Estimating Catchment-Scale Sediment Yield from Bank Erosion using Simple Distributed Variables: An Example from Victoria, Australia.

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Abstract: Riverbanks can be a dominant sources of sediment in catchments. Several attempts have been made to predict rates of bank retreat from channel, catchment, and flow characteristics. Many of these are meander models that are not appropriate for whole of catchment analyses. The SedNet model (Prosser et al, 2001) is a general model of catchment scale erosion, including a streambank component and was used to provide continental estimates of erosion as part of the Australian National Land and Water Resources Audit. Several limitations have been recognised in the streambank erosion component of SedNet. This project is aimed at developing a more accurate model for predicting sediment yield from bank erosion at the catchment scale.

In this paper we report a framework for a generic bank erosion model that accounts for fluvial entrainment and mass failure processes. The rate of bank erosion along a stream link is considered a function of stream power, bank height, and bank strength. The model will be developed based on information contained in widely available data sets. For Victoria, these data sets include the statewide assessment of physical stream conditions (SOS), the Index of Stream Condition (ISC), and stream gauging records, while the Atlas of Australian soils and Ausrivas databases provide national coverage.

Bank height is one of the model components and is used as an example of the derivation of inputs from widely available data sets for six basins using the SOS database. In most basins there is a statistically significant relationship between easily derivable surrogates of channel forming characteristics and an average bank height, although these were different for different basins. The model predicts to some extent using the example of the Goulburn River basin (20,000 km^2). Examining the model using the actual parameters of some of the surrogates may better capture the variability in stream bank height. When all of the variables in the model have been compiled, the output of the model will be tested by comparing the results with published information e.g. sediment yields, and lateral migration rates of bank erosion

Keywords: *Streambank erosion; Stream power; Bank strength; Erosion modelling*

1. INTRODUCTION

Riverbanks can be the dominant source of anthropogenic sediment in drainage basins. In some catchments, the stream banks have supplied over 50 % of sediment to the river system (e.g. Grimshaw and Lewin, 1980; Simon et al., 2000). Stream bank retreat rates can vary by orders of magnitude: e.g. 1.5m/ year in the Obion-forked Deer river system, West Tennessee , USA, (Simon, 1989), about 50m/ year in the Gila river, Arizona, USA, and > 100m/ year in the Toutle river system, WA, (Simon, 1992). These ranges reflect the diversity of channel-disturbance characteristics, environmental settings, and boundary materials in supplying bank sediment to the river system.

There are three process groups active in stream bank erosion: subaerial, fluvial entrainment, and mass failure processes (Abernethy and Rutherfurd, 1998; Couper and Maddock, 2001). The subaerial process is active throughout the river system but is particularly dominant in headwater reaches (Abernethy and Rutherfurd, 1998), fluvial processes generally dominate in mid-basin reaches (e.g. Graf, 1983; Lawler, 1995) and mass failure processes tend to dominate in the downstream reaches (Lawler 1995; Lawler et al. 1999). The overall rates of bank erosion are controlled by fluvial processes that remove bank material that may be delivered to the bank toe by mass failure (Osman and Thorne, 1988; Zonge .et al, 1996).

2. BANK EROSION MODELLING

Many attempts have been made to relate the rate of bank retreat to channel, catchment, and flow characteristics (e.g. Brice, 1982; Hooke, 1980; Nanson and Hickin, 1983; Odgaard, 1987; Osman and Thorne, 1988). These characteristics include local slope, bank width, bank curvature, catchment area, distribution of flow velocity (primary and secondary), and the position of influencing flow on a bend. These have variably been incorporated in predictive models, the majority of which are meander models rather than general models of bank erosion. These models are site specific and hence have limited use in predicting the rates of bank erosion at basin scale. An exception is the SedNet model, which predicts bank erosion at regional scales (Prosser et al., 2001). The model incorporates a component for predicting stream bank erosion across Australia and was used to provide continental estimates of erosion as part of the National Land and Water Resources Audit (Prosser et al., 2001). The developers of SedNet recognize that the bank erosion component is one of the least accurate elements of the model. Streambank erosion is modeled using regression on global meander datasets (Rutherfurd, 2000). The model assumes that all stream banks (i.e. below gully networks) are 3m high, that bank vegetation reduces erosion rates to zero, and that 50% of bank material is bedload.

3. OBJECTIVES OF THE RESEARCH PROJECT

The objective of this research is to improve the estimates of catchment-scale sediment yield from bank erosion, so that the estimates are no less accurate than other variables in the SedNet model. For application to large regions, the approach must utilize generally available distributed variables. The work is in its early stages, but here we present the conceptual model of bank erosion, and an example of how we estimate the dimensions of a key variable of that model (bank height) across a large catchment, by using easily available distributed data.

