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Riverbank erosion and its importance to uncertainties in large-scale sediment budgets

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Abstract In previous studies sediment budgets have been modelled at national and regional scales across many areas of Australia. Of the three dominant erosion processes considered (gully, hillslope and riverbank), riverbank erosion has been identified as having large systematic errors. In this paper we determine riverbank erosion rates by relating the average rate of meander migration to catchment or river attributes (e.g. discharge, riparian vegetation), and show that these typically only explain a small amount (<50%) of the variability in observed erosion rates. We demonstrate a methodology for deriving rates of riverbank erosion for 25 sites in southeastern Australia from historical river plan surveys, and present preliminary results from these surveys which support previous findings that the rates of meander migration and bank erosion for many Australian rivers are low by global standards. The paper also presents progress towards the development of an improved empirical model of riverbank erosion.

Key words meander migration; riverbank erosion; sediment budget; SedNet; spatial models

INTRODUCTION

The spatial modelling of erosion processes and linkages with downstream impacts in rivers, particularly in terms of changes in physical habitat (e.g. elevated suspended sediment levels, smothering of bedforms by sand slugs) is important in helping land management authorities target catchment rehabilitation. The National Land and Water Resources Audit of Australia (NLWRA, 2001) was undertaken in part to help address these issues at the national scale. An outcome of this work was the development of SedNet (Prosser *et al.*, 2001; Wilkinson *et al.*, 2005), a spatially distributed sediment budgeting model. SedNet couples erosion, hydrological, and sediment transport modelling to predict sediment loads and deposition throughout river networks, utilizing digital elevation models (DEM) and regional resource surveys (e.g. land use, vegetation, erosion, soil, flood plain maps).

The three main fluvial erosion processes considered in the model are hillslope (sheet/rill), gully and riverbank erosion. For both hillslope and gully erosion, predicted rates of erosion are reasonably well constrained, respectively, by a well established and tested model (the seasonally adjusted Revised Universal Soil Loss Equation, Lu *et al.*, 2003), and by detailed mapping of gully extent (Hughes & Prosser, 2003). By contrast, riverbank erosion has received less attention from researchers in Australia, and much of the uncertainty in sediment budget applications (e.g. De Rose *et al.*, 2004) can be attributed to uncertainties regarding the contribution made by riverbank erosion.

The rate of riverbank erosion is partly determined by the gradual migration of rivers across their flood plains, eroding previously deposited alluvial sediments and bedrock. Additionally, there maybe catastrophic channel enlargement where streams rapidly degrade their bed and banks during large flood events (Rutherfurd, 2000). The contribution made by channel (bank and/or gully) erosion relative to hillslope processes (sheet/rill) can be resolved using ^{137}Cs and ^{210}Pb radionuclide tracers (Wallbrink *et al.*, 1998). Studies have demonstrated that gully and riverbank erosion, rather than hillslope processes, are the dominant source of suspended sediment in many Australian rivers. Typically more than 50%, and as much as 90%, of the sediment being transported in many of Australia's rivers (e.g. the Murrumbidgee River, Wilkinson *et al.*, 2005) is derived from subaerial processes and much of this can be attributed to erosion from the bed and banks of river channels.

Despite its importance, the few measurements of riverbank erosion undertaken in Australia are limited by either a short survey period or small spatial coverage. These surveys also tend to over-represent the most actively eroding sections of rivers (i.e. outside banks of meander bends) and there may be inadequate scaling of rates measured on one bend to the assessment of bank erosion along an entire river. To redress this paucity of specific field data we have measured river bank erosion by comparing changes in the location and planform of rivers at 25 sites in southeastern Australia. The sites are located along relatively long river reaches, and span two periods between three dates of survey: the late 1800s, 1935 and 1985 (Finlayson *et al.*, 2004; Wilson *et al.*, 2005). This paper presents preliminary results from these surveys and provides a review of the status of our understanding of riverbank erosion in Australia with respect to spatial modelling for large basin sediment budgets. The Murray-Darling Basin, covering an area of approximately 1×10^6 km^2, is used as a case study.

