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Vegetation and longitudinal coarse sediment connectivity affect the ability of ecosystem restoration to reduce riverbank erosion and turbidity in drinking water

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Abstract

It is a substantial challenge to quantify the benefits which ecosystems provide to water supply at scales large enough to support policy making. This study tested the hypothesis that vegetation could reduce riverbank erosion, and therefore contribute to reducing turbidity and the cost of water supply, during a large magnitude flood along a 62 km riparian corridor where land cover differed substantially from natural conditions. Several lines of evidence were used to establish the benefits that vegetation provided to reducing eleven riverbank erosion processes over 1688 observations. The data and analyses confirmed that vegetation significantly reduced the magnitude of the riverbank erosion process which was the largest contributor to total erosion volume. For this process, a one percent increase in canopy cover of trees higher than five metres reduced erosion magnitude by between two and three percent. Results also indicate that riverbank erosion was likely to be affected by direct changes to the riparian corridor which influenced longitudinal coarse sediment connectivity. When comparing the impact of these direct changes on a relative basis, sand and gravel extraction was likely to be the dominant contributor to changed erosion rates. The locations where erosion rates had substantially increased were of limited spatial extent and substantial change in river form had not generally occurred. This suggests that the trajectory of river condition and increasing turbidity are potentially reversible if the drivers of river degradation are addressed through an ecosystem restoration policy.

1 Introduction

Domestic water use is expected to increase significantly over the coming decades, with the majority of demand anticipated to be in cities (UN, 2018). At the same time, deteriorating ecosystem condition in many locations has increased the risk and vulnerability of water

supply (Renaud et al., 2013). Consequently urban communities are struggling to build safe, reliable and economically viable water supply infrastructure (Browder et al., 2019).

It is a substantial challenge to quantify the benefits which ecosystems provide to water supply at scales large enough to support policy making (Villamagna et al., 2013; Vogl et al., 2017).

Site specific evidence of these benefits is necessary to instil confidence amongst decision makers that ecosystem restoration could achieve water supply objectives (UN, 2018; Vogl et al., 2017). However effective restoration also depends on identifying the drivers of ecosystem deterioration and designing measures which are appropriate for local conditions (UN, 2018).

Ecosystem restoration for *water quality* objectives has the potential to improve water availability, reduce risk and vulnerability, and contribute to many of the sustainable development goals (Browder et al., 2019; UN, 2018).

Analysis of the water supply catchments of approximately 300 large cities (population > 750 000) over the 1900-2005 period indicate that conversion of natural land cover to cropland and rangeland increases sediment loads and water treatment costs (McDonald et al., 2016). Even where little natural land cover remains, it continues to deliver water quality benefits. For example in South East Queensland (SEQ) Australia only one third of the natural land cover remains. However suspended sediment concentrations were significantly lower in channels which drain through natural land cover in flow events which ranged up to 1 in 50 annual exceedance probability (AEP) in magnitude (Olley et al., 2015).

Channel erosion is the dominant contributor to sediment loads in SEQ (Olley et al., 2013; Wallbrink, 2004), and in many other locations (Bull, 1997; Miller et al., 2014; Palmer et al., 2014). Historically it has been difficult to quantify the influence of riparian vegetation on erosion of *riverbanks* at scales large enough to support policy making (Brooks and Brierley,

2000; Hoyle et al., 2012). Advances in technology have now allowed both riverbank erosion volume and riparian vegetation canopy cover to be quantified across large spatial scales (Roering et al., 2013; Tomsett and Leyland, 2019). While canopy cover is only one aspect of vegetation, empirical studies indicate a relationship between such above ground biomass and below ground root biomass (Jenkins et al., 2004).

The effect of above and below ground vegetation biomass on riverbank erosion varies depending on sediment calibre and flow related factors. These variables interact to result in a wide variety of riverbank erosion processes. Such processes include stripping of alluvium in high flow energy conditions (Nanson, 1986; Warner, 1997); scour of the riverbank toe leading to geotechnical failure of cohesive (silt and clay sized) sediment (Simon et al., 2000; Thorne and Tovey, 1981); or saturation of the riverbank leading to sediment liquefaction (Grove et al., 2013; Hungr et al., 2001; Thorne, 1993). Vegetation may reduce riverbank erosion by reducing flow energy and hydraulic scour, and increasing sediment cohesion (Daly et al., 2015; Docker and Hubble, 2008; Järvelä, 2002; Lopez and Garcia, 1998; Pollen-Bankhead and Simon, 2010). Conversely in some instances, vegetation may increase riverbank erosion by obstructing flow and creating localised increases in velocity, or creating preferential subsurface flow paths along root networks (Bennett et al., 2002; Fox and Wilson, 2010; Pollen-Bankhead and Simon, 2010; Rominger et al., 2010; Simon and Collison, 2002). It is unclear how beneficial vegetation is to reducing riverbank erosion along riparian corridors where land cover differs substantially to natural conditions, particularly during large floods (~1% AEP) when flow related forces are high. We are not aware of any studies which have quantified the relationship between canopy cover and riverbank erosion processes along contiguous sections of river at a catchment scale.

Sediment transport is an important aspect of riparian ecosystems, with sand and gravel sized particles influencing channel form and silt and clay sized particles transporting sorped nutrients downstream (Kellner and Hubbart, 2017; Mayer et al., 1998; Smith et al., 2001). The magnitude and efficiency of sediment transport from erosion source through a channel network is referred to as sediment connectivity (Brierley et al., 2006; Brunsden and Thornes, 1979; Mishra et al., 2019). It is a function of both morphological aspects of a catchment and processes driven by the flux of water and sediment (Heckmann et al., 2018; Hooke, 2003; Wohl et al., 2019). Once sediment is in a channel network, it can be stored in more transient features such as bars and benches (sediment stores) or in more permanent features such as floodplains and terraces (sediment sinks) (Fryirs, 2013; Fryirs et al., 2007). The geomorphic change observed in a particular reach may have been influenced by changes elsewhere in the channel network (Brierley and Fryirs, 2005; Lisenby and Fryirs, 2017; Wohl et al., 2019). Examining sediment connectivity is a way to gain a better understanding of the sometimes nonlinear geomorphic response to disturbance and the ability of a river to recover from such disturbances (Brierley and Fryirs, 2005; Wohl et al., 2019).

The influence of direct changes to riparian corridors which interrupt the longitudinal (reach to reach) connectivity of coarse sediment (sand and gravel sized particles) on geomorphic response has been well documented. These direct changes include the construction of dams, and sand and gravel extraction. Dams can affect erosion rates by trapping coarse sediment and altering flood hydrographs (Brandt, 2000; Habersack et al., 2016; Olive and Olley, 1997; Petts and Gurnell, 2005; Young et al., 2001). Riverine sand and gravel extraction can affect erosion rates by altering the balance between sediment supply and the energy a river has to transport it. These direct changes may influence riverbank erosion both up and downstream

over varying time scales, so contemporary conditions may be a result of historical as well contemporary disturbances.