4. PROPOSED BANK EROSION MODEL

We are developing a generic bank erosion model based on process understanding that will utilise existing datasets. The aim is to predict the rate of bank erosion from Victorian streams at basin scale. For Victoria, the datasets that we will use to populate the model include stream characteristics from an Index of Stream condition (ISC, Ladson and White, 1999), the Victorian Statewide Assessment of Physical Stream Condition (SOS, Ian Drummond and associates, 1985) and Victorian water resources data warehouse, while databases like Australian river assessment system (Ausrivas), the Atlas of Australian Soils together with estimation of soil properties by McKenzie et al (2000), and geological information, provide national coverage.

The fluvial processes active in bank erosion will be approximated by stream power (Bagnold, 1960). Mass failure processes are induced by many factors such as pore water pressure, matric suction (Simon et al., 2000), seepage forces, antecedent soil moisture condition (Hooke, 1979), and the force of gravity. For a basin scale model it seems practically difficult to take into account of all such factors for mass failure processes. However, their role in mass failure process will be effective only when a bank attains a critical height (Thorne, 1982; and Lawler, 1995). In this model, we consider this situation as “height constrained”. We also consider that the degree of future cycles of mass failure will depend upon the effective removal of the basal sediment and collapsed blocks at the bank toe (Thorne, 1990). In this case, fluvial processes will determine the degree of bank erosion. Hence in the long run, the bank height together with stream power may approximate the contribution of fluvial entrainment and mass failure processes along a river link.

There are three resisting forces to bank erosion: the viscosity of flow (affected by temperature), cohesive strength of bank materials and the reinforcing strength of riparian roots. In Australia we can generally ignore the temperature effect, so the generic bank erosion (BE) model along a stream link can be framed as:

$$BE = f\,(\text{stream power, bank height, bank strength}). \tag{1}$$

4.1. Model Component

Stream power

Stream power has been used in many descriptions of fluvial systems: processes such as channel migration rate (Annandale, 1995; Bagnold, 1960; Lawler, 1995; and Nanson and Hickin, 1986,), bedload transport rate (Bagnold, 1977); channel pattern (Knighton and Nanson, 1993). Hence, we will use stream power per unit bank area (Ω_x, kPad^{-1}) of stream in every stream link x (m) to approximate bank erosion by fluvial processes. Excess shear stress threshold (τ_{ex}, kPa) will initialize the erosion process described below (Osman and Thorne, 1988). Both Ω_x and τ_{ex} will be calculated as

$$\Omega x = \rho g Q_{bx} S_x / H_x \quad \text{and} \tag{2}$$

$$\tau_{ex} = \rho g H_x S_x \tag{3}$$

where ρ (1000 kgm^{-3}) is the fluid density, g (9.81ms^{-2}) is the acceleration due to gravity, Q_{bx} (MLd^{-1}) is the bankfull discharge calculated from instantaneous flow record, H_x (m) is the depth or height of the bank and S_x (dimensionless) is the energy slope all along a link x.

Bank (total) strength

The total strength of streambank (τ_{tx}, kPa) along a link x can be calculated as

$$\tau_{tx} = C_{rx} + C_x + \sigma_x \tan\Phi \tag{4}$$

where C_{rx} (kPa) is the apparent cohesion due to riparian roots, C_x (kPa) and Φ_x (degree) are the cohesion and internal friction angle of bank materials respectively, and σ_x (kPa) is the total shear stress normal to the failure plane.

Based on the critical shear stress threshold (Osman and Thorne, 1988), a bank will fluvially erode when $\tau_{ex} > \tau_{tx}$ i.e. when τ_{tx} / τ_{ex} is less than unity along a link x. The amount of eroded bank material under such condition will be approximated by the unit stream power using the method of Prosser et al. (2001).

