e.g. Radoane *et al.*, 1995; Archibold *et al.*, 2003). These findings may be explained by variations between photos that could include seasonal changes in vegetation growth related to rainfall; direction of the sun; and photo resolution. There were no other photographs available so it was not possible to investigate these variations or use other techniques to counteract them.

4.2. Field Gully Measurements

Thirty three gullies were chosen; approximately 3 to 6 gullies per site were investigated. The spatial variation of the sites is shown in Figure 1; site 5 was found to be inaccessible and was not used. The selection of gullies was mostly governed by access to the gully, and permission from the land holder. The cross-sectional area of each gully was measured at the headcut and mid-point. The soil bulk density measurements were taken from the topsoil and sub-surface B soil horizon of both the headcut and mid-point of the gully using standard metal soil cores (vol. = 91.952cm^3). All soil cores were oven-dried (105°C) for 24 hours and weighed to estimate the dry soil bulk density of each core. The particle size distribution was determined by taking a soil sample from each soil horizon. This was either taken by extracting the soil next to the gully headcut by a hand auger or digging into the sidewall profile at each horizon at the headcut and mid-point of each gully. The samples were then oven dried, the gravel component sieved out and then sent to the CSIRO soil laboratory for Mid Infra-Red (MIR) analysis to determine the percentage of sand, silt and clay (CSIRO Land and Water Analytical Services and the Grains Research and Development Corporation (GRDC), 2005). The particle size proportions were then separated between suspended load and bed load, based on Walling *et al.* (2000) analysis of suspended sediment particle size (equal to or less than 0.063 mm). This fraction includes clay, silt and fine sands. The proportion of suspended sediment was estimated for the entire soil profile at the headcut and mid-point, taking account of the soil profile area that would have existed prior to gully erosion.

4.3. Uncertainty Analysis Methods

A Monte Carlo simulation of the gully erosion model (Equation 1) was used because this gives an estimate of the probability distribution of the model output to be produced, as well as the contribution of uncertainty from each parameter within the model to be analysed.

A probability distribution function (*pdf*) was produced for each of the four model parameters from the measurements of the 33 gullies, as per methods in Storch and Zwiers (2001). The *pdf* was then smoothed using a box-car filter with a width of 21 elements and then converted into the cumulative distribution function (*cdf*). The drawing of each realisation from each variable needs to occur randomly (Salas 1992). Owing to the random drawing of variables to produce each iteration of the model output, there is a need to either assume that all variables are not correlated or to account for this correlation using sequential Monte Carlo simulation (Veihe and Quinton, 2000). Although it can be assumed that some dependence must exist between these variables, in this particular sample none was found, and thus all variables were assumed to be independent. The Monte Carlo simulation was performed by randomly selecting a parameter value based on the *cdf* (Veihe and Quinton, 2000). Each set of values of the four variables was then passed through the model (Equation 1) resulting in a prediction for G_x, This calculation was repeated one million times to produce a distribution of G_x outcomes. This analysis was performed for each rate of erosion.

5. RESULTS

5.1. Aerial Photo Analysis Results

The results from the aerial photo interpretation indicate that there is considerable spatial and temporal variation between changes in length of the 33 gullies. Table 1 gives the average, median and range of the changes in gully length for both the first and second periods of the API. The range of these results is considerable. The second period reveals a larger variation over the 7 sites. The effect of these variations on the gully model will be investigated in the subsequent uncertainty analysis.

Table 1: Gully length change (m/yr) over the two time periods by API (n=33)

	First period	Second period
Average	1.87	3.36
Median	0.49	0
Minimum	-8.08	-2.53
Maximum	14.85	30.25

5.2. Gully Field Measurement Results

The results used in the uncertainty analysis from the field in Jugiong Creek catchment are from the mid-point of the gully only. This was because while collecting the measurements in the field, and considering both the gully headcut and mid-point results, the mid-point values represented the properties and dimensions of most of the gully. While the gully headcut results seem to give relatively localised dimensions and properties. The results are shown in Table 2 and illustrate the difference in variability between model variables found in the Jugiong Creek catchment.

Table 2: Parameters for the analysed gullies by field measurements (n=33)

	Cross - section (m^2)	Dry soil bulk density (t/m^3)	Proportion of suspended load
Average	23.56	1.4	0.55
Median	14.46	1.5	0.55
Minimum	0.48	1.1	0.34
Maximum	117.17	1.8	0.82

5.3. Uncertainty Analysis Results

The Monte Carlo simulation enabled the mean suspended sediment contribution from a gully to be assessed from this population data. The mean and standard deviation G_{x1} was 30 ± 140 t/yr of suspended sediment for the first erosion period and 60 ± 230 t/yr (G_{x2}) for the second erosion period. In addition, a distribution of model outcomes that can be related to an outcome probability was produced (not shown). The standard deviation from the mean gives an indication of the large amount of possible outcomes that could be expected from this model. A number of studies illustrated in Salas (1992) state the importance of having model outputs as probabilities for decision making processes in environmental management.

The final and probably the most important part of this analysis is to assess the relative parameter uncertainty contributing to the overall model uncertainty using the Monte Carlo simulation (Salas, 1992). G_x was calculated using the average value for one input variable, with the remaining inputs using the full *cdf*. This enabled evaluation of the relative contribution of each input variable (α, Pss, ρ, r) to the uncertainty in the G_x output. This process was carried out for erosion rate periods one and two (see Table 3). The methods used in this assessment were similar to the methods used in the model uncertainty evaluation in Hession and Storm (2000).

Table 3: The average and standard deviation of the gully model for the erosion rate found in the first period (Gx1) and the erosion rate found in the second period (Gx2) in assessing the relative contribution to the model uncertainty from each variable. Average values used are in parentheses.

