1 An investigation of controlling variables of riverbank erosion in sub-tropical Australia

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1 Abstract

A large proportion of the uncertainty surrounding catchment sediment budget modelling has been attributed to sediment supplied from riverbank erosion. Some of the variables influencing riverbank erosion are bend curvature, specific streampower, riparian vegetation, and in some instances sand and gravel extraction. The empirical relationship between these variables and observed riverbank erosion across 78km of the Upper Brisbane River, Australia was investigated. No significant relationship was found between curvature, specific streampower and riverbank erosion. The role of riparian vegetation relative to sediment supply from riverbank erosion varied with spatial location, susceptibility of a reach to erosion, and human disturbance such as sand and gravel extraction. Despite not having data on substrate type the model described approximately 37% of the variation in observed riverbank erosion. It appears that inclusion of a management practice factor in riverbank erosion models is justified, where appropriate, and may improve model performance.

2 Introduction

In many regions around the world water quality has been impacted by point and diffuse sources of pollution. While progress has been made reducing point sources of pollution, management of diffuse source pollution still presents a significant challenge (Duda, 1993). Consequently management of diffuse source pollution has been the focus of substantial government investment (NLWRA, 2001; US EPA, 2003). The sediment component of diffuse source pollution is commonly measured through suspended sediment yield, which is typically defined as clay and silt sized material moving in suspension in river flow (Wilkinson *et al.*, 2009). Heightened suspended sediment yield can adversely impact aquatic biodiversity and ecological function (Bilotta and Brazier, 2008); reduce storage capacity of reservoirs (Lu *et al.*, 2004); and increase water treatment costs (Holmes, 1988). The relationship between processes which deliver sediment to a river and consequent downstream suspended sediment yield is often complicated by the large spatial scales over which these processes operate and the presence of sediment depositional areas (Wilkinson *et al.*, 2009). Catchment scale sediment budget models are therefore commonly used to capture the relationship between sediment sources, transport pathways and sinks (Wilkinson *et al.*, 2009).

Catchment sediment budget models are frequently used to target management actions and inform policies aimed at reducing suspended sediment yield (Lu *et al.*, 2004; Hughes and Croke, 2011; Wilkinson *et al.*, 2014). These models are often based on a combination of erosion and sediment transport physical process knowledge, and empirical data (Wilkinson *et al.*, 2009). The inclusion of physical process models allows the suspended sediment yield response to potential management actions to be estimated (Wilkinson *et al.*, 2014). The physical process models assume that suspended sediment yield is limited by supply from hillslope, gully and riverbank erosion sources (McKergow *et al.*, 2005; Wilkinson *et al.*, 2009). Obtaining data to validate modelled sediment supply from these erosion sources at a catchment scale is a recognised limitation of these models (Wilkinson *et al.*, 2009; Hughes and Croke, 2011).

A large proportion of the uncertainty surrounding catchment sediment budget modelling has been attributed to sediment supplied from riverbank erosion (De Rose *et al.*, 2005). For example Bartley *et al.* (2008) found modelled riverbank erosion rates underestimated observed rates over 14km in Northern Queensland, Australia (Figure 1). It is important to understand the cause of this uncertainty as evidence suggests that riverbank erosion is the

dominant source of sediment in many Australian rivers (Wasson *et al.*, 1998; Prosser *et al.*, 2001). Due to the historical difficulty of obtaining empirical riverbank erosion data at large spatial scales, sediment budget models attempt to capture the primary controlling variables affecting riverbank erosion rates (Wilkinson *et al.*, 2009). Some commonly used controlling variables of riverbank erosion are bend curvature, streampower and riparian vegetation.

The relationship between riverbank erosion and bend curvature has been studied extensively (Ikeda *et al.*, 1981; Nanson and Hickin, 1986; Darby *et al.*, 2002; Tal and Paola, 2007). These investigations range in complexity and are generally approached from either a geomorphological or fluid mechanics discipline (Seminara, 2006; Camporeale *et al.*, 2007). An assumption common to many of the approaches is that flow remains constant (Camporeale *et al.*, 2007). Bend curvature is not included in many sediment budget models; however it is commonly examined in relation to riverbank erosion rates.

While many studies have emphasised the link between small scale velocity distributions and riverbank erosion (ASCE, 1998; Darby *et al.*, 2010), streampower is commonly used in catchment scale modelling as a measure of a river's ability to do geomorphic work (Leopold *et al.*, 1964). Calculating specific streampower ($\dot{S}$, equation 1) has the advantage of accounting for valley confinement on increased flow velocities. Bankfull discharge is commonly used to represent the most geomorphically effective discharge (Dury, 1961; Bartley *et al.*, 2008; Wilkinson *et al.*, 2009). Energy grade slope is an important component of specific streampower calculations, as it reflects the rate of energy conversion from potential to kinetic (Bagnold, 1966). Due to the difficulty of estimating energy grade slope it is common to use either channel slope (Knighton, 1999; Parker *et al.*, 2011); water surface slope (Yang, 1972; Lecce, 1997); or bankfull flow water surface slope (Larsen *et al.*, 2006). Each approach may be appropriate depending on the geomorphic behaviour of an individual river (Yang, 1972).

$$\dot{S} = \frac{g \rho Q S}{W} = \tau_0 \bar{v} \quad (1)$$

Where $\dot{S}$ = specific streampower (Wm^{-2}); g = gravitational constant (9.8 ms^{-2}); ρ = density of water ($1,000 \text{ kgm}^{-3}$); Q = discharge ($\text{m}^3 \text{ s}^{-1}$); S = energy grade slope; W = flow width (m); τ_0 = mean boundary shear stress (Nm^{-2}); and $\bar{v}$ = mean velocity (ms^{-1}).

The influence of riparian vegetation on riverbank erosion is dependent on a range of biotic and abiotic factors (Corenblit *et al.*, 2007). Although most studies conclude riparian vegetation reduces erosion (Millar, 2000; Micheli and Kirchner, 2002; Brooks *et al.*, 2003), some have found it plays a minor role in relation to other physical factors such as particle size of the riverbank sediment (Nanson and Hickin, 1986; Bettess and White, 1987). We are not aware of any studies which have quantified its influence over extensive (>50km) contiguous sections of river.

Riverbank erosion rates can also be influenced by sand and gravel extraction (Kondolf, 1997; Rinaldi *et al.*, 2005). Separating the influence of sand and gravel extraction from other physical drivers of riverbank erosion is challenging. However where extraction rates exceed bedload delivery rates it has been found to play a role in altered riverbank erosion behaviour (Rinaldi *et al.*, 2005). This impact is generally not captured in sediment budget models and

we are not aware of any studies which look at the influence of sand and gravel extraction on riverbank erosion over large spatial scales.

The aim of this study was to investigate whether there is an empirical relationship at a large spatial scale between observed riverbank erosion and the primary controlling variables mentioned above. The study area spans 78km of the subtropical Upper Brisbane River (UBR) in South-East Queensland (Figure 1), where geomorphic work is dominated by flood events. Channel erosion (which includes riverbank and gully erosion) was found to be the dominant source contributing to sediment yield in the catchment (Olley *et al.*, 2013). The Esk Formation geology which underlies the majority of the study area (Figure 1) was found to contribute 50% of the sediment yield in the catchment (Douglas *et al.*, 2007). Therefore the riverbank erosion data presented in this study have two applications as suggested by Bartley *et al.* (2008): they provide location specific knowledge which may help target river rehabilitation and revegetation programs; and large spatial scale validation data which could inform application of sediment budget models.