Attributing change in riverbank erosion rate to particular drivers is challenging, particularly when multiple disturbances such as clearing of natural land cover or direct changes are present (Phillips, 2001; 2003). Some of this complexity can be disentangled by comparing the spatial and temporal coincidence of change in reach-scale erosion rate with catchment scale land use changes which influenced longitudinal coarse sediment connectivity (Brierley and Fryirs, 2005; Kondolf, 1994; Kondolf and Swanson, 1993; Wohl et al., 2019). Understanding the trajectory of river change can help identify rehabilitation options that can work with contemporary processes to enhance river recovery (Brierley et al., 2002). This is essential as river recovery is rarely the reverse of the degradation trajectory, due to thresholds of behaviour being exceeded and hysteresis (Brooks and Brierley, 2004; Brooks et al., 2006; Fryirs et al., 2018).

The aim of this study was to test the hypothesis that vegetation could reduce riverbank erosion, and therefore contribute to reducing turbidity, during a large magnitude flood along a 62 km riparian corridor where land cover differed substantially from natural conditions. The study area lies between SEQ's largest water supply dam and its largest water treatment plants (WTPs; Figure 1), and contains several sand and gravel extraction sites. The combined output of the Mt Crosby WTPs supply up to 40% of the total drinking water for SEQ (Seqwater, 2013). In a smaller magnitude flood which occurred subsequent to the large magnitude flood, turbidity reached the highest ever recorded at these WTPs. We use multiple lines of evidence to answer several questions which arise from the above hypothesis. First, how did the magnitude of riverbank erosion and deposition vary spatially during the flood, and which

processes contributed the most to these total volumes. Riverbank deposition was analysed to gain insight into the trajectory of river condition which contributed to the high turbidity experienced in the smaller magnitude flood. Second, what was the influence of riparian vegetation on riverbank erosion processes during the large magnitude flood. Third, did direct changes to the riparian corridor which influenced longitudinal coarse sediment connectivity contribute to riverbank erosion during the large magnitude flood. Finally, what does change in erosion rates in relation to historical land use changes indicate about the drivers of the observed trajectory of turbidity and the measures in addition to vegetation which would be necessary to assist river recovery.

Figure 1 Mid Brisbane River (MBR) study area

2 Study Area

2.1 Characteristics of the Mid Brisbane River (MBR)

The Brisbane River starts near Mt Stanley and travels for 309 km before discharging into Moreton Bay. It has a total catchment area of 13,560 km² (Stock, 1990). For the Mid

Brisbane River (MBR), catchment area at the top of the study area begins at 7,020 km², increases by 2,967 km² after being joined by the major Lockyer Creek tributary, and ends at 10,529 km². The MBR has a mean annual discharge of approximately 884 m³s⁻¹ (143001C gauge Figure 1). However the hydrology of the Brisbane River is better defined by extremes of below and above average discharge, driven largely by patterns of ocean-atmosphere variability such as the El Niño Southern Oscillation and Interdecadal Pacific Oscillation (Figure 2)(Cook et al., 2016; Rustomji et al., 2009). Large floods occurred in 1841, 1893 (two major events), 1974 and 2011 (Kemp et al., 2015; Syme et al., 2017). The MBR has a Strahler stream order of 8 and is incised into the surrounding geology forming a partly-confined, mildly sinuous macrochannel. It is a mixed load system and contains bank attached bar, bench and inset floodplain geomorphic units inset within the macrochannel. High terraces are also a common feature across the study area (Abernethy, 2011a; Brizga, 2000b). The planform of the macrochannel has changed very little since the earliest records in the area (Brizga, 2000b; Kemp et al., 2015).

Figure 2 Mean hourly discharge at 143001C over the gauge record

2.2 Riparian vegetation

The accounts of first European explorers (~1823) and historical photographs from the late 19th century indicate prominent sand and gravel deposits and dense, well-established riparian vegetation covering channel benches and inset floodplains. Common riparian vegetation species included Weeping Bottlebrush (*Melaleuca viminalis*), River Oak (*Casuarina cunninghamiana*), River Myrtle (*Waterhousia floribunda*), Black Bean (*Castanospermum australe*), Blue Gum (*Eucalyptus tereticornis*), and Red Cedar (*Toona australis*) (Young, 1990). The catchment vegetation was characterised by mixed communities of forest and grassland (Kemp et al., 2019). As European settlement expanded in the 1850s, largescale vegetation clearing occurred for timber, agriculture and livestock pasture (Brizga, 2000b; Kemp et al., 2015). Despite vegetation clearing occurring across both the catchment and channel network, the majority of erosion occurred in the channel network (Kemp et al., 2019). Historical photos show that riparian vegetation had been extensively cleared by the early 1900s (Brizga, 2000b; Kemp et al., 2015). The riparian vegetation present today comprises a thin cover of some exotic species and sparse mature native species which remained from the extensive clearing (Brizga, 2000b; Kemp et al., 2015). Blue Gum and Red Cedar are common on the mid and upper banks while Black Bean, River Myrtle, Weeping Bottlebrush and River Oak are common on the lower banks, with Weeping Bottlebrush and River Oak showing signs of limited recruitment (McCosker, 2000).

2.3 Direct changes to the MBR influencing longitudinal coarse sediment connectivity

Beginning in the early 1900s the Brisbane River was the major source of high quality sand and gravel for construction in the region (DPI, 1995; O'Flynn and Thornton, 1990). Material suitable for extraction occurs in discrete pockets and these have been the focus of large-scale extraction activities. Also beginning in the early 1900s several major water supply and flood mitigation storages were constructed. The first was Lake Manchester Dam in 1916 (26,200

ML; Figure 1); followed by Somerset Dam on a major tributary to the Brisbane River in 1959 (380,000 ML); and finally Wivenhoe Dam in 1984 (1,650,000 ML; Figure 1). Flow regulation of the MBR resulted in little change to average annual flow volumes, but substantial changes to baseflow rates and flood peaks, durations and recession rates (Brizga, 2000a). Wivenhoe Dam has a catchment area of 7,020 km² and traps nearly all of the sediment delivered to it from its upstream catchment (Brizga, 2000b; Caitcheon et al., 2001; Prosser et al., 2003). Using the relationships presented in Brune (1953), Brizga (2000b) estimated the trap efficiency of Wivenhoe Dam to be 98%. Similarly, Lake Manchester Dam was estimated to have a trap efficiency of approximately 97% (Brizga, 2000b). Several weirs along Lockyer Creek, a major tributary of the MBR which enters downstream of Wivenhoe Dam, also trap a substantial amount of coarse sediment (Brizga, 2000b). Consequently the MBR only receives coarse sediment from its own channel and smaller tributaries entering below the dam (Brizga, 2000b). Despite changes to the longitudinal connectivity of coarse sediment caused by the above direct changes, analysis of bed levels in the catchment indicated no significant incision over the last approximately 100 years, except for 5-6km downstream of Wivenhoe Dam (Johnson, 2005; Kemp et al., 2015). The stability of the bed is suggested to be due to bedrock, coarse bedload and armouring (DSITIA, 2014; Kemp et al., 2015).