Bank height

This component will characterize the limiting condition for bank stability with respect to mass failure for which an average bank height (H_x, m) and critical bank height (H_{cx}, m) or the estimate of driving and resisting forces along a bank link is essential. Under the force of gravity a stream bank can fail by several types of failure mechanism for which there is ideally a need for stability analyses capable of simulating these special conditions. However, for computational efficiency, the majority of failures along a stream can be approximated by frequently encountered failure types: planar and rotational along a stream link (e.g. Darby and Thorne, 1996, and 1997; Lawler, 1995; Millar and Quick, 1998). A best-fit regression against plausible explanatory variables including catchment and channel characteristics will be used for estimating the H_x, along a stream link x as

$$H_x = f\,(Qb, CA, S, W, Rd, L, T, Cl, G, Vt) \tag{5}$$

where Qb (ML/d) is the bankfull discharge, CA (Km^2) is the catchment area, S (%) is the riverbed slope, W (m) is the top width of a stream, Rd (%) is the riparian cover, L (Km) is the river reach/link length, T (code) is the texture of bank soils, Cl (%) is the clay content of bank material (A and B horizons), and G (code) is the group of bank geology and Vt (code) is the valley type.

The methods of Millar and Quick (1998) will be adapted for calculating the H_{cx} or the factor of safety ($FS_m = H_{cx} / H_x$) for rotational failure while that of Darby and Thorne (1996) will be used for planar failure.

In both methods the riparian strength (C_{rx}) will be incorporated to simulate its stability influence. A probabilistic approach (Darby and Thorne, 1996; Huang, 1983) will be used to identify these failure types as well as to estimate the fraction of failed (bank) link (l/L_x), using the distribution of geotechnical properties of bank material along a link (e.g. Simon, 1989). A stream link will be predicted to fail by mass failure when $FS_m < 1$ for both failure types. The volume of bank material eroded under such conditions for both types of mass failure, together with their likely future cycles, will be estimated using the methods of Darby and Thorne (1996).

A bank link or its fraction will be considered eroded if $\tau_{tx} / \tau_{ex} < 1$ and/or $FS_m < 1$. In all cases the amount of bank material eroded will be estimated by the methods described above under bank strength and bank height components.

5. MODEL TESTING

Detailed work has been conducted by other researchers in various basins particularly in the Latrobe, Goulburn and Western Port catchments (e.g. Abernethy and Rutherfurd, 1998). Therefore, these have been proposed as pilot basins for developing and testing the model. The output of the model will ultimately be compared with the existing information (e.g. lateral migration rate and/or total suspended solid transport) from these Victorian streams. At this stage, testing is limited to establishing whether widely available data bases can provide estimates of model parameters. Below is an example for estimating bank height.

6. PRELIMINARY ANALYSIS

We have different databases/sets namely SOS, and Ausrivas for stream characteristics in Victoria. Also, we have cross-section measurements for some of the streams in the Goulburn River basin referred to hereafter as 'independent datasets' (Indata). We undertook regression analysis to see if an average bank height ($H_{x,}$) along a streamlink can be estimated from distributed surrogate measures that are more likely to be available from distributed data-bases. To do this we first checked that the above databases are equivalent by testing their central tendency in $H_{x.}$ The non-parametric Mann-Whitney method was used as none of the data bases have H_x normally distributed (Ryan –Jioner test, $P>0.01$). The result was that the databases are not statistically different i.e. the null hypothesis that the median H_x of SOS and Indata ($P=0.40$) or SOS and Ausrivas ($P=0.67$) are equal can not be rejected at $\alpha=5\%$. This provides some statistical evidence that these databases are from the same bank height population.

Next the SOS database, that contains roughly 200 attributes of channel characteristics for 840 sample reaches of the Victorian streams, was used unless stated otherwise to develop the relationships with H_x The variables chosen for regression against H_x are as follows.

(i) Catchment area upstream of a node/site (CA) as surrogate for bankfull discharge (Q_b);

(ii) Texture (T) of bank soil and percentage clay content of streambank profile (Cl) as surrogate for the shear strength of bank soil. The latter was obtained from the Atlas of Australian Soils, and from the estimation of soil properties by McKenzie et al (2000);

(iii) The percentage of riparian tree cover (Rd) as a surrogate for riparian root strength or apparent cohesive strength (C_{rx}). The T, Cl, and Rd altogether thus act as a surrogate of total bank strength along a stream link x;

(iv) The hydraulic geometry parameters of a stream namely top width (W), length (L), bed slope (S) and landscape e.g. valley type (vt) for representing the variability in Q_b and the shape factors of a stream.

At first, scatter plots between these individual variables for H_x were plotted at the state (Victoria) level. Individual scatter plots between H_x and each of the above explanatory variables did not show any definite relationships ($n=840$). This indicates the variability of the relationships, which can't be explained by an individual variable at the state level. As a next step, the data was stratified by geology, landscape type, and land system. But none of these stratifications improved the relationships. Analyses were then undertaken at the basin level. Six basins: Goulburn, Hopkins, Wimmera, South Gippsland, Latrobe, and Glenelg were selected to represent the various conditions/types of basins in Victoria. The relationships between these variables and H_x are briefly described below.