Figure 1 Upper Brisbane River (UBR) study area showing reach divisions, gauges and major tributaries. Inset panels show location of study site within the UBR catchment, and location of the UBR catchment within Queensland, Australia

3 Study Area

The UBR catchment is subtropical with average temperatures ranging from 21°C in winter to 29°C in the summer season (October to February). Rainfall falls predominantly in summer and ranges from approximately 1007 mm^y⁻¹ in the south-east of the catchment to approximately 564 mm^y⁻¹ in the north-west (Shellberg and Brooks, 2007). The UBR discharges into Wivenhoe Dam (Figure 1), which is the largest municipal water supply reservoir in the State of Queensland (Shellberg and Brooks, 2007). The UBR flows through the Esk Formation which contains sedimentary and volcanic rocks, predominantly Triassic in age, and alluvial deposits (Brizga and Finlayson, 1996). It is bounded by the D'Aguilar and Yarraman Palaeozoic blocks to the east and west respectively (Brizga and Finlayson, 1996). A defining characteristic of the river is its incision into the surrounding geology forming a partly-confined mildly sinuous macrochannel (defined below), with large meander wavelength and some irregular meanders (Brizga and Finlayson, 1996; Brennan and Gardiner, 2004; Shellberg and Brooks, 2007).

The macrochannel planform geometry has changed very little since the earliest aerial photographs in 1951 (Brizga and Finlayson, 1996). It is approximately 250m wide on average, however it can vary from 160m to 400m across the study area. The macrochannel bank height is generally around 12-13m above the thalweg. Within the macrochannel exists an alluvial channel with slightly higher sinuosity connected to inset floodplains and benches (Brennan and Gardiner, 2004; Shellberg and Brooks, 2007). The bed of the UBR is comprised of a gravel and cobble layer overlying sand, which becomes noticeably sandier downstream of the confluence with Maronghi Creek (Figure 1) (Brizga and Finlayson, 1996; Brennan and Gardiner, 2004). Point and alternate bars comprised of gravel and cobble are common, as are pool and riffle sequences (Brizga and Finlayson, 1996; Brennan and Gardiner, 2004). Inset features are comprised of gravel, sand, silt and clay and a small number of islands are present (Brizga and Finlayson, 1996; Brennan and Gardiner, 2004).

The UBR hydrology is extremely variable compared to rivers of similar size in Australia and globally, due to large differences between common and rare flood magnitudes and large annual variability in peak discharge (Brizga and Finlayson, 1996; Rustomji *et al.*, 2009). The variability of the flood regime and partly-confined valley setting predisposes the river to large magnitude geomorphic change when low frequency, high magnitude flood events occur (Brizga and Finlayson, 1996; Brierley and Fryirs, 2005).

Historical photos from the region show dense riparian vegetation in the early colonial period (Figure 2, left panel). As European settlement progressed, native vegetation was cleared extensively for cultivation and pasture, and stock caused substantial damage to riparian vegetation and riverbanks (Brizga and Finlayson, 1996). These land use changes exacerbated stripping of geomorphic units inset within the macrochannel during flood events, and inhibited re-colonisation of vegetation (Brizga and Finlayson, 1996). The extent of riparian vegetation remains low today, with 46% of the stream length surveyed for riparian vegetation by Johnson (2005) categorised as very poor and 26% categorised as poor (Figure 2, right panel).

Sand and gravel extraction has occurred throughout the UBR for several decades (Brizga and Finlayson, 1996; Shellberg and Brooks, 2007). Establishing the long term on and offsite impacts of this extraction is complicated by the episodic nature of geomorphic activity in the river (Shellberg and Brooks, 2007).

Figure 2 Example of the condition of riparian vegetation in the Upper Brisbane River in 1884 (left panel); and 2012 (right panel). Note: the exact location of the historical photo was unknown, and the comparison of riparian vegetation change is indicative only.

4 Materials and Methods

4.1 Estimating riverbank erosion

LiDAR surfaces for approximately 78 km of the main stem of the UBR were captured in May 2001 and June 2011 and used to create 1x1m digital elevation models (DEMs). The 2001 LiDAR was captured using an Optech Airborne Laser Terrain Mapper 1020 system. A flying height of 400m and a swathe width of 150m were used. The accuracy of the capture was $\pm 0.15\text{m}$ in the z direction and $\pm 0.4\text{m}$ in the x and y directions. The accuracy of the DEM was verified through survey data collected in the field. The results of this comparison showed that the DEM was accurate to within 30cm for at least 80% of the data. The 2011 LiDAR was captured using a Toposys Harrier 68i/G1 LiDAR system. A flying height of 700m and a swathe width of 730m were used. The accuracy of the capture was $\pm 0.15\text{m}$ at one sigma (67% confidence level). In lieu of a ground survey, the 2001 DEM was used to test the LiDAR accuracy and provide additional adjustment values. Orthophotography was captured simultaneously with the 2011 LiDAR using the scanner's integrated camera. Both LiDAR captures had point densities 1m^{-2} .

A DEM of Difference (DoD) was created to estimate riverbank erosion between 2001 and 2011. An initial limit of detection (LoD) of 0.21 m was calculated using the error propagation methods of Taylor (1982), similar to Brasington *et al.* (2003) and Lane *et al.* (2003). To assess the agreement of the LiDAR captures, elevation at 400 locations on bitumen roads across the spatial extent of the capture were analysed and variation was found to be within the error bounds above. A new probabilistic LoD was determined to detect difference at the 95% confidence interval by multiplying the above value by a t-value of 1.96, giving a revised LoD of 0.41m (Taylor, 1997). To avoid any potential errors caused by grasses and small vegetation changes within the riparian corridor influencing bare-earth LiDAR returns, a final spatially uniform LoD of 0.5 m was chosen. The final DoD was visually inspected and any areas of erosion less than 20m^2 were removed. This approach was appropriate as the geomorphic process of interest was high magnitude riverbank erosion that may be correlated to primary controlling variables at large spatial scales. The magnitude of the geomorphic change was therefore much larger than the estimated noise and a spatially uniform error estimate was justified (Passalacqua *et al.*, 2015). It is acknowledged that factors used to derive spatially variant error estimates may be relevant in some sections of the river, such as vegetation density and slope (Wheaton *et al.*, 2010). This was addressed during the visual

inspection of the DoD by removing estimates where vegetation and slope interactions were suspected to have influenced LiDAR accuracy.

The area of standing water in 2001 and 2011 was defined using slope and valley bottom floor (MrVBF, Gallant and Dowling (2003)) layers as inputs into a segmentation algorithm within the Definiens software package. The resulting layer was validated through visual inspection of aerial imagery and used to exclude sections of the DoD influenced by standing water.

Discharge over the 2001-2011 period was dominated by a large flood event in January 2011. The 2011 flood event reached a mean daily discharge of $3,407 \text{ m}^3\text{s}^{-1}$ and a maximum daily discharge of $6,725 \text{ m}^3\text{s}^{-1}$ at the 143009A gauge (Figure 3).