2.4 The 2011 and 2013 floods

From late 2010 to early 2011 the region experienced a particularly severe La Niña event, which led to above average rainfall in the Brisbane River catchment (BoM, 2011; Qld Government, 2011). On the 12th of January 2011, heavy rainfall in the upper Lockyer Creek catchment, in the Mid Brisbane catchment, and releases from Wivenhoe Dam, resulted in a peak discharge at 143001C of greater than 10,000 m³s⁻¹ (Figure 1 and Figure 2)(Qld Government, 2011). Turbidity at the Mt Crosby WTPs (Figure 1) reached approximately

1,500 NTU during the flood (Seqwater, 2013). Following the flood AEP estimates for 143001C were revised by Syme et al. (2017).

Two smaller floods occurred in early 2013 (Figure 2). The first flood reached a peak mean hourly discharge of approximately $2,400 \text{ m}^3\text{s}^{-1}$ at 143001C on the 29th of January. During this event turbidity at the Mt Crosby WTPs reached approximately 4,000 NTU which was the highest ever recorded (Seqwater, 2013), and substantially higher than the water quality objective of 15 NTU for drinking water in the catchment (DERM, 2010). A strong correlation ($R^2 \sim 0.94$) between turbidity and total suspended solids has been reported in the catchment (Olley et al., 2017). The second flood reached a peak mean hourly discharge of approximately $1,900 \text{ m}^3\text{s}^{-1}$ at 143001C on the 3rd of March. During this second event turbidity at the Mt Crosby WTPs reached approximately 500 NTU (Seqwater, 2013).

3 Materials and Methods

3.1 Estimating riverbank erosion and deposition caused by the 2011 flood

Riverbank erosion and deposition volumes were estimated using LiDAR data of the study area captured in 2009, and in June 2011 after the flood. The LiDAR captures were used to create a 1x1 m Digital Elevation Model (DEM) of Difference (DoD), where positive values indicated erosion and negative numbers indicated deposition. Both captures had a vertical accuracy of $\pm 0.15 \text{ m}$ at one sigma (68% confidence level). A conservative limit of detection (LoD) of 0.5 m was used (Taylor, 1982; 1997). This approach was considered appropriate as the geomorphic process of interest was riverbank erosion or deposition at the study area scale (approximately 62km). Magnitude of geomorphic change at this scale was therefore much larger than the estimated noise (Passalacqua et al., 2015). The final DoD and aerial imagery captured simultaneously to the LiDAR were visually inspected to remove: any areas of erosion or deposition less than 20 m^2 ; any values suspected of being influenced by sand and

gravel extraction activities; any values suspected to have been influenced by areas of high vegetation density or slope (Wheaton et al., 2010); and sections influenced by standing water. The remaining riverbank erosion and deposition DoD values were converted to polygons, which are referred to as erosion or deposition observations in subsequent analyses.

3.2 Downstream variation in riverbank erosion and deposition

To quantify downstream variation in riverbank erosion and deposition, a polygon of the macrochannel was digitised and divided into 63 meandering or relatively-straight reaches numbered in a downstream direction (Figure 1). In sections of the MBR where the macrochannel was relatively straight for several kilometres, reach divisions were defined approximately every kilometre.

3.3 Defining geomorphic units and zones

Riverbank erosion and deposition can vary depending on channel form, and larger spatial scale factors such as valley confinement (Brierley and Fryirs, 2005). Similar channel form and degree of valley confinement were identified by comparing the inundation extent of different magnitude river discharges. Inundation extents were determined using a HEC-RAS model which had 662 cross-sections, used normal depth as the upstream boundary condition and a rating curve at the Mt Crosby weir as the downstream boundary condition. Ground elevations for cross sections were extracted from the 2009 LiDAR DEM of the Mid Brisbane catchment. Bathymetric data was collected after the 2011 flood at 65 sites across the study area to estimate below water level elevations. It is acknowledged that these data would reflect the post 2011 flood bathymetry. Previous studies have indicated that the MBR bed has been relatively stable since the 1950s (Brizga, 2000b; Kemp et al., 2015). Therefore the error introduced by use of post-flood bathymetry is unlikely to be substantial. Manning's roughness coefficients were estimated initially from Chow (1959) then calibrated to the rating curve at 143001C (Figure 1) using flow weighting. Prior to flow weighting channel

roughness was estimated as 0.04, and overbank roughness as 0.07. Flow heights from the HEC-RAS model were compared to heights estimated from a hydrological model maintained by the regional water supplier (Seqwater, 2011) at several locations throughout the study area and found to be in agreement. The modelled 2011 flood extent was also compared to a 2011 flood extent digitised from debris lines by a local council and found to agree.

3.3.1 Geomorphic units

Channel form was categorised into geomorphic units using inundation extents estimated from the HEC-RAS model, riverbank height and slope layers derived from the 2009 DEM, and aerial photography. The inundation extent for discharge of a given magnitude estimated by HEC-RAS was related to the AEP estimates for the contemporary 'with dam' scenario provided by Syme et al. (2017). In some instances geomorphic units were inundated consistently by an estimated AEP flow (e.g. a 1 in 20 AEP event). In other instances the AEP of a given HEC-RAS modelled inundation extent was estimated by assuming a linear relationship between the relevant flow categories presented in Syme et al. (2017). The geomorphic units identified included (the approximate AEP flow each unit was inundated by are presented in brackets): bank attached bar (1 in 3.5 AEP), bench and vegetated island (1 in 20 AEP), inset floodplain (1 in 70 AEP), terrace (between 1 in 80 and 1 in 100 AEP), and colluvial slope (Figure 3). Note benches and vegetated islands were lumped due to similarity of inundation frequency.

Figure 3 Geomorphic units defined in the study area (note vegetated islands are not shown)

3.3.2 Geomorphic zones

Different degrees of valley confinement were identified using the 2011 flood extent and categorised into geomorphic zones. The defined zones were Wivenhoe Pocket where inundation was extensive (reaches 1-19); Savages Crossing where flow was largely contained within the macrochannel (reaches 20-33); Burtons Bridge where inundation extents increased slightly (reaches 34-40); and Kholo where flow was again largely contained within the macrochannel (reaches 41-63)(Figure 1).