	Model mean (variable mean) G_{x1}	**Model mean (variable mean) G_{x2}**	**Standard deviation G_{x1}**	**Standard deviation G_{x2}**	**Relative contribution to model uncertainty % G_{x1}**	**Relative contribution to model uncertainty % G_{x2}**
Cross-sectional area	31.6 (23.4 m^2)	58.5 (23.4 m^2)	82.7	139	39.0	39.6
Proportion of suspended sediment	31.6 (0.54)	58.5 (0.54)	132	225	2.20	2.40
Soil bulk density	31.6 (1.44 t/m^3)	58.5 (1.44 t/m^3)	134	229	1.10	0.90
Erosion rate 1	31.6 (1.73 m/y)	58.5 (3.19 m/y)	40.4	74.5	70.2	67.7
Full model	31.6	58.5	135	231	0	0

The reduction in the standard deviation from that of the full model reflects the amount of uncertainty that could be reduced by that particular variable in the full model output. This assessment indicates the effect of parameter variability on the model output. It seems that the variables P_{ss} (proportion of suspended sediment) and ρ (dry soil bulk density) only vary the output slightly, between 2.4% and 0.9%, in both model outputs (G_{x1} and G_{x2}). Therefore very little model improvement would be gained in reducing the uncertainty in these parameter values to produce less uncertainty in the model output. When cross-sectional area was considered however, the model uncertainty could be reduced by approximately 40%. That is, the known variation in the cross-sectional area is producing approximately 40% of the uncertainty in the model. The largest amount of uncertainty in both model outputs is attributed to the erosion rate. For G_{x1}, the proportion of uncertainty that can be attributed to the rate of erosion when using the first period values is 70%. For G_{x2}, the proportion of uncertainty attributed to the model output is 68%. The sum of the proportion of error for each parameter value (either for G_{x1} and G_{x2}) is over 100%, indicating that the relative contribution of uncertainty from the model parameters is non-linear. Thus, it is surmised that if more information was known about the variable nature of the erosion rate, the uncertainty in the model prediction would be considerably reduced.

6. DISCUSSION

This study does not evaluate how representative the 33 gullies studied are of all the gullies in the Jugiong Creek catchment, nor in south-eastern Australia generally. A similar study was undertaken by Rustomji (2006) and found that the cross-sectional area that most represented the Lake Burragorang catchment was 23 m^2, similar to the average gully cross-sectional area found in Jugiong.

Gully erosion rates measured for Jugiong Creek catchment indicate that over the last 54 years gullies have eroded up to 30 m/yr via headcut retreat rates but the average rate was found to be between 1.8 and 3.3 m/yr, although this average is highly influenced by outliers. Therefore, it may be more reasonable to consider median erosion rates to estimate recent gully headcut retreat rates (between 0 and 0.5 m/y). Other studies in south-eastern Australia, using various methods, have estimated gully erosion rates at between 0.23 to 3.4 m/y for recent times (e.g Crouch 1983; Crouch 1987; Sneddon *et al.* 1988). World estimates of gully erosion rates vary between extremes of 0.4 to 51 m/y (Vandekerckhove *et al.*, 2003; Seginer

1966). Therefore the gully headcut retreat rates found in Jugiong Creek may be reasonable estimates to use for recent gully erosion rates. Thus, it may be more reasonable to use a range of erosion rates within these estimates to produce reasonable predictions of suspended sediment yield estimates from gullies.

It is evident from the present number of gullies in Jugiong Creek catchment and the erosion rates found in this study that a reduction in sediment (both suspended and bed load) has occurred since the last 50 to 60 years at a catchment scale. The SedNet gully sub-model, as an example of another gully model, estimates current gully erosion rates on half the previously high (and unknown) gully erosion rates of the 1820s to 1900. There is probably little relevance of these rates to present sediment predictions from gullies and a simple halving of the rate is probably more uncertain than the erosion rates found in this paper. Therefore, as a way forward to improve gully erosion modelling, the inclusion of an erosion rate, which is from relatively current rates of erosion, may provide a step forward in better model estimates of the amount of suspended sediment attributed to gully erosion. It is acknowledged that API and other estimates of gully erosion rates are time consuming to measure, however, there are many studies of these erosion rates that exist in the literature and could be used as approximate values. Further reduction in the uncertainty of gully erosion model predictions may involve targeting of further API studies or using other methods to estimate gully erosion rates in various areas of Australia that are of concern regarding a high contribution of sediment from gully erosion.

7. CONCLUSION

The major outcomes from this uncertainty analysis of gully erosion modelling include:

- a considerable variation in gully parameter values was found across the catchment;
- the variability in parameter values produced many possible modelled outcomes to predicting the amount of suspended sediment delivered to the stream network from an individual gully over the long term (~ 54 years);
- when using average parameter values, most of the uncertainty in the model outcome can be attributed to the gully erosion rate (70%), and cross-sectional area (40%) with little effect from the variability found in the proportion of suspended sediment and dry soil bulk density; and

Previous gully erosion model outcomes have determined average sediment contributions and not given such choices as this current analysis reveals. The use of model output distributions can allow decisions and risk assessments to be made. Therefore allowing an element of choice for catchment managers or policy makers in assessing a gully's contribution to the catchments suspended sediment yield.

In addition, this study has determined that gully erosion rates are a considerable source of uncertainty in the gully erosion model used. This type of uncertainty analysis is invaluable to future gully erosion model development. The outcome, using the values from Jugiong Creek catchment, has found that future calibration and model validation efforts should be focused on those variables contributing to most of the model uncertainty, i.e. gully erosion rate and then cross-sectional area.

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