Figure 3 UBR discharge at gauge 143009A for the 2001-2011 period

4.2 Classification of geomorphic units within the macrochannel

Geomorphic units inset within the macrochannel were digitised as a means of identifying geomorphic complexity throughout the river (Croke *et al.*, 2013; Fryirs and Brierley, 2013). The geomorphic units were defined using the 2001 DEM and derived datasets (such as riverbank height and slope layers); and aerial photography from 2009 and 2011. The geomorphic units identified include (Figure 4): water; bed material (exposed bars comprised of obvious sand and gravel deposits, adjacent to channel, sparse vegetation); vegetated islands (vegetated areas isolated from main channel banks and perched above bed material); benches (long, relatively narrow and level feature running parallel to the river bounded by distinctly steeper slopes above and below); inset floodplain (extensive somewhat flat surfaces formed above benches and at an intermediate level between the bed material and the high terrace); terrace (upper, relatively level surface usually higher than 12 metres above the thalweg); and colluvial slopes (steep hillslopes impinging directly on the channel margin).

All geomorphic units defined above were used to describe geomorphic complexity, however those classified as water and bed material were excluded from subsequent analyses (i.e.

geomorphic units analysed for erosion were vegetated islands, benches, inset floodplains, terraces and colluvial slopes). The aim of this paper was to investigate relationships between some primary controlling variables used to model riverbank erosion at large spatial scales and observed erosion. Change in the extent of water and bed material geomorphic units is influenced by complex entrainment and deposition processes which are unlikely to be captured by these variables. Additionally, the accuracy of DoD estimates from bed material geomorphic units are less certain due to sand and gravel extraction.

Figure 4 Typical channel form and defined geomorphic units in the Upper Brisbane River (note colluvial slopes are not represented in this example).

4.3 Reach delineation based on meandering

A polygon of the macrochannel was digitised and divided into 79 curving or relatively-straight reaches in a downstream direction (reach 1 was the most upstream and reach 79 the furthest downstream). The complex form of inset features within the macrochannel and the variability of the UBR hydrology, made defining a representative bend curvature problematic. Therefore this approach examines the relationship between coarse scale

curvature of the macrochannel and riverbank erosion, rather than bend radius of curvature as applied in other studies (e.g. Nanson and Hickin (1986)).

Riverbank erosion volumes were normalised by the area of each reach (excluding the water and bed material geomorphic units) to derive an erosion volume per unit area metric. A channel bifurcation in reaches 46-49 was not fully captured by the LiDAR and prevented a complete estimate of riverbank erosion being determined. These reaches were therefore excluded from further analysis, leaving 75 reaches covering 78km (Figure 1).

4.4 Geomorphic zone delineation

Spatial variation in geomorphic processes across a catchment are strongly influenced by valley confinement (Montgomery, 1999; Brierley and Fryirs, 2005). The 2011 flood extent was used as an indication of valley confinement to identify three geomorphic zones in the study area (Figure 1). An Upper zone where flood extent was largely confined to the macrochannel (reaches 1-31); a Middle zone where the flood extent was partly-confined on one side of the river (reaches 32-67); and a Lower zone where the flood extent was partly-confined but spread much farther across the floodplain (reaches 68-79).

4.5 Specific streampower

Specific streampower over the 2001-2011 period was calculated using gauged discharge data, a relationship between discharge and contributing area, a HEC-RAS model, and equation 1. The 2011 flood event extended laterally beyond the LiDAR capture in some locations (Figure 1). To allow modelling of this event in HEC-RAS, the 2001 LiDAR DEM was merged with a 1 second DEM of the UBR catchment captured by the Shuttle Radar Topography Mission (SRTM) in February 2000 (Gallant *et al.*, 2011). The LiDAR and SRTM derived DEMs were compared at several locations throughout the UBR main stem and found to be in reasonable agreement.

The HEC-RAS model had 962 cross-sections, used critical depth as the upstream boundary condition and normal depth as the downstream boundary condition. Bed slope was approximated from the 2001 water surface slope. Manning's roughness coefficients were estimated initially from Chow (1959) then calibrated to rating curves at two gauges within the study area using flow weighting (143007A and 143009A, Figure 1). Prior to flow weighting channel roughness was set to 0.035, and overbank roughness values ranged from 0.06 in the Upper geomorphic zone to 0.04 in the Middle and Lower geomorphic zones. The modelled peak flood extent was compared to a flood extent digitised from debris lines by a local council and found to be in reasonable agreement.

HEC-RAS outputs were used to develop a relationship between discharge, flow width and energy grade slope at every cross section across the study area. The model was run for twenty-five discharge profiles using steady flow analysis which covered the range of conditions experienced between 2001 and 2011. These profiles ranged from 6.25 – 6,726 m³s⁻¹ measured at 143009A. Due to the influence of water in the 2001 LiDAR DEM it was not possible to obtain exact channel bathymetry. Cross-sectional modelled discharges are therefore in addition to discharge in the channel at the time of the 2001 LiDAR capture. Discharge across the study area at the time of the LiDAR capture was estimated through a relationship between discharge at 143007A and 143009A and contributing area. This was added to modelled discharge so that flow width and energy grade slopes from the model more accurately simulated conditions under observed discharges.

Flow width and energy grade slope relating to each discharge profile were averaged for cross-sections within the 75 reach divisions. Discharge for each reach was calculated using data from 143007A and 143009A, and a relationship between discharge and contributing area. Specific streampower was calculated using three discharge estimates: macrochannel bankfull discharge estimated from the HECRAS cross sections; maximum daily discharge; and mean daily discharge. For specific streampower estimates using maximum and mean daily discharge cumulative specific streampower was calculated, similar to Larsen *et al.* (2006), by linearly interpolating between modelled discharge, flow width and energy grade slopes to calculate equation 1 for the estimated maximum and mean daily discharge at each reach over the 2001-2011 period. This form of the specific streampower equation integrates over the 2001-2011 period and therefore changes the units to joules per metre squared (Jm^{-2}). Pool and riffle sequences in the river occasionally resulted in high energy grade slopes at low discharges. As the majority of the 2001-2011 period had low discharges (Figure 3) and cumulative specific streampower was calculated for estimates derived from maximum and mean daily discharge, these high energy grade slopes propagated into unrealistically high cumulative specific streampower totals. As this was not an accurate reflection of the streampower available for erosive work, 10 Jm^{-2} was used as a specific streampower threshold below which calculated daily specific streampower data was discarded. This was appropriate so calculations better reflected the characteristics of geomorphically significant events in the UBR.

4.6 Riparian vegetation

Vegetation information was derived from the 2001 LiDAR capture through the vegetation plot methods of Neldner *et al.* (1999); and foliage projected cover (FPC) methods of Specht (1970) and Specht *et al.* (1995). Vegetation height classes (0-2m; 2-5m; 5-10m; 10-30m; >30m) were then defined using the Specht *et al.* (1995) classification system. Using digital video data and ground truthing, a vegetation map of high accuracy was derived at a 1:4000 scale.

Polygons representing vegetation above five metres in height were chosen to align with woody, single-stemmed trees in the Specht *et al.* (1995) classification. These polygons were used in subsequent analyses and are referred to as large woody vegetation (LWV) in the remainder of the article. To allow comparison between reaches, the area of LWV overlying geomorphic units excluding bed material was normalised by the corresponding area to derive a proportion of LWV. These metrics were expressed as a percentage to facilitate interpretation of results.