3.4 Definition of riverbank erosion process

Riverbank erosion processes were defined for each erosion observation using form identified in the DoD, datasets derived from the pre and post-flood DEMs, and aerial imagery. Details on criteria used in the definition of each process category are provided in Supplementary material 1. A combination of processes often occurred. In these circumstances the dominant process was assigned if it was identified over greater than or equal to approximately 70% of the polygon. The erosion process categories defined were:

- Stripping (St) due to the concentration of flow energy removing alluvium (Nanson, 1986; Warner, 1997);
- Erosion due to scour around vegetation (Sc_{veg})(Gurnell et al., 2012);

- Scour of riverbanks ($Sc_{riv.bank}$). For erosion with a height of ≥ 2 m, geotechnical failure was also assumed to have occurred, similar to the threshold suggested by Lawler (1995). Several categories of geotechnical failure were defined.
 - Cantilever or slab geotechnical failures ($Sc_{riv.bank} + G.F_{cant-slab}$) were lumped together due to their similarity of form;
 - Translational geotechnical failures ($Sc_{riv.bank} + G.F_{transl}$)(Abernethy, 2011a)
 - Sapping geotechnical failures due to sediment moisture or subsurface flow conditions ($Sc_{riv.bank} + G.F_{sapp}$) (Fox and Wilson, 2010; Grove et al., 2013).
 - Wet-flow failure where sediment liquefaction occurred ($Sc_{riv.bank} + W.F.$)(Grove et al., 2013);
 - If several of the above geotechnical failure processes were present in relatively equal proportions a combination category was used ($Sc_{riv.bank} + G.F_{comb}$).
- Sapping geotechnical failures ($G.F_{sapp}$) where erosion due to sediment moisture or subsurface flow conditions occurred in isolation of scour;
- Wet-flow failure ($W.F.$) where sediment liquefaction occurred in isolation of scour; and
- A combination (Comb.) category when the characteristics of the erosion processes outlined above were present in relatively equal proportions, and no process dominated.

3.5 Sediment characteristics at selected erosion process sites

Sediment data were collected at nine locations to determine characteristics which could have contributed to an erosion process occurring (Figure 1). Three sites were located at some of the largest magnitude observations of erosion which had lengths parallel to the channel.

These sites were MBR_2 and MBR_5 where scour and cantilever-slab geotechnical failure ($Sc_{riv.bank} + G.F_{cant-slab}$) occurred, and MBR_3 where a combination of stripping (St) and

scour and cantilever-slab geotechnical failure occurred. Three sites were located at some of the largest wet-flow failure sites (W.F.) (MBR_1, MBR_8, and MBR_9). Finally three sites were located on the outside of meanders where erosion might have been expected due to higher flow velocities, yet very little actually occurred (non-eroding sites; MBR_4, MBR_6, and MBR_7). All sediment data were collected between September and October 2013.

At each site particle size distribution and erodibility information were determined at the riverbank toe and face. Particle size distributions were determined using a combination of sieving and hydrometers. Sediment erodibility data (critical shear stress, t_c ; and erodibility coefficient, k_d) were collected in duplicate for the riverbank toe and face at each site using a miniature jet erosion test (mini-JET) device (Simon et al., 2010). Critical shear stress (t_c) represents the energy required for erosion to commence, and erodibility (k_d) represents the rate it will proceed once initiated. Tests were performed on sections of riverbank which had minimal vegetation root networks to ensure they reflected sediment properties alone. Some developments in interpreting mini-JET results have recently been published (Haddadchi et al., 2018; Rose et al., 2018), however for the current study the ‘iterative’ approach to determining t_c and k_d was used to allow more direct comparison to values in the literature.

3.6 Definition of deposition process and sediment origin

Similar to the riverbank erosion process definition, deposition form identified in the DoD and DEM derived datasets were used to define deposition process and infer sediment origin (Brierley and Fryirs, 2005). If a deposition polygon occurred on a riverbank immediately below an erosion polygon, that erosion was assumed to be the source of the deposited sediment ($\text{Deposit}_{\text{riv.bank}}$). If the deposition polygon was surrounding isolated vegetation or woody debris in either the pre-flood (2009) or post-flood (2011) LiDAR and imagery, deposition was assumed to be due to the influence of that vegetation on flow characteristics

(Deposit_{veg})(Gurnell et al., 2012). If a deposition polygon did not meet any of the above criteria, the source of deposited sediment was assumed to be upstream sources. This category was separated into low slopes ($\leq 15^\circ$ of the post-flood 2011 LiDAR; Deposit_{US-LS}) and high slopes ($> 15^\circ$ of the post-flood 2011 LiDAR; Deposit_{US-HS}). Similar to the erosion process definition, if the above deposition characteristics were present in relatively equal proportions a combination category was defined (Comb.).

3.7 Riparian vegetation

Riparian vegetation canopy cover was quantified using a canopy height model (CHM) derived from the 2009 and 2011 LiDAR captures. These models were visually inspected to ensure no errors due to buildings or powerlines were present. CHM values greater than 5m in height were extracted and converted to polygons. Previous studies in the region indicate that CHM values higher than 5m align with woody, single-stemmed trees in the Specht et al. (1995) classification (McMahon et al., 2017). These polygons are referred to as large woody vegetation (LWV) in the remainder of the article.

LWV was analysed at a reach, geomorphic unit and erosion observation (polygon) scale. At a reach scale, the area of LWV canopy cover per reach area (excluding the area of standing water) was calculated from the pre-flood (2009) LiDAR. At a geomorphic unit scale, the area of LWV canopy cover per geomorphic unit area of each reach was calculated, also excluding the area of standing water. These data were calculated from both the pre-flood (2009) and post-flood (2011) LiDAR to determine change in LWV cover caused by the 2011 flood. Finally at an erosion observation scale, the area of LWV from the pre-flood (2009) LiDAR covering each erosion observation (polygon) was calculated.

3.8 Sand and gravel extraction

The location of sand and gravel extraction sites across the study area was determined using the Water Entitlements Register Database (WERD) maintained by the then Queensland Department of Environment and Resource Management, and inspection of aerial imagery. Sand and gravel extraction reaches were defined when extraction was evident over the 2001-2011 period. This time period was chosen as it roughly corresponds to the interval between substantial flood events in the catchment. Extraction activities over the 2001-2011 period occurred on benches and inset floodplains in reaches 17-18 and 53-54; bank attached bars in reaches 31-32; and bank attached bars, benches and inset floodplains in reaches 38-41.

3.9 Quantifying the influence of riparian vegetation and sand and gravel extraction on riverbank erosion

The influence of riparian vegetation and sand and gravel extraction on riverbank erosion magnitude was evaluated using a generalised least squares (GLS) model (Eq. 1) created in the R statistical environment (R Core Team, 2015). The response variable was the natural logarithm of erosion volume (m^3) for each erosion observation (polygon). Independent variables included presence or absence of sand and gravel extraction in the reach of the observation, a categorical variable indicating the type of erosion process, and the percentage of LWV cover over the observation (polygon). Interaction terms between the presence or absence of extraction and LWV, and between erosion process and LWV were also included. Only erosion observations from the bank attached bar, and bench and vegetated island geomorphic units with some LWV cover (i.e. $\text{LWV} > 0$) were analysed. Model residuals indicated differences in variance with erosion process and LWV. Therefore a variance structure was defined as a function of both of these variables. Further details on the modelling approach and the data used to inform the model are presented in Supplementary materials 2.

$$\begin{aligned} \ln(Erosion)_i = & \alpha_0 + \beta_1 Extraction + \beta_{2i} Process_i + \beta_3 LWV \\ & + \beta_4 (Extraction \times LWV) + \beta_{5i} (Process_i \times LWV) \\ \varepsilon_i \sim & N(0, \sigma^2 \times Process_i \times e^{LWV}) \end{aligned} \quad (1)$$

As the natural log of erosion was used as the dependent variable in the GLS model, parameter estimates for the *LWV* term relate to the proportional change in erosion that follow from a one percent increase in the *LWV* canopy cover continuous variable, all other drivers remaining unchanged (Wooldridge, 2013). For the *extraction* or *erosion process* categorical variables, parameter estimates relate to proportional change in erosion (given by $e^{\beta_x} - 1$) associated with a level change, all other drivers remaining unchanged, where β_x relates to β_1 or β_{2i} in the above equation (Wooldridge, 2013).