BACKGROUND

Rutherfurd (2000), based on a global review of river bend migration data, suggested that the best predictor of the migration rate of rivers (M, in m year^{-1}) was bankfull discharge or mean annual flood discharge (Q):

$$M = 0.0435Q^{0.6008} \tag{1}$$

Despite the moderate correlation (R^2 = 0.43) of this relationship, there remained on average, an order of magnitude variation in the observed migration rate for any given discharge.

Walker & Rutherfurd (1999) further showed (equation (2)) that the meander migration rate could be related to gross stream power ($\rho g Q_{bf} S_e$, where ρ = 1000 kg m^{-3}, g = 9.8 m s^{-2}, Q_{bf} is bankfull discharge in m^3 s^{-1}, and S_e is the energy slope approximated to the mean channel gradient). Although the relationship is not as strong (R^2 = 0.35) as that for bankfull discharge alone, the introduction of slope into a predictive model for bank erosion has important consequences for spatial modelling applications as will be seen in the next section.

$$M = 0.025(\rho g Q_{bf} S_e)^{0.53} \tag{2}$$

Walker & Rutherfurd (1999) also showed that a high degree of prediction could be achieved where information about bank resistance (texture, D_{50}), and channel width and depth was available. In general, however, because these data are not readily available for large river networks, models of this form are not as useful in spatial modelling applications.

Of the data analysed by Rutherfurd (2000), only three sites were from Australian rivers and all of these had meander migration rates well below the global average (equation (1)). Additionally, one of the sites (0.58 m year^{-1}) was interpreted to be an overestimate because of the unusual severity of flood events during the three year measurement period. Rutherfurd (2000) also indicated much lower rates for the major lowland rivers such as the Murray and Darling-Barwon Rivers.

A review of 13 surveys in Australia presently being undertaken by the authors, suggests that meander migration rates rarely exceed 1 m year^{-1} and are less than 0.3 m year^{-1} in most situations. These include recent findings from erosion pin and sequential aerial photographic investigations in such diverse rivers as the Kiewa in Victoria (Grove, personal communication), and the Burdekin in Queensland (Bainbridge, 2004). (Space limitations preclude presentation of the review here). Consequently, it makes little sense to directly apply global trends to Australian rivers for spatial modelling applications, and coefficients in equations (1) and (2) need to be reduced to more accurately reflect bank erosion rates observed in Australian rivers.

SPATIAL MODELLING APPLICATIONS

In the initial application of the SedNet model at continental scales (Prosser *et al.*, 2001; NLWRA, 2001) the bankfull discharge relationship (equation (1)), with a reduced coefficient of 0.008, was implemented to predict average rates of lateral riverbank erosion for Australian river networks. Bankfull discharge was in turn estimated by a process of basin-wide regionalization of the 1.58-year recurrence interval flow on the annual maximum time series, calculated from the daily flow series recorded at hydrometric gauging stations. The predicted lateral erosion rate was then multiplied by the bank height (H), reach length (L) and an average dry bulk density (DBD) for flood plain alluvium of 1.5 t m^{-3}, to derive average riverbank erosion rates in tonnes per year (BE, equation (3)). Further to this, because woody riparian vegetation is known to reduce bank erosion rates (Frankenberg, 1996), a simple ramp function is introduced to exclude the proportion of bank with riparian vegetation (PR).

$$BE\,[\mathrm{t\ year^{-1}}] = 0.008Q^{0.6}(1-PR)H\cdot L\cdot DBD \tag{3}$$

For the Murray-Darling Basin (MDB, Fig. 1(a)) this model resulted in an initial estimate for the total delivery of sediment from riverbank erosion to rivers of 19 Mt year^{-1} (Hughes & Prosser, 2003). Although erosion rates were predicted to rarely exceed 0.5 m year^{-1}, an important aspect of this model (Fig. 1(a)) was the estimated high levels of erosion (>0.3 m year^{-1}) along lowland rivers, contrasting with the limited evidence of very low rates of meander migration for these rivers (Woodyer, 1978; Tilleard *et al.*, 1994). It was thus clear that applying equation (3) across a large basin resulted in over-prediction of bank erosion rates, particularly along the lower