4.7 Sand and gravel extraction

The location and volume of sand and gravel extraction throughout the UBR was available through the Water Entitlements Register Database (WERD) maintained by the then Queensland Department of Environment and Resource Management. However extraction volumes were not required to be reported after 2007 due to a change in relevant legislation. Therefore extraction volumes over the 2001-2007 period were used as an indication of extraction intensity in each reach. Extraction intensity was defined as a categorical variable with the following levels: 'none', 'low' ($< 1500 \text{ m}^3$ total extraction over the 2001-2007 period) and 'high' ($1,500 - \sim 35,000 \text{ m}^3$ total extraction over the 2001-2007 period). Low sand and gravel extraction intensity occurred in reaches 17-18, 23-25, 27-28, and 63-66; and high extraction intensity occurred in reaches 35-36, and 56-60. Care was taken to avoid the influence of sand and gravel extraction on DoD estimates by removing the bed material geomorphic units and inspection of aerial photography across the study area. Any DoD values suspected of being influenced by sand and gravel activities were removed.

4.8 Empirical relationships

The relationship between the controlling variables evaluated in this study and observed riverbank erosion was determined using a generalised least squares (GLS) regression model created in the R statistical environment (R Core Team, 2015). The specific streampower (calculated using macrochannel bankfull, maximum daily and mean daily discharge) and LWV variables were scaled ($(\text{observation} - \text{mean})/\text{standard deviation}$) before use in the GLS model. Initially all possible explanatory variables (curvature, each specific streampower estimate individually, LWV, extraction intensity, and geomorphic zone) and their interactions were included. Residuals indicated greater variance for the geomorphic zone variable; therefore a variance structure was defined as a function of geomorphic zone.

Spatial autocorrelation was evaluated by plotting residuals against distance downstream, and through a semivariogram defined as a function of pairwise stream distance among sites. The residual plot indicated no substantial autocorrelation of residuals except for reaches 33-42 which were consistently under-predicted by the model. However no pattern was detected in the semivariogram, indicating that spatial autocorrelation was adequately addressed through the explanatory variables.

Plots of residuals against explanatory variables indicated that normality and homogeneity could be safely assumed. The fixed component of the GLS model was selected using backward step-wise model selection based on Akaike's Information Criterion (AIC) (Sakamoto *et al.*, 1986). Multicollinearity between explanatory variables was evaluated using the variance inflation factor (VIF). The final model was cross-validated by iteratively removing each reach, refitting the model to the remaining data, and making a prediction at the missing reach. These cross-validated erosion predictions were compared to observed erosion and used to calculate the Pearson's squared-correlation coefficient of the model.

5 Results

5.1 Downstream changes in geomorphic units

The bench and vegetated island geomorphic units were a similar height above the thalweg and were combined to simplify the analysis (Figure 5). Similarly the terrace and colluvial slope geomorphic units were combined to simplify the analysis. The water geomorphic unit shows a consistent variation across the UBR, most likely reflecting pool and riffle sequences (Figure 5). Downstream of reach 37 occasionally these pools comprise a greater proportion of reach area, and in these reaches the area of bed material is generally reduced most likely due to being inundated. Terrace-colluvial slope geomorphic units are present in nearly every reach. There is a general inverse relationship, albeit with some variation, between proportions of bed material and vegetated island-bench/inset floodplain geomorphic units. This suggests that at the reach scale depositional units may be dominated by either bed material or alternatively vegetated island-benches/inset floodplains. There is no clear downstream pattern to the presence of vegetated island-benches and inset floodplains, with both geomorphic units equally represented in the majority of cases, with some oscillations. However notable exceptions occur for reaches 7-9, 39-43 and 62-63 where the proportion of vegetated island-benches dominate; and for reaches 3-4, 13, 56, 68-69 and 78 where the proportion of inset floodplains dominate.

Figure 5 Spatial variation in geomorphic unit area (note vegetated island-bench and terrace-colluvial slope geomorphic units have intentionally been aggregated to simplify the analysis)

5.2 Spatial variation of riverbank erosion

In total approximately 2,134,800 m³ of riverbank erosion occurred between 2001 and 2011 across the 75 reaches. The average reach erosion volume was approximately 28,400 m³, however there was substantial spatial variation above and below this average (Figure 6). Approximately 87% (~1,861,300 m³) of this total eroded from the thirty highest eroding reaches. The top ten eroding reaches produced around 58% of all erosion. Although these reaches are spread across the UBR, some sections stand out as having particularly severe erosion. The section from reach 54 to 65, excluding reach 61, accounted for 49% (~1,049,500 m³) of the total volume alone, including the highest erosion volume of ~175,900 m³ in reach 56. Between reaches 72 and 79 was also a highly eroding section of river, contributing 20% (~419,400 m³) of the total volume. Four of the top ten eroding reaches include known sand and gravel extraction sites, and three others (reaches 54, 55 and 62) are immediately upstream of sand and gravel extraction sites (Figure 6).

Figure 6 Riverbank erosion volume per reach, showing sand and gravel extraction intensity

Vegetated island-bench geomorphic units eroded consistently along the length of the river (Figure 7), possibly due to their proximity to the thalweg. For reaches 54 and 55, erosion occurred on both vegetated island-bench and inset floodplain geomorphic units, however inset floodplains were the dominant source. The highest erosion from inset floodplains occurred in reach 56, which delivered approximately 154,700 m³. The source of erosion for the highly eroding reaches 58, 62, and 65 was predominantly vegetated island-benches, with reach 58 reaching a peak of 173,300 m³. For the highly eroding reaches 72-79, vegetated island-benches and inset floodplain geomorphic units eroded relatively consistently, apart from a large peak in vegetated island-bench erosion in reach 73. Terrace-colluvial slopes were generally stable across the length of the river, except for a spike of erosion volume in reach 73 (Figure 7).

Figure 7 Riverbank erosion volume per geomorphic unit and reach, showing sand and gravel extraction intensity

5.3 Empirical relationship between controlling variables and riverbank erosion

The specific streampower estimate calculated using mean daily discharge explained more variation in observed riverbank erosion data than estimates using macrochannel bankfull or maximum daily discharge data. Therefore in the remainder of the article when cumulative

specific streampower is referenced it is referring to that calculated using mean daily discharge unless stated otherwise. The individual relationships between riverbank erosion volume per unit area (m^3m^{-2}), curvature, cumulative specific streampower (Jm^{-2}), LWV (%), and geomorphic zone are presented in Figure 8. Riverbank erosion (m^3m^{-2}) in the Upper geomorphic zone is substantially lower than in the Middle and Lower zones, both in variation and median value. While the variation of cumulative specific streampower (Jm^{-2}) is roughly comparable across the three zones, the median value in the Upper zone is approximately 250 Jm^{-2} higher than in the Middle and Lower geomorphic zones. LWV (%) was also noticeably higher in the Upper geomorphic zone (with median value of ~30%) compared to the generally similar median values of ~17% in the Middle and Lower geomorphic zones. Median values of erosion volume per unit area and cumulative specific streampower for curving and relatively straight reaches were similar; however curving reaches had slightly higher median values of LWV (%). High extraction intensity reaches had noticeably higher median riverbank erosion volumes per unit area, and substantially greater variation than other extraction intensity reaches.