Plots of residuals against explanatory variables indicated normality and homogeneity for both the bank attached bar and bench and vegetated island models. Spatial autocorrelation was evaluated by plotting residuals against distance downstream, and through a semivariogram defined as a function of pairwise stream distance among erosion observations. Both the residual plot and the semivariogram indicated that spatial autocorrelation was adequately addressed through the explanatory variables. Model performance for each geomorphic unit was measured using pseudo- R^2 values and a leave-one-out cross-validation.

3.10 Determining change in erosion rates in relation to historical land use changes

The change in erosion rates in relation to land use changes was assessed using historical photos taken from riverbanks and aerial photos. The historical aerial photos focused on erosion rates at MBR_2 and MBR_5 in the 1974, 2011 and 2013 floods, and on sand and gravel extraction over the 1974 to 2011 period.

4 Results

4.1 Spatial variation in riverbank erosion and deposition magnitude in the 2011 flood

4.1.1 Riverbank erosion

In total approximately 1,138,416 m³ of riverbank erosion occurred between 2009 and 2011 across the 63 reaches (Figure 4). There was substantial reach to reach variation, however it was generally high in sand and gravel extraction reaches. Bank attached bars and benches eroded the most (28% and 50% of the total erosion volume respectively; Table 1), with the stripping process (St) being the dominant contributor (23% on bank attached bars and 14% on benches). The scour and cantilever or slab geotechnical failure process ($Sc_{riv.bank} + G.F._{cant-slab}$) did not contribute a large erosion volume (15%; Table 1), however it often occurred on the outside of meanders and eroded into higher geomorphic units such as inset floodplains and terraces (Figure 5). Bank attached bars and benches eroded consistently across the geomorphic zones (Supplementary materials 3). Field data indicated that sediment at $Sc_{riv.bank} + G.F._{cant-slab}$ process sites was easily erodible, wet-flow failure sites generally had more sand (Supplementary materials 4), and non-eroding sites had bedrock or indurated gravel deposits either at the surface or at a shallow depth below it (for example MBR_4 and MBR_7 in Figure 5). While sediment at non-eroding sites displayed higher critical shear stress (t_c) and lower erodibility coefficients (k_d) (Supplementary materials 4), given their location on the outside of meanders and the associated high flow velocities they would have experienced in the 2011 flood, it is likely that bedrock and indurated gravel deposits were the primary reason for their stability.

Figure 4 Total erosion and deposition volume per reach across the study area. White bars indicate sand and gravel extraction reaches.

4.1.2 Riverbank deposition

For deposition, approximately 534,025 m³ occurred between 2009 and 2011 across the 63 reaches (Figure 4). The spatial distribution was more varied than riverbank erosion with some reaches experiencing no deposition as defined here, and other reaches experiencing large volumes. Generally those reaches with high deposition were sand and gravel extraction reaches. The majority was from upstream sources and deposited on areas of low slope on bank attached bars (76%; Table 2).

4.2 Influence of large woody vegetation (LWV) on riverbank erosion in the 2011 flood

Data from before the 2011 flood confirmed vegetation cover was low across the study area, with the majority of reaches having LWV cover of approximately 20% (Supplementary materials 5). LWV cover was comparable on the bank attached bar and bench geomorphic units (median values of 22% and 29% respectively; Supplementary materials 5).

The bank attached bar GLS model contained 772 observations once observations with no LWV cover or erosion process categories with insufficient observations were removed, had a pseudo- R^2 of 0.25 and a cross validated R^2 of 0.23. The bench and vegetated island GLS model contained 916 observations once observations with no LWV cover were removed, had a pseudo- R^2 of 0.46 and a cross-validated R^2 of 0.42. The cross-validated R^2 values indicate that overfitting was not a major concern for both models. To illustrate the relationship between LWV and erosion process, slope terms derived from the GLS regression (β_x) are plotted for significant (<0.05) and marginally significant (<0.1) terms in Figure 6 and Figure 7.

LWV cover significantly reduced erosion on both geomorphic units for the stripping process (St; Figure 6 and Figure 7) which was the dominant contributor to total erosion volume in the 2011 flood (Table 1). For this process the slope of the relationship indicated that a 1% increase in LWV cover reduced St by 1.9% (± 0.57) and 2.8% (± 0.84) for bank attached bars and benches respectively (Supplementary materials 6). LWV increased erosion for scour and combination geotechnical failure ($Sc_{riv.bank} + G.F_{comb}$) on bank attached bars, and sapping geotechnical failure ($G.F_{sapp}$) on benches. The slope of these relationships indicated that a 1% increase in LWV cover increased erosion by 1.5% (± 1.46) and 1.8% (± 1.03) respectively (Figure 6 and Figure 7). However these processes only contributed approximately 1% to the total erosion volume in the 2011 flood (Table 1).

Table 1 Percent (%) of erosion volume (m³) contributed by each erosion process on each geomorphic unit. In brackets and italics are percent (%) of total observations of erosion.

Erosion process	Geomorphic unit					<u>Total</u>
	<i>Bank attached bar</i>	<i>Benches and vegetated islands</i>	<i>Inset floodplain</i>	<i>Terrace</i>	<i>Colluvial slope</i>	
St	23 (24)	14 (5)	2 (<1)	1 (<1)	<1 (<1)	40 (30)
Sc_{veg}	<1 (1)	<1 (2)	<1 (<1)		<1 (<1)	1 (4)
Sc_{riv.bank}	1 (8)	2 (17)	<1 (1)	<1 (1)	<1 (1)	3 (28)
Sc_{riv.bank} + G.F._{cant-slab}	1 (1)	6 (3)	3 (1)	6 (<1)	<1 (<1)	15 (5)
Sc_{riv.bank} + G.F._{transl}	1 (2)	4 (7)	<1 (1)	1 (1)	1 (1)	6 (12)
Sc_{riv.bank} + G.F._{sapp}	<1 (<1)	1 (2)	<1 (<1)	<1 (<1)	<1 (<1)	1 (2)
Sc_{riv.bank} + W.F.	<1 (<1)	10 (4)	1 (1)	1 (<1)	<1 (<1)	12 (6)
Sc_{riv.bank} + G.F._{comb}	1 (1)	9 (2)	2 (<1)	1 (<1)	<1 (<1)	13 (4)
G.F._{sapp}		<1 (<1)	<1 (<1)	<1 (<1)	<1 (<1)	<1 (1)
W.F.	<1 (<1)	3 (1)	2 (1)	<1 (<1)	<1 (<1)	5 (2)
Comb.	1 (4)	2 (2)	1 (<1)	<1 (<1)	<1 (<1)	4 (7)
<u>Total</u>	28 (42)	50 (45)	10 (5)	10 (4)	1 (4)	1,138,416 m³ (N = 2360)

Table 2 Percent (%) of deposition volume (m³) contributed by each erosion process on each geomorphic unit. In brackets and italics are percent (%) of total observations of deposition.