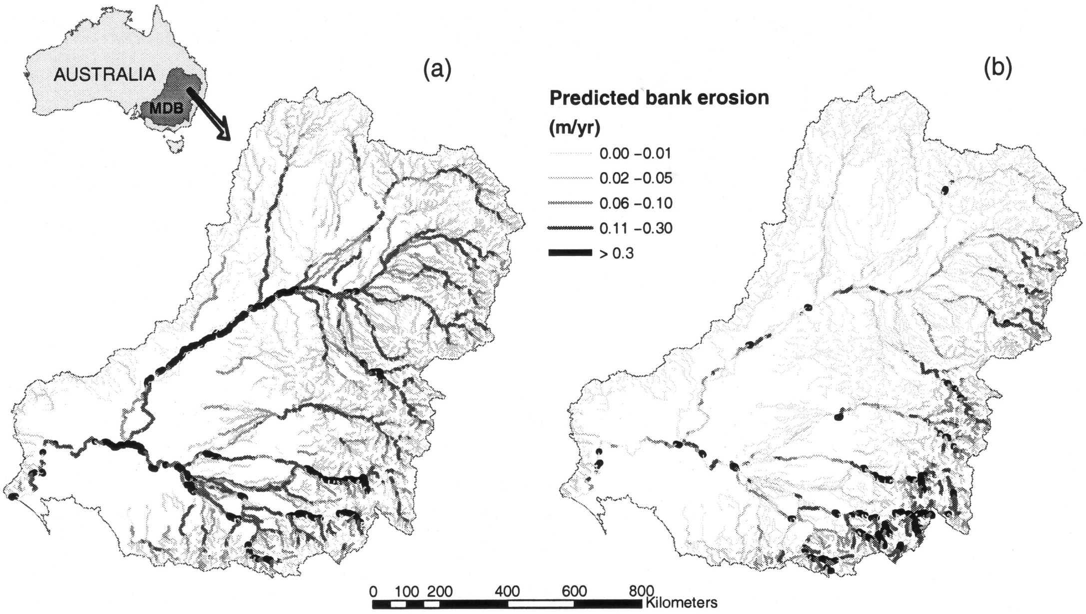

Fig. 1 Predicted riverbank erosion rates (m year^{-1}) for rivers in the Murray-Darling basin using empirical models based on: (a) bankfull discharge and riparian vegetation (equation (3)); (b) stream power, riparian vegetation and flood plain width (equation (4)).

reaches of major rivers. In upper reaches, and in cases of channel enlargement (as reviewed by Rutherfurd, 2000), predicted rates were lower than suggested by present-day channel dimensions.

Consequently, an alternate equation based on the stream power relationship of Rutherfurd (equation (2)) was implemented in subsequent re-assessment of the sediment budget for the MDB (equation (4), De Rose *et al.*, 2004). An additional ramp function was introduced to account for rocky gorges, where it is unreasonable to expect the same levels of riverbank erosion as in alluvial reaches. This resulted in a new estimate (Fig. 1(b)) for the total delivery of sediment from riverbank erosion to rivers of 9 Mt year^{-1}, 45% of the initial estimate for the MDB.

$$BE\,[\mathrm{t\ year}^{-1}] = 0.00002\rho g Q_{bf} S(1-PR)(1-\mathrm{e}^{-0.008.F_x})H\cdot L\cdot DBD \qquad (4)$$

The effect of introducing slope into the empirical model for riverbank erosion can be seen clearly in the spatial pattern of riverbank erosion in Fig. 1. The decrease in channel slope along lower river reaches has the effect of greatly reducing predicted rates of bank erosion for downstream reaches, typically to less than 0.1 m year^{-1}. Hence, although the stream power based equation (4) does not appear to provide as good a statistical predictor of global migration rates (Rutherfurd, 2000), the spatial pattern provided by this model is more consistent with our present understanding of the distribution of riverbank erosion in large river networks in Australia. The different estimates of total sediment supply to the MDB river network, suggest that there are potentially large systematic errors in predicting riverbank erosion using these relatively simple empirical models without sufficient model calibration.