Figure 8 Relationships between explanatory and dependent variables (note: dotted lines in the top row of plots indicate geomorphic zone divisions)

The results of the final GLS regression model are presented in Table 1 and equation 2. The explanatory variables selected based on AIC were cumulative specific streampower, LWV, extraction intensity and geomorphic zone; and interactions between cumulative specific streampower-LWV, cumulative specific streampower-extraction intensity, LWV-extraction

intensity, and LWV-geomorphic zone. VIF scores were less than 2 for all explanatory variables, indicating no significant collinearity. The cross-validated R^2 of the final model was approximately 0.37. This indicates that while several significant relationships were found, unexplained variation was still present.

Table 1 Generalised least squares regression results between observed riverbank erosion and controlling variables (note: parameter estimates for the cumulative specific streampower and LWV variables are in response to a one standard deviation increase from the overall mean of these explanatory variables)

	Estimate	Std. Error	<i>t</i> value	<i>Pr</i> (> <i>t</i>)
Intercept	0.079	0.019	4.119	<0.001
Cumulative specific streampower	-0.0004	0.018	-0.022	0.983
LWV	0.042	0.020	2.127	0.038
Low extraction intensity	-0.029	0.055	-0.53	0.598
High extraction intensity	0.290	0.135	2.145	0.036
Middle geomorphic zone	0.176	0.071	2.49	0.016
Lower geomorphic zone	0.162	0.073	2.216	0.031
Cumulative specific streampower × LWV	-0.034	0.019	-1.776	0.081
Cumulative specific streampower × Low extraction intensity	0.051	0.040	1.271	0.209
Cumulative specific streampower × High extraction intensity	0.242	0.135	1.797	0.077
LWV × Low extraction intensity	-0.030	0.049	-0.616	0.540
LWV × High extraction intensity	-0.641	0.328	-1.957	0.055
LWV × Middle geomorphic zone	-0.022	0.065	-0.342	0.734
LWV × Lower geomorphic zone	-0.171	0.080	-2.14	0.036

$$Erosion_{ij} = 0.79 - 0.004CSP_{ij} + 0.042LWV_{ij} - 0.029LEI + 0.29HEI + 0.176MGZ + 0.162LGZ - 0.034CSP_{ij} \times LWV_{ij} + 0.051CSP_{ij} \times LEI + 0.242CSP_{ij} \times HEI - 0.03LWV_{ij} \times LEI - 0.641LWV_{ij} \times HEI - 0.022LWV_{ij} \times MGZ - 0.171LWV_{ij} \times LGZ$$

$$\varepsilon_{ij} \sim N \left(\begin{matrix} 0, 0.08_{j=Upper} \\ 0, 0.308_{j=Middle} \\ 0, 0.199_{j=Lower} \end{matrix} \right) \quad (2)$$

Parameter estimates report the impact of a one standard deviation increase from the mean for the continuous explanatory variables CSP – cumulative specific streampower and LWV – large woody vegetation. The LEI – low extraction intensity, HEI – high extraction intensity, MGZ – middle geomorphic zone, and LGZ – lower geomorphic zone categorical variables act as ‘switches’ to model change in erosion which results when moving from the baseline levels of extraction intensity (no extraction) and geomorphic zone (Upper geomorphic zone). Interaction terms between the continuous and categorical variables (cumulative specific streampower and extraction intensity, LWV and extraction intensity, and LWV and geomorphic zone) report how a one standard deviation increase in cumulative specific streampower or LWV affects erosion in reaches with the relevant level of extraction intensity in the appropriate geomorphic zone. The ϵ_{ij} terms report the residual for the i th reach in the j th geomorphic zone.

The change in erosion in response to a standard deviation increase in cumulative specific streampower, LWV and the cumulative specific streampower-LWV interaction term for different extraction intensities in each geomorphic zone is summarised in Figure 9 and in the appendix. The interaction term between cumulative specific streampower and LWV was negatively related to erosion ($-0.034 \pm 0.019 \text{ m}^3\text{m}^{-2}$) and marginally significant ($p = 0.081$). However the magnitude of this parameter was small given that erosion ranged from 0 - $1.27 \text{ m}^3\text{m}^{-2}$. In high extraction intensity reaches, cumulative specific streampower was positively related to erosion ($0.242 \pm 0.135 \text{ m}^3\text{m}^{-2}$). Although this relationship was also only marginally significant ($p = 0.077$), the magnitude of this parameter was large given that erosion in high extraction intensity reaches ranged from $0.07 - 1.27 \text{ m}^3\text{m}^{-2}$. The mean and standard deviation of cumulative specific streampower was 854 and 535 Jm^{-2} respectively. In high extraction intensity reaches cumulative specific streampower ranged from 193 – 2241 Jm^{-2} meaning that the estimated relationship was not due to unreasonable extrapolation. These results indicate that a 535 J m^{-2} increase in cumulative specific streampower in high extraction reaches resulted in $0.242 \pm 0.135 \text{ m}^3\text{m}^{-2}$ more erosion ($p = 0.077$).

Figure 9 Relative change of erosion () in relation to a standard deviation increase (SD) in cumulative specific streampower and large woody vegetation across different levels of extraction intensity and geomorphic zone. Arrows denote the direction of effect and arrow length denote the magnitude of the effect. The relative magnitude of erosion for different levels of extraction intensity and geomorphic zone is indicated through the length of the intercept term () (note: CSP – cumulative specific streampower, LWV – large woody vegetation)

The influence of LWV varied across the geomorphic zones and extraction intensities. The LWV main effect term was positively related to erosion ($0.042 \pm 0.02 \text{ m}^3 \text{ m}^{-2}$; $p = 0.038$). LWV was a strong negative driver of erosion in high extraction intensity reaches ($-0.641 \pm 0.328 \text{ m}^3 \text{ m}^{-2}$; $p = 0.055$) and in the Lower geomorphic zone ($-0.171 \pm 0.08 \text{ m}^3 \text{ m}^{-2}$; $p = 0.036$). The mean and standard deviation of LWV % were 21.6 and 12 respectively. LWV % ranged from ~14 – 30.4% in high extraction intensity reaches and from 1.36 – 29.26% in the Lower geomorphic zone, meaning that the estimated relationship was not due to unreasonable

extrapolation beyond the data. These results indicate that a 12% increase in LWV in high extraction intensity reaches could reduce erosion by $0.641 \pm 0.328 \text{ m}^3 \text{ m}^{-2}$ ($p = 0.055$). In the Lower geomorphic zone, a 12% increase in LWV could reduce erosion by $0.171 \pm 0.08 \text{ m}^3 \text{ m}^{-2}$ ($p = 0.036$).

Erosion in high extraction intensity reaches was significantly higher than reaches with no extraction ($0.29 \pm 0.135 \text{ m}^3 \text{ m}^{-2}$; $p = 0.036$). The Middle ($0.176 \pm 0.071 \text{ m}^3 \text{ m}^{-2}$; $p = 0.016$) and Lower ($0.162 \pm 0.073 \text{ m}^3 \text{ m}^{-2}$; $p = 0.031$) geomorphic zones had significantly more erosion than the Upper zone.