Deposition process	Geomorphic unit					<u>Total</u>
	<i>Bank attached bar</i>	<i>Benches and vegetated islands</i>	<i>Inset floodplain</i>	<i>Terrace</i>	<i>Colluvial slope</i>	
Deposit_{riv.bank}	<1 (1)	1 (4)	<1 (<1)	<1 (<1)	<1 (<1)	1 (6)
Deposit_{veg}	<1 (4)	<1 (2)	<1 (<1)	<1 (<1)		1 (7)
Deposit_{US-LS}	76 (57)	6 (13)	<1 (1)	<1 (1)	<1 (<1)	82 (71)
Deposit_{US-HS}	<1 (4)	1 (5)	<1 (1)	<1 (<1)	<1 (<1)	2 (10)
Comb.	13 (3)	1 (2)	<1 (<1)			14 (6)
<u>Total</u>	90 (69)	9 (26)	<1 (2)	<1 (2)	<1 (1)	534,025 m³ (N = 833)

Figure 5 Field sites showing the height and proximity to low flow channel of eroding riverbanks at MBR_2 and MBR_5 after the 2011 flood; the presence of bedrock at the riverbank toe and face at MBR_4; and the presence of indurated gravel deposits at the riverbank toe at MBR_7

Figure 6 GLS model predictions of the natural log of erosion volume for 25th, 50th and 75th quantiles of LWV for significant erosion processes in extraction and non-extraction reaches on bank attached bars. Error bars indicate standard errors.

Figure 7 GLS model predictions of the natural log of erosion volume for 25th, 50th and 75th quantiles of LWV for significant erosion processes in extraction and non-extraction reaches on bench and vegetated islands. Error bars indicate standard errors.

4.3 Other land use changes which contributed to riverbank erosion during the 2011 flood

At some locations where the scour and cantilever or slab geotechnical failure ($Sc_{riv.bank} + G.F._{cant-slab}$) process occurred in the 2011 flood, erosion is occurring at a rate unprecedented since the time of settlement (Figure 8; Kemp et al. (2015)). This suggests the river has crossed a threshold of stability at these locations. As vegetation extent was similar in the 1974 and 2011 floods, other land use changes which interrupted the longitudinal connectivity of coarse sediment, such as construction of the dam and sand and gravel extraction, are likely to be the driver of this response. While no quantified data on changes to longitudinal coarse sediment connectivity was available, we discuss these changes here in a qualitative manner to frame changes in reach scale erosion rates within their catchment coarse sediment connectivity context (Brierley and Fryirs, 2005; Wohl et al., 2019). The impact of these land use changes on longitudinal coarse sediment transport in other locations is well documented and can inform hypotheses about their impact (Kondolf, 1997; Rinaldi et al., 2005).

A large volume of riverbank erosion occurred just downstream of Wivenhoe dam in reach 1 (Figure 4), most likely caused by high flow velocities from dam releases. However there were no other peaks in erosion in close proximity to the dam, as might be expected if changes to longitudinal coarse sediment connectivity caused by the dam were a major driver of changed erosion rates.

While it is difficult to attribute exceedance of this threshold to a specific land use change conclusively, several lines of evidence suggest that on a relative basis sand and gravel extraction was the dominant contributor to changed erosion rates in the 2011 flood compared to Wivenhoe dam. These lines of evidence include: erosion was generally high in extraction reaches (Figure 4); individual observations of erosion were higher in extraction reaches (the *Extraction* term in isolation in the regression table presented in supplementary materials 6); the presence of extraction in a reach affected the slope of the relationship between LWV and erosion on bank attached bars (Figure 6); and the instances of scour and cantilever or slab geotechnical failure ($Sc_{riv.bank} + G.F_{cant-slab}$) where riverbanks appear to have crossed a threshold of stability were either in sand and gravel extraction reaches, or in close spatial proximity (Figure 8).

4.4 What does change in erosion rates in relation to historical land use changes indicate about the drivers of the observed trajectory of turbidity

The MBR corridor was densely vegetated before clearing occurred (1892 photo in Figure 9). As vegetation clearing progressed historical photos indicate erosion occurring (1898 photo in Figure 9). Despite this clearing and the significant role of LWV in reducing riverbank erosion (Figure 6 and Figure 7) the river remained relatively resilient to changes to vegetation extent, as can be seen by the similarity in form between 1907 and 2017 shown in the middle panels

of Figure 9. The prevalence of bedrock and indurated gravel deposits (Figure 5) is likely a major contributor to this resilience.

A combination of land use change pressures (low vegetation extent, the construction of Wivenhoe dam and sand and gravel extraction) appear to have been necessary before the change in riverbank erosion rates at some scour and cantilever or slab geotechnical failure

($Sc_{riv.bank} + G.F_{cant-slab}$) sites occurred in the 2011 flood (see bottom panels of Figure 9).

Given the points outlined above, on a relative basis sand and gravel extraction is likely to be the dominant contributor to these locations crossing a threshold of stability.

The contribution from the MBR to the record peak turbidity in the 2013 flood was likely due to a combination of: reduced vegetation extent on bank attached bars and benches after the 2011 flood (supplementary materials 5) and therefore a reduction in its mitigating effect on processes such as St (Figure 6 and Figure 7); increased erosion rate at some $Sc_{riv.bank} + G.F_{cant-slab}$ sites (Figure 8); and remobilisation of sediment deposited during the 2011 flood on bank attached bars (Table 2).

Figure 8 Historical aerial photos for selected $Sc_{riv.bank} + G.F_{cant-slab}$ process sites (Reach 17, MBR_2; Reach 35, MBR_5) and sand and gravel extraction reaches (Reaches 38-42 and 53-54). Oblique aerial photo shows the Burton's Bridge geomorphic zone close to the peak of the 2011 flood (photo courtesy of Dan Garcia, Seqwater).

Figure 9 Examples of historical and contemporary channel condition. 1892 (top left): example of the height and density of uncleared riparian vegetation, John Oxley Library. 1898 (top right): evidence of erosion scarps in a thinly vegetated reach, most likely due to the floods in 1893, Queensland State Archives; 1907 (middle left): illustrates vegetation clearing of lower geomorphic units had occurred, John Oxley Library; 2017 (middle right): the same reach as shown in the middle left panel indicating similar river form and vegetation extent, Google Earth. Note that vegetation appears vertically compressed in this image; 1995 (bottom left): Riverbank at MBR_5 is not eroding and has established vegetation, photo courtesy of Ellie Skoien; 2017 (bottom right): Substantial riverbank erosion now occurring at MBR_5.