Regression of the scatter plots, using backward eliminating regression analysis after screening for collinear variable(s) did indicate significant relationships between these variables and H_x for each basin. Table 1 describes the significant variables in each basin. Note that the relationships are different for each basin.

Table 1. Significant variables for H_x by basin at $\alpha=10\%$

River basin	Significant variables[1]	R2 (adj)	No in sample
Wimmera	LogCA, Rd, T, Cl, and S	84	21
Glenleg	CA, and S	75	36
S. Gippsland	LogCA,and Rd	71	25
Hopkins	LogCA, Rd, T, and Vt	79	28
Latrobe	Rd, Vt, T, and W	66	26
Goulburn	CA, Cl, Rd	89	23

[1] The regression equations for each basin are as follows

Wimmera : $4.206-0.38S+0.22T-0.097Cl+0.164Rd+0.91LogCA$ (6)

Glenleg : $1.24+0.00039CA+0.23S$ (7)

S. Gippsland : $0.9726-0.0259Rd+1.74LogCA$ (8)

Hopkins : $-1.1212+0.62Vt+0.161T+0.0112Rd+0.47LogCA$ (9)

Latrobe : $3.103-0.64T+0.108W+0.204Vt-0.015Rd$ (10)

Goulburn : $-1.5010+0.00033CA+0.091Cl+0.0091Rd$ (11)

The primary reason for different relationships is that the basins have different physiological and climatic conditions. Outliers and skewed data are influencing the relationships in each basin. Also the collinearity among the variables is different for different basins. The surrogates for total shear strength (T, Cl, and Rd) are particularly inconsistent, indicating that better data on this component may be needed.

It is important to note here, however, that CA was consistently (mostly) significant, probably reflecting the importance of channel forming discharge normally considered at bankfull stage (Q_b) in the analysis.

Finally, to test the validity of predictive relationship for H_x at the basin scale, independent bank height data from the Goulburn River basin was used. (Figure 1).

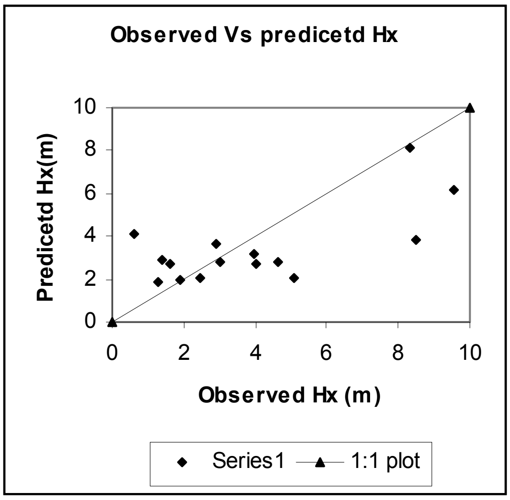

Figure 1. 1:1 plot of observed Vs predicted H_x for Independent datasets.

Figure 1 indicates that the explanatory capability of the regression is limited. This is reflected by the coefficient of efficiency of the model (E=42%). Unfortunately the Goulburn River Hx data are all from gauging stations which may not be "typical". We will be pursuing alternative measures such as more direct estimates of Q_b, exploring the use of riparian cover data from the ISC in combination with the information on tensile strength of riparian roots, combined with limited field sampling. We are encouraged by the strength of the initial regression relationships, (Table 1), although clearly there is more work to do to clearly assess whether data from the general databases will provide the data required to adequately parameterise the bank erosion model.

7. CONCLUSION

A generic bank erosion model has been framed for estimating the rate of bank erosion in a river system at the basin scale. It has three components namely stream power, bank height and bank strength. The challenge lies in the parameterisation of these components using widely available datasets for enabling broader application of the model.

Preliminary analysis was undertaken for estimation of the height component of the model, using the SOS database for Victorian streams. In all basins (six) examined there exist statistically significant relationships among H_x, and explanatory variables in the database (R^2 from 66-89%), although the relationships were different for each basin. However, based on limited data, the model performance was only moderate, with the coefficient of efficiency of being 42%. This indicates that the surrogates used may not capture the variability in the bank height well. Actual parameters of some of the surrogates e.g. bankfull discharge and the bank strength will be tested. Thus when all of the variables in the model have been compiled, it will be compared with results from published sources e.g. lateral migration rates of bank for testing the efficiency of the model and assess whether it is an improvement over the present SedNet bank erosion model.

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