6 Discussion

6.1 Physical significance of riverbank erosion over 2001-2011 period

The total riverbank erosion volume from the analysed geomorphic units was large (2,134,800 m^3), and the period was clearly geomorphically significant. It is important to note that the riverbank erosion volumes presented above are an underestimate of the total erosion in the UBR over the 2001-2011 period, as the bed material geomorphic units and areas affected by water were excluded. A LiDAR based study of riverbank erosion over 100 km^2 of the nearby Lockyer catchment over a similar period (2010-2011) indicated roughly similar erosion volumes ($\sim 2,269,000 \text{ m}^3$) (Croke *et al.*, 2013).

The focus of this study was sediment supplied from riverbank erosion and deposition was not examined. Therefore it was not possible to determine the significance of this erosion volume to sediment yield transported to Wivenhoe Dam, and further downstream to Moreton Bay. While other studies indicated that the 2011 flood event deposited large volumes of sediment in Moreton Bay (Coates-Marnane *et al.*, 2016), it was not possible to attribute a proportion of that deposition to erosion from the study area.

6.2 Relationship between controlling variables examined and riverbank erosion

6.2.1 Curvature

No significant relationship was found between curvature of the macrochannel and riverbank erosion in the UBR. Two factors may have influenced this lack of relationship. The first is the partial-confinement of the UBR system. In a partially confined system the increased velocities associated with bend curvature (Seminara, 2006) are unlikely to be high enough to overcome the strength of confining materials and be associated with increased erosion. The small volume of erosion of the terrace and colluvial slope geomorphic units suggests they are the geologic constraint controlling river planform (Figure 7). The second potential factor is the highly variable hydrology of the UBR. The hydrological variability and complex array of inset geomorphic units made defining a representative bend curvature at a reach scale, similar to Nanson and Hickin (1986), difficult. Additionally many studies of bend curvature assume constant discharge (Camporeale *et al.*, 2007), which is not geomorphically relevant to the UBR. The lack of a significant relationship between erosion and curvature and the erosion of inset geomorphic units (Figure 7) support the findings of other researchers, namely that the UBR planform is largely stable and that the majority of geomorphic response to flood events involves reworking of inset geomorphic units (Brizga and Finlayson, 1996; Shellberg and Brooks, 2007). The macrochannel of the adjacent Lockyer and Mid Brisbane catchments have similarly been found to be relatively stable (Fryirs *et al.*, 2015; Kemp *et al.*, 2015).

6.2.2 Cumulative specific streampower

Sediment budgets commonly model sediment supply from riverbank erosion as a mean annual rate, derived by integrating over several decades (Wilkinson *et al.*, 2009). While this is necessary to enable land use scenarios to be compared, it also makes capturing the dynamics of riverbank erosion challenging (Bartley *et al.*, 2008). Bankfull discharge is often used in the calculation of specific streampower to estimate peak force exerted on riverbanks (Larsen *et al.*, 2006). In the above analyses, specific streampower calculated using macrochannel bankfull discharge explained less of the variation in observed riverbank erosion than specific stream calculated using other discharge estimates. Bankfull discharge has been found to be a good indicator of effective geomorphic discharge in alluvial rivers (Carling, 1988). However in hydrologically variable, partially-confined rivers with macrochannels similar to the UBR, a more complex relationship has been documented (Heritage *et al.*, 2001). As large floods have more potential to erode and transport sediment (Wolman and Miller, 1960; Charlton, 2007), cumulative specific streampower calculated using maximum daily discharge might be expected to be strongly correlated to observed riverbank erosion. This was not found in the current study however. If specific streampower is taken to represent 'a surrogate for the sum of flow forces acting on a specific reach of stream bank over a designated time period' as suggested by Larsen *et al.* (2006), it's likely that mean daily flow better represents the conditions experienced in a reach than maximum daily flow, which may only be reached for a short time. Heritage *et al.* (2001) found that geomorphic change was most correlated to the entire flow regime. In the current study the best estimate of the entire flow regime in the UBR appears to be cumulative specific streampower calculated using mean daily flow.

No significant relationship was found between the cumulative specific streampower main effect term calculated using mean daily discharge, and riverbank erosion. The most accurate approximation of specific streampower was calculated with the datasets available. This involved varying energy grade slope with discharge, similar to Phillips and Slattery (2007), to better approximate conditions of geomorphically significant events in the UBR. There is no obvious physical reason why discharge, energy grade slope and flow width would not be related to riverbank erosion. One possible explanation may be that the riverbank erosion processes occurring in the UBR were not directly related to the parameters in equation 1. For example wet flow riverbank erosion has been found to be common in other catchments in SEQ (Grove *et al.*, 2013; Thompson *et al.*, 2013; McMahon *et al.*, 2014). However the riverbank erosion form in the UBR was evaluated using the criteria outlined in Grove *et al.* (2013) and McMahon *et al.* (2014), and only approximately three instances were identified. The lack of a significant relationship may instead be related to the partial-confinement of the river. In this setting a confined reach with smaller flood width and consequently higher specific streampower may not be directly related to heightened riverbank erosion, as the confinement is most likely caused by indurated sediment or bedrock and little material may be available to be eroded. This does not necessarily discount the importance of specific streampower as a factor in riverbank erosion in the UBR, but rather other controlling variables such as erodibility of the channel margin may dominate contemporary river behaviour.

6.2.3 Riparian vegetation

The influence of riparian vegetation on riverbank erosion is affected by a complex interaction between discharge, vegetation and substrate characteristics. The vegetation examined in this study is restricted to large (>5m) single stemmed trees (LWV). Rigid stemmed vegetation such as this will exert varying influence on flow resistance and velocity distributions

depending on whether it is submerged or emergent (Bennett *et al.*, 2008; Nepf, 2012), and the ratio of canopy height to water depth (Nepf and Vivoni, 2000). The root systems of such vegetation interact with hydrologic and mechanical properties of the substrate to impart varying degrees of resistance to riverbank erosion (Simon and Collison, 2002; Docker and Hubble, 2008; Pollen-Bankhead and Simon, 2010). Vegetation will exert varying degrees of influence depending on riverbank erosion process, the location of root structures relative to riverbank failure planes, and the ratio of rooting depth to bank height (Abernethy and Rutherford, 1998; Abernethy and Rutherford, 2000). While roots from large trees have been found to reinforce a greater proportion of riverbanks compared to smaller vegetation (Wynn *et al.*, 2004), rooting depth relative to bank height was not quantified in the current study. The influence of riparian vegetation on riverbank erosion will also vary throughout a hydrograph (Pollen-Bankhead and Simon, 2010). These processes operate at a finer temporal and spatial resolution than those examined here.