5 Discussion

The data and analysis presented above confirm the hypothesis that vegetation could reduce riverbank erosion, and therefore contribute to reducing turbidity, during a large magnitude flood along a 62 km riparian corridor where land cover differed substantially from natural

conditions. The distribution of bedrock or indurated gravel deposits and discrete pockets of alluvium influenced the spatial distribution of erosion at a catchment scale. Bank attached bars and benches eroded the most, with the stripping process (St) being the dominant contributor. Where the St erosion process occurred on those geomorphic units, the presence of LWV significantly reduced its magnitude. Low vegetation extent and direct changes to the riparian corridor which influenced longitudinal coarse sediment connectivity, such as the construction of Wivenhoe dam and sand and gravel extraction, all contributed to the observed riverbank erosion in the 2011 flood. When comparing the impact of direct changes to the riparian corridor on a relative basis, sand and gravel extraction was likely to be the dominant contributor to changed erosion rates. The contribution from the MBR to the record peak turbidity in the 2013 flood was likely due to: reduced vegetation extent after the 2011 flood, and therefore a reduction in its mitigating effect on riverbank erosion processes such as St; increased erosion rates at $Sc_{riv.bank} + G.F_{cant-slab}$ sites such as MBR_2 and MBR_5; and remobilisation of sediment deposited during the 2011 flood on bank attached bars. As the locations where erosion rates had substantially increased had a limited spatial extent and in general substantial change in river form has not occurred, the trajectory of MBR condition and increasing turbidity are potentially reversible if the drivers of river degradation are addressed through an ecosystem restoration policy.

5.1 Spatial variation in riverbank erosion in the 2011 flood

Erosion of the MBR in response to the 2011 flood event exhibited substantial variation between reaches, similar to other bedrock-alluvial rivers (Hoyle et al., 2008; Konsoer et al., 2016; Toone et al., 2014). Bedrock and indurated gravel deposits influence river processes in the catchment through bed stability (Brizga, 2000b; Kemp et al., 2015), partial confinement by the valley margins (represented by the colluvial slope geomorphic unit which experienced little erosion; Table 1), and reinforcement of other geomorphic units such as benches (at non-

eroding field sites). Erosion on the inside of meanders has been reported in other locations when outer bank materials are armoured or contained bedrock (Thorne, 1991; Warner, 1997). Similarly in the MBR, erosion of the inner bank inset within the macrochannel often occurred when the outer bank was either the valley side (represented by the colluvial slope geomorphic unit), confining terraces, or contained bedrock or indurated gravel deposits (Figure 5). Erosion appeared to occur wherever flow related factors (either flow energy or riverbank saturation) overcame the strength of isolated pockets of alluvium, whether they occurred on the inside or outside of meanders of the macrochannel.

Noncohesive coarse sediment dominates bank attached bars in the study area (Brizga, 2000b; Wong, 1995). These sediments are more readily mobilised than cohesive sediments (Hjulstrom, 1935; Shields, 1936). When combined with the close proximity of this geomorphic unit to the thalweg, and consequently the greater flow energy experienced during the 2011 flood, this may explain the frequent occurrence and large contribution to total erosion volume of the stripping (St) process (Table 1). The remaining geomorphic units had a higher proportion of cohesive sediment (Supplementary materials 4). Due to the severe La Niña event in 2010 and 2011, pre-wetting is likely to have weakened this sediment and influenced erosion volume. Riverbank water table dynamics exert a large influence on geotechnical strength (Rinaldi et al., 2004), however it was not possible to assess this influence with the data available.

5.2 Influence of large woody vegetation (LWV) on riverbank erosion in the 2011 flood

While riverbank erosion at locations with no vegetation cover is relevant for catchments where land cover is substantially different to natural conditions, the analysis was restricted to observations with some LWV cover to quantify the benefits provided by vegetation. The significant reduction in the magnitude of the stripping (St) process with increasing LWV

cover quantifies the relationship which was speculated upon by Warner (1997). As the logarithm of erosion volume was used, the untransformed relationship between increasing LWV cover and riverbank erosion magnitude would be exponential in shape. This indicates that the benefit imparted by an increase in LWV cover would be greatest in areas with minimal current cover. For two processes increasing LWV cover was associated with increasing riverbank erosion. It is possible that LWV created an obstacle to flow and led to localised increases in velocity and consequently erosion for the $Sc_{riv.bank} + G.F._{comb}$ process on bank attached bars (Rominger et al., 2010); and vegetation roots created preferential subsurface flow paths which led to sapping geotechnical failure at susceptible locations on benches (Fox and Wilson, 2010). However both these processes were minor contributors to overall erosion volume (1%; Table 1).

The erosion process definitions aimed to capture some of the variation in sediment characteristics and flow related factors which were not able to be quantified to a comparable spatial extent and resolution as erosion and canopy cover. However the GLS regression models still contained unexplained variation. A regional study which excluded bank attached bars, found that streampower was not significantly related to riverbank erosion (McMahon et al., 2017). However some measure of flow energy may be particularly important for describing variation in erosion on bank attached bars, as they contained a high proportion of noncohesive sediment that can be readily mobilised, and there was substantial unexplained variation in the model (pseudo- R^2 0.25).

Generally the processes where *no* significant relationship between LWV and erosion was found were those which involved crossing of a geotechnical threshold and collapse of large sections of riverbank. For example, scour of the riverbank toe is a major driver of the $Sc_{riv.bank}$

+ $G.F_{cant-slab}$ erosion process (Simon et al., 2000). This scour is influenced by flow related factors not quantified in the current study. It is possible that at locations at risk of this process, once scour of the toe increased the riverbank angle to an extent where geotechnical failure occurred, there was not a detectable relationship between increasing LWV and reduced erosion on the failed portion of riverbank. This is in contrast to the $Sc_{riv.bank} + G.F_{transl}$ process where the failed material retained the pre-flood riverbank orientation and a significant relationship with LWV was found on benches (Figure 7). The significant relationship between LWV and reduced erosion for the $Sc_{riv.bank}$ process suggests that vegetation could play a role in reducing scour of the toe. It is possible that other processes which did not have a significant relationship with LWV (such as $W.F.$ and $Sc_{riv.bank} + W.F.$) also occurred when a threshold was crossed and large sections of riverbank collapsed, but drivers were related more to saturation of riverbank sediment than to changes in riverbank geometry (Grove et al., 2013; Stout et al., 2018).