BANK EROSION RATES IN SOUTHEAST AUSTRALIA

To help redress the paucity in bank erosion data for Australian basins, a research project has been initiated to evaluate the long-term rates of lateral bank erosion for a selection of river reaches in southeast Australia (Finlayson *et al.*, 2004). To avoid problems associated with short survey periods, or bias towards points of high bank activity, the methodology has been to determine long-term average rates of lateral erosion by comparing the change in location of riverbanks over relatively long sections of river (10–50 km or more) and survey periods of several decades. Survey reaches had a wide range of contributing catchment area (390–15 000 km^2).

Survey periods were pre-determined by existing river surveys in southeast Australia. The earliest known surveys were undertaken between 1866 and 1895 for regional planning and land development around the time of European settlement. These are often referred to as "Parish Plans" and show the location of left and right river margins. Sections of these rivers were resurveyed in detail in 1935, for assessing the stability of major river channels of Victoria where erosion was acute (Thompson, 1938; Strom, 1941). The locations of all rivers were again mapped in 1985 as part of the 1:25 000 topographic map series for Victoria. These surveys thus provide two distinct periods for investigating change in the location of rivers: a 38–69 year period following initial land development and a later period of 50 years encompassing significant flow regulation to many of the rivers, coupled with variable riparian rehabilitation.

To evaluate channel planform changes, each of the survey plans was digitized and registered for the three dates of survey using ArcGIS software, with spatial adjustments made using first-order linear transformation with five link (control) points. Cadastral (land tenure) boundaries are common to all survey plans and were used as the basis for the transformations. In most cases residual errors for the location of river margins were within 8 m. Polygons representing losses or gains in the channel area due to river migration were created by intersecting initial polygons representing river channel and non-river (flood plain) regions for the surveys encompassing each time period. Area losses occur where the river has abandoned its previous course and is undergoing active accretion, while gains occur where the river has "colonized" previous flood plain areas due to lateral riverbank erosion, avulsions and meander cutoffs.

Losses and gains in area should balance unless: (a) there has been net channel contraction or expansion during each period, and (b) errors in mis-registration of surveys. Avulsions and meander cutoffs were separately identified and later excluded from the calculation of riverbank erosion, as they often represent a shift in the location of the river, without necessarily eroding intervening flood plain deposits. The adjusted losses and gains in flood plain area were converted to rates of change in area per unit length of channel, by dividing by the reach length and period of survey, thus deriving the average rate of lateral bank erosion (m year^{-1}).

Results for the two survey periods are presented in Fig. 2 for 15 of the 25 reaches investigated to date. These suggest a remarkable degree of consistency in long-term erosion rates despite the large range in upstream catchment area and expected discharge.

Averaged rates (average of losses and gains) for the early period range from 0.06 to 1 m year^{-1}, although most sites are between 0.2 and 0.44 m year^{-1}. For the latter period, average erosion rates range from 0.15 to 0.47 m year^{-1}. Figure 2 shows that for most