Not surprisingly then the relationship between LWV and riverbank erosion observed across the study area was complex. As a main effect term LWV was positively related to erosion, however the magnitude of this erosion was small ($0.042 \pm 0.02 \text{ m}^3\text{m}^{-2}$; $p = 0.038$). If isolated trees were located at the top of riverbanks vulnerable to erosion, the additional weight of the tree may have contributed to erosion (Abernethy and Rutherford, 2000). Isolated stands of trees may also deflect flow and lead to localised scour (Gurnell *et al.*, 2012). The positive relationship between LWV and erosion occurred for the LWV main effect term in isolation. This suggests that the erosion occurred in isolation from factors involved in the specific streampower calculation such as discharge, energy grade slope and flow width. This gives weight to the explanation that the relationship is caused by finer scale factors not captured by these variables such as scour, however it was not possible to determine this conclusively in the current study. The cumulative specific streampower-LWV interaction term, while marginally significant ($p = 0.081$) and also small in magnitude ($-0.034 \pm 0.019 \text{ m}^3\text{m}^{-2}$), indicates that the relationship between increasing riverbank erosion and increasing cumulative specific streampower is negative with increasing LWV. In this instance, LWV appears to be reducing the energy available for geomorphic work and therefore riverbank erosion. In highly eroding areas, the influence of LWV was considerably larger in magnitude. For example in high extraction intensity reaches a one standard deviation increase in LWV reduced erosion by $0.641 \pm 0.328 \text{ m}^3\text{m}^{-2}$ ($p = 0.055$); and in the Lower geomorphic zone by $0.171 \pm 0.08 \text{ m}^3\text{m}^{-2}$ ($p = 0.036$). Despite not having data on substrate type, vegetation position in relation to riverbank erosion processes and small scale velocity distributions, the role of LWV in these reaches is either significant or marginally significant and physically meaningful in magnitude. These results suggest that in reaches which suffered large magnitude riverbank erosion, even a modest increase in LWV (12%) would significantly reduce a riverbanks susceptibility to erosion.

6.2.4 Sand and gravel extraction

Sand and gravel extraction has been linked to altered river behaviour where extraction rates exceed natural sand and gravel transport rates (Erskine, 1990; Kondolf, 1997; Rinaldi *et al.*, 2005). Geomorphic change will occur when energy is available which is excess to that required to convey water through a fluvial system (Kondolf, 1997). Excess energy is dissipated through mechanisms such as bend meandering, flow resistance by vegetation and sediment transport amongst others. Transport rates of sand and gravel sized sediment are particularly influential on fluvial form (Kondolf, 1997). Sand and gravel extraction disrupts the balance between sediment supply and transport capacity (Erskine, 1990; Kondolf, 1997). This can create a nickpoint which incises bed elevation progressively upstream, and leads to

1 downstream bed incision due to additional energy being available for geomorphic work
2 (Erskine, 1990; Kondolf, 1997; Rinaldi *et al.*, 2005). This bed incision can lead to riverbank
3 instability due to undercutting (Erskine, 1990; Kondolf, 1997; Rinaldi *et al.*, 2005). A river
4 may adjust to excess transport capacity through increased meandering or sourcing sediment
5 from riverbanks (Rinaldi *et al.*, 2005). If a river has less ability to adjust its bed elevation,
6 channel width or meandering behaviour, it may reduce transport capacity in other ways.

8 High intensity sand and gravel extraction reaches had significantly more riverbank erosion
9 ($0.29 \pm 0.135 \text{ m}^3 \text{ m}^{-2}$; $p = 0.036$) than reaches with no extraction. The magnitude of this effect
10 was large given that erosion ranged from $0 - 1.27 \text{ m}^3 \text{ m}^{-2}$. Cumulative specific streampower in
11 high intensity sand and gravel extraction reaches was positively related to riverbank erosion,
12 marginally significant and of large magnitude ($0.242 \pm 0.135 \text{ m}^3 \text{ m}^{-2}$, $p = 0.077$). This analysis
13 of a continuous longitudinal river profile over a large spatial scale supports the suggestion by
14 Kondolf (1997) that sand and gravel extraction leads to sediment-starved water prone to
15 erosion. With the current study design up and downstream incision, and the influence of those
16 processes on riverbank instability, could not be captured explicitly. As reach lengths averaged
17 around 1km, some of this response may have been captured within reach divisions. However
18 lateral riverbank instability within reach divisions could be captured explicitly.

20 Local characteristics of the UBR are important determinants of its response to sand and
21 gravel extraction. The bed of the UBR is comprised of a gravel and cobble layer overlying
22 sand, which becomes noticeably sandier downstream of the confluence with Maronghi Creek
23 (Figure 1) (Brizga and Finlayson, 1996; Brennan and Gardiner, 2004). The UBR also
24 displays characteristics of a sediment supply-limited system (Shellberg and Brooks, 2007).
25 One explanation of the different river behaviour in high intensity sand and gravel extraction
26 reaches may be that the riverbank substrate was more erodible in those reaches. Sand and
27 gravel extraction will be targeted to reaches with the largest resource available for extraction.
28 If sand and gravel extraction reaches were in general more erodible, it may explain the
29 increased erosion and increasing erosion with increasing cumulative specific streampower.
30 While the influence of tributaries on discharge has been accounted for through the specific
31 streampower calculation, the influence of sediment input from tributaries was not. The
32 increased amount of sand in the riverbed downstream of Maronghi Creek may indicate a
33 substantial sediment input from that tributary. If availability of sand and gravel material, and
34 the implications of that on erodibility, were the primary explanatory factor one would
35 intuitively expect similar relationships in low intensity sand and gravel extraction reaches to
36 be significant. However the explanatory variables examined here had no significant
37 relationships with riverbank erosion in low intensity sand and gravel extraction reaches.

39 Without stratigraphic and sedimentological data, it is not possible to apportion conclusively
40 the relationships in high intensity sand and gravel extraction reaches to either natural fluvial
41 processes or response to extraction. As sand and gravel extraction volumes were not reported
42 over the entire 2001-2011 period, it was not possible to compare sand and gravel extraction
43 rates to bedload sediment transport rates directly. Given the full body of evidence available
44 however, it appears likely that sand and gravel extraction rates in high intensity reaches have
45 exceeded natural sand and gravel transport rates to an extent that there is a detectable
46 difference in river behaviour. As the UBR is constrained in how it can respond by an
47 armoured bed and partial confinement, which limits its ability to dissipate excess energy
48 through incision or increased meandering, the river can only source additional sediment to
49 satisfy the increased transport capacity of discharge from inset features. When combined with
50 the UBR's natural tendency toward large magnitude geomorphic change due to extreme flood

events and partial confinement, this may explain the large magnitude erosion of inset features presented in Figure 7. There are low levels of LWV across the UBR, in general and in high intensity sand and gravel extraction reaches (Figure 8). However the influence of LWV on dissipating excess energy and reducing riverbank erosion in high intensity extraction reaches appears to be substantial. Therefore the relationships in high intensity sand and gravel extraction reaches are likely to be the result of a complex interaction between river behaviour in an armoured bed and partially-confined setting; extraction rates exceeding natural sand and gravel transport rates; and altered river behaviour in response to that sand and gravel extraction.

6.3 Implications for riverbank erosion modelling in sediment budgets

While measured loads and concentrations support the assumption that sediment yield is limited by supply from erosion sources (McKergow *et al.*, 2005; Wilkinson *et al.*, 2009), supply of sediment from riverbank erosion over large spatial scales is heterogeneous and nonlinear. Recent work has shown that channel erosion (which includes gully and riverbank sediment sources) is the dominant erosion process contributing to sediment yield in waterways in the South-East Queensland region (Olley *et al.*, 2013). Catchments in the region where riparian vegetation has been cleared have also been shown to generate 50 to 200 times more sediment than catchments with fully vegetated channels (Olley *et al.*, 2015). In the UBR, which had a mean LWV cover of around 22%, the role of vegetation relative to sediment supply from riverbank erosion varied with spatial location, susceptibility of a reach to erosion, and human disturbance such as sand and gravel extraction. Riparian vegetation appears to have played a significant and physically meaningful role in reducing riverbank erosion in highly eroding reaches, however in other reaches was associated with small magnitude riverbank erosion. This is most likely due to a complex interaction between small scale velocity distributions around isolated trees and geotechnical properties of riverbanks. These findings highlight the difficulty of upscaling site based riverbank erosion studies, which often focus on highly eroding reaches, to larger spatial scales (De Rose *et al.*, 2005). These nonlinearities would contribute to the uncertainty surrounding riverbank erosion in sediment budget models.

The controlling variables used to model riverbank erosion attempt to capture spatial variation in the driving and resisting forces exerted on riverbanks. This balance of forces approach has proven effective in smaller scale studies where it is more feasible to adequately quantify the driving forces related to discharge, and the resisting forces related to soil strength and riparian vegetation (Simon and Collison, 2002). At large spatial scales adequately quantifying the soil strength component of resisting force is a significant challenge. This component plays a major role in the spatial variation in riverbank erosion behaviour (Hoyle *et al.*, 2008; Konsoer *et al.*, 2016). Catchment scale studies of riverbank erosion commonly use flat depositional areas as a means of identifying erodible soil (Gallant and Dowling, 2003; Wilkinson *et al.*, 2009). The definition of geomorphic units in the current study followed a similar approach. However the small magnitude of erosion in reaches 33-42 (Figure 8), which had a similar proportion of geomorphic units to other reaches (Figure 5), highlights the limitations of this approach. It is possible that the fluvial form in these reaches was created by different processes which altered their resistance to erosion (Chorley, 1962). Given the dynamics and complexity of processes operating in the riparian corridor (Ward *et al.*, 2001), collection of field calibration data would be particularly valuable for riverbank erosion models of a particular catchment. While balance of forces conceptual models are a useful reference point to understand complex fluvial behaviour (Grant *et al.*, 2013), when they are parameterised using remotely sensed data in isolation they are unable to capture variations in soil strength which may be driven by a catchment's evolutionary history over geologic time.

Some approximation of soil strength can be made either remotely or with limited field work however. For example the geomorphic zone variable derived by using flood extent as an approximation of valley confinement in this study improved the fit of the model. This can inform how geomorphic processes vary spatially and result in changing river behaviour (Church, 1992; Montgomery, 1999). Additionally determining the River Style of a river to be modelled (Brierley and Fryirs, 2005), such as the partial confinement of the UBR, may inform which components of a balance of forces approach may have greater importance to a particular river. For example the cumulative specific streampower variable was not significant in isolation in the UBR. While these approaches are not adequate to capture the full complexity of within reach variation (Hoyle *et al.*, 2008), they may improve the performance of riverbank erosion modelling at large spatial scales without requiring extensive field data collection.

Finally human disturbance, in the form of sand and gravel extraction, was an important variable improving model performance in the current study. Significantly different relationships were discernible in high extraction intensity reaches between cumulative specific streampower, LWV and riverbank erosion (Table 1). These relationships are likely the result of complex feedbacks and interactions between fluvial form, discharge and vegetation (Corenblit *et al.*, 2007); changed river behaviour in response to land use change since European settlement (Brooks and Brierley, 2004); and management responses to those dynamics (Chin *et al.*, 2014). Despite not having data on substrate type and limitations due to the timing of the LiDAR captures, the model described approximately 37% of the variation in observed riverbank erosion by including variables which reflect the balance of forces exerted on riverbanks and management practices in the form of sand and gravel extraction. In many sediment budget models, sediment supplied from hillslope erosion is estimated using the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1997) which explicitly incorporates management practices. From the analysis presented here it appears that inclusion of a similar management practice factor in riverbank erosion models is justified, where appropriate, and may improve model performance.

7 Conclusions

The high resolution dataset used to evaluate the relationship between controlling variables of riverbank erosion and observed riverbank erosion revealed complex interactions. Characteristics of the Upper Brisbane River study area, such as its partial-confinement, bed armouring and limited sediment supply, established the boundary conditions within which the controlling variables interacted. This resulted in the meandering and specific streampower main effect terms not having significant relationships, however relationships were apparent for interaction terms between specific streampower and large riparian vegetation, and specific streampower and high intensity sand and gravel extraction reaches. The role of large riparian vegetation in relation to riverbank erosion varied in complex ways across the study area, indicating feedbacks between physical and management factors, be it vegetation management or sand and gravel extraction. Despite not having data on substrate type across the study area the model described approximately 37% of the variation in observed erosion. This indicates that even in the absence of detailed field data, including variables which can approximate spatial variation in geomorphic processes and some index of human disturbance where appropriate, can improve the performance of large spatial scale riverbank erosion models.

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10 Appendix

10.1 Overall equation

$$\begin{aligned} Erosion_{ij} = & 0.79 - 0.004CSP_{ij} + 0.042LWV_{ij} - 0.029LEI + 0.29HEI + 0.176MGZ \\ & + 0.162LGZ - 0.034CSP_{ij} \times LWV_{ij} + 0.051CSP_{ij} \times LEI + 0.242CSP_{ij} \\ & \times HEI - 0.03LWV_{ij} \times LEI - 0.641LWV_{ij} \times HEI - 0.022LWV_{ij} \times MGZ \\ & - 0.171LWV_{ij} \times LGZ \end{aligned}$$

$$\varepsilon_{ij} \sim N \begin{pmatrix} 0, 0.08_{j=Upper} \\ 0, 0.308_{j=Middle} \\ 0, 0.199_{j=Lower} \end{pmatrix}$$

Where ε_{ij} is the residual of the i th reach in the j th geomorphic zone, parameter estimates correspond to a standard deviation increase in explanatory variables, CSP – cumulative specific streampower, LWV – large woody vegetation, LEI – low extraction intensity, HEI – high extraction intensity, MGZ – middle geomorphic zone, and LGZ – lower geomorphic zone.

10.2 Upper geomorphic zone (31 reaches)

10.2.1 No extraction (24 reaches)

$$Erosion_{ij} = 0.079 + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

10.2.2 Low extraction intensity (7 reaches)

$$Erosion_{ij} = 0.079 + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

10.3 Middle geomorphic zone (32 reaches)

10.3.1 No extraction (21 reaches)

$$Erosion_{ij} = (0.079 + 0.176) + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

$$Erosion_{ij} = 0.255 + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

10.3.2 Low extraction intensity (4 reaches)

$$Erosion_{ij} = (0.079 + 0.176) + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

$$Erosion_{ij} = 0.255 + 0.042LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

10.3.3 High extraction intensity (7 reaches)

$$Erosion_{ij} = (0.079 + 0.29 + 0.176) + 0.242CSP_{ij} + (0.042 - 0.641)LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

$$Erosion_{ij} = 0.545 + 0.242CSP_{ij} - 0.599LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

10.4 Lower geomorphic zone (12 reaches)

10.4.1 No extraction (12 reaches)

$$Erosion_{ij} = (0.079 + 0.162) + (0.042 - 0.171)LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$

$$Erosion_{ij} = 0.241 - 0.129LWV_{ij} - 0.034CSP_{ij} \times LWV_{ij}$$