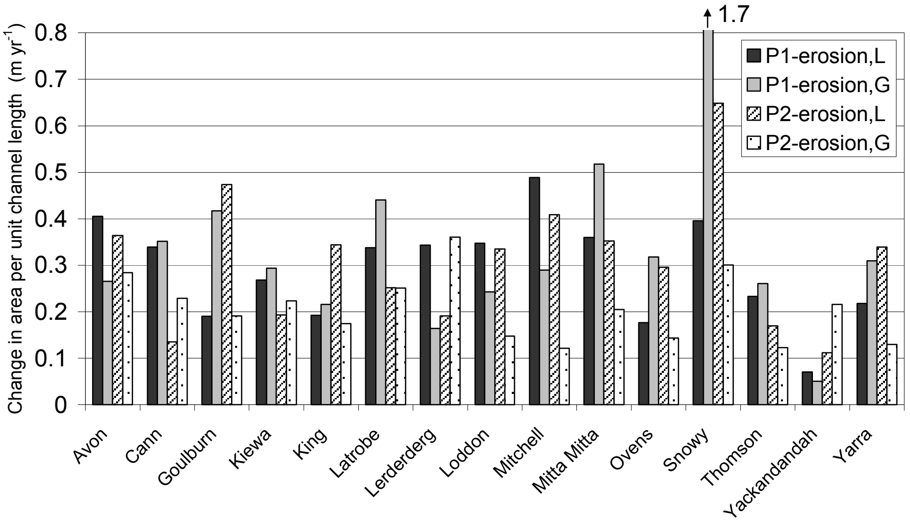

Fig. 2 Losses (L) and gains (G) in channel area (excluding evulsions and cutoffs) for 15 river reaches in southeast Australia for two time periods: 1866/95–1935 (P1) and 1935–1985 (P2).

sites, there has been a decrease in erosion rates between periods (the mean of all sites for the latter period is 75% of that for the early period), and this is to be expected given the likely consequences of river regulation on decrease in effective flows for the later period.

The accuracy of the above method has been successfully tested at one survey site (Kiewa River) by direct comparison with an erosion pin survey by Grove (personal communication). This investigation extended over a relatively short period of 1.5 years (June 2002–January 2004) at five locations along the same length of the river as analysed in the historical surveys. The erosion pin rates are similar to or below the longer-term average rate of 0.2 m year^{-1} estimated for the period 1935–1985. Lower rates derived from erosion pin measurements are probably due to the short survey period which did not encompass a sufficient range of major rainfall/flood events. The results presented in Fig. 2 would thus appear to represent reliable estimates of long-term average rates of riverbank erosion.

The data presented in Fig. 2 have yet to be examined in relation to discharge, stream power and riparian vegetation cover. A preliminary comparison of erosion rates to catchment area, however, suggests that a relationship is likely to exist with annual discharge. Of the sites examined, for example, the Snowy River with average rates of 1.0 and 0.47 m year^{-1} for the two periods, respectively (Fig. 2), is the largest of the rivers investigated (15 000 km^2, as measured at the downstream end of the survey reach). In contrast, Yackandanda Creek with the lowest average erosion rates of 0.06 and 0.16 m year^{-1} for the two periods, is the smallest stream investigated (390 km^2).

To date, the only survey that has directly compared the performance of the stream power based equation (4) with measured bank erosion rates is that of Bainbridge (2004), who examined a 250-km reach of the upper Burdekin River in Queensland. Sequential aerial photographs at 71 sites, combined with field cross-section surveys, were used to measure change in bank location between the mid 1960s and 1999–2002. Results suggested that 45% of the surveyed sites had no appreciable change in channel width or location as they were within error limits (5 m) for detecting change. For the remaining sites, bank erosion varied from –0.36 (channel abandonment and narrowing) to 0.7 m year^{-1}, although the majority of sites were less than 0.3 m year^{-1}. The reach average rate was 0.0753 m year^{-1} and this compared surprisingly well with a predicted lateral bank rate of 0.0728 m year^{-1} using equation (4).

The results from surveys in southeast Australia (Fig. 2), when compared to the global review of bend migration by Rutherfurd (2000), confirm that rates of bank erosion for many Australian rivers are low by international standards. It would appear that average reach length lateral migration rates are rarely greater than 0.5 m year^{-1}and typically less than 0.3 m year^{-1}, and this is at the lower end of the 0.3 to 10 m year^{-1} range in global bend migration rates for rivers with similar bankfull discharge.

We will continue this work by examining the relationship between the surveyed bank erosion data (Fig. 2) and discharge, stream power and riparian vegetation. This will help assess the conditions under which equations (1)–(4) are suitable for estimating bank erosion in Australian rivers.

CONCLUSIONS

Riverbank erosion is an issue of major importance to sediment budgets in Australian river basins. However, the use of existing models of riverbank migration without adequate calibration can lead to large systematic errors in the prediction of bank erosion rates. There is a dearth of measured rates of riverbank erosion in Australian rivers. We have presented some progress towards measurement of riverbank erosion from sites in south-east Australia, and this confirms previous findings of the low rates relative to global average trends. Additionally this data will allow us to make future improvements to models of riverbank erosion.

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