5.3 Other land use changes which contributed to riverbank erosion during the 2011 flood

The $Sc_{riv.bank} + G.F_{cant-slab}$ erosion process sites where field data was collected (MBR_2 and MBR_5) were largely stable in the 1974 flood, yet experienced high erosion volumes in the 2011 flood which was comparable in magnitude (Figure 8 and Figure 2). The hydrograph shape and pre-wetting conditions during these events would have differed. Other authors have considered the influence of the 2011 flood hydrograph on riverbank erosion but were unable to apportion the influence of the dam conclusively without detailed data on riverbank sediment properties (Abernethy, 2011a; b; DSITIA, 2014). Similarly with the data available it was not possible to determine the influence of different pre-wetting conditions between the 1974 and 2011 floods. While it was not possible to dismiss the influence of hydrograph shape and pre-wetting conditions on the observed erosion without other data, given the magnitude of erosion which occurred at these sites a more likely explanation may be that the relationship

between driving and resisting force at these locations has changed. Continuing erosion in future floods is likely to lead to a realignment of the macrochannel planform at these locations, which is unprecedented in the catchment since European settlement.

Wivenhoe dam provides high water supply and flood mitigation value to the region due to the highly variable climate, however it also has a large impact on longitudinal coarse sediment connectivity. Many Australian rivers are considered to be sediment supply limited, and the Brisbane River displays similar characteristics (Shellberg and Brooks, 2007; Tooth and Nanson, 1995). Therefore this interruption to longitudinal coarse sediment connectivity would further reduce the amount of sediment supplied to reaches downstream. While channel incision has been reported in response to dam construction in many locations (Brandt, 2000), the bed of the MBR has remained reasonably stable albeit with some scour several kilometres downstream from the dam wall (Kemp et al., 2015). Bedrock, coarse bedload and armouring is likely to have contributed to this stability (DSITIA, 2014; Kemp et al., 2015).

Sand and gravel extraction in the MBR is removing shorter residence time sediment stores from bank attached bars and benches, and longer residence time sediment sinks from inset floodplains. All of these extraction locations were captured by the river during the 2011 flood event and should be considered part of the main channel (see Photo in Figure 8)(Kondolf, 1994). Extraction has been reported to affect riverbank erosion both up and downstream . However these effects have generally been in response to extraction from the bed, which has not occurred in the MBR. Sediment extraction from bank attached bars, benches and inset floodplains in the MBR would create a sediment deficit in the already sediment supply limited catchment, which is now receiving less coarse sediment due to construction of Wivenhoe dam (Brizga, 2000b). It is possible this led to the river attempting to source

additional sediment from along its channel during the 2011 flood when the macrochannel was laterally connected. Combined with the propensity of the MBR to only erode where discrete pockets of alluvium and flow related factors allowed, this may explain the higher volume of erosion in extraction reaches (Supplementary materials 6), the erosion of previously stable sediment sinks in extraction reaches (such as in MBR_2), and the erosion of previously stable sediment sinks in close proximity to extraction reaches (such as MBR_5). For processes where LWV reduced riverbank erosion on bank attached bars, the presence of sand and gravel extraction in a reach increased the slope of the relationship. This suggests that LWV is reducing the impact of the ‘hungry water’ caused by extraction (Kondolf, 1997), as found elsewhere in the region (McMahon et al., 2017). The time between large magnitude floods which laterally connected the entire macrochannel is likely to explain the time lag between sand and gravel extraction and river response. While extraction provides valuable material for construction, there are few options to mitigate its impact and it is a growing problem around the world (UN, 2014).

5.4 What does change in erosion rates in relation to historical land use changes indicate about the drivers of the observed trajectory of turbidity.

No large magnitude changes to riverbank erosion rates were apparent from the time of European settlement to 2010. The vegetation clearing which occurred after European settlement did not result in large scale change in channel form of the MBR in subsequent flood events (1907 and 2017 photos in Figure 9), as it did in many other Australian rivers (Brooks and Brierley, 2000; Brooks et al., 2003; Fryirs et al., 2018). The macrochannel of the MBR was present at the time of European settlement (Kemp et al., 2015), and does not reflect a response to disturbance as found elsewhere in Australia (Hoyle et al., 2008). However erosion did occur on alluvium inset within the macrochannel (1898 photo in Figure 9; Kemp et al. (2015)). It is likely that vegetation clearing on inset geomorphic units increased erosion

rates and the partial confinement and macrochannel form of the MBR efficiently flushed that eroded sediment downstream (Brierley et al., 2002). This hypothesis may explain the resilience of the MBR, and the macrochannels of other regional rivers, to disturbance yet the increased rate of sediment deposition noted in the receiving water of the Brisbane River (Moreton Bay) after European settlement (Coates-Marnane et al., 2016). Changes to longitudinal coarse sediment connectivity caused by the construction of Wivenhoe Dam and sand and gravel extraction are likely to be the cause of the coarsening of bed material reported by Wong (1995), however characteristics of the MBR such as partial confinement and the presence of bedrock and indurated gravel deposits imparted a high degree of resilience.

It seems likely that due to the resilience of the MBR, a combination of land use change pressures and the large magnitude 2011 flood were needed before a threshold of erosion rate was exceeded. These land use change pressures have likely increased flow energy by interrupting longitudinal coarse sediment connectivity or removing historical sediment stores and sinks, and reduced resisting force through vegetation clearing. This may explain why a key erosion threshold was breached in the MBR macrochannel while the macrochannels of adjacent catchments, which did not experience the same combination of land use changes, were resilient to the same flood (Fryirs et al., 2015; McMahon et al., 2017). It would be difficult to attribute exceedance of this threshold to a specific land use change conclusively (Phillips, 2001; 2003). However given the significant relationships between extraction and heightened riverbank erosion found elsewhere in the region (McMahon et al., 2017), the difference in response to the 2011 flood between the MBR and other regional catchments, and recorded impacts of extraction around the world, it seems highly likely that this practice is contributing to riverbank erosion risk in the catchment.

The contribution of the MBR to the record turbidity peak in the first 2013 flood was likely due to a combination of increased erosion rates and remobilisation of sediment deposited after the 2011 flood. As the second flood in 2013 had far lower turbidity, on a relative basis the main driver of the record turbidity peak in the first 2013 flood is likely to be remobilisation of sediment from all upstream sources deposited on bank attached bars during the 2011 flood. The Lockyer Creek catchment (Figure 1) has been found to be a large contributor to regional sediment loads (Douglas et al., 2003), experienced substantial erosion in the 2011 flood (Croke et al., 2013; Grove et al., 2013; Thompson et al., 2013), and is likely to be a major contributor to the deposited sediment.

If conditions in the catchment remain unchanged, it is likely that substantial erosion of inset geomorphic units will continue in future floods. The combination of sediment trapping and removal has likely created a sediment deficit in the already sediment-supply limited system. This deficit may initiate erosion of other historically stable sediment stores and sinks in the catchment in future events. All sediment characteristics measured in the MBR have t_c values towards the lower range of values in the literature and k_d values toward the upper range (Klavyon et al., 2017), however erosion at MBR_2 and MBR_5 pose a substantial risk to sediment loads in future floods due to their proximity to the low-flow thalweg and their substantial height (Figure 5). Sediment at these sites require little energy for erosion to commence (low t_c) and will erode at a relatively high rate once initiated (high k_d) (Supplementary materials 4). The W.F. erosion process is regionally significant and represented approximately 17% of the total erosion volume in the MBR ($Sc_{riv.bank} + W.F.$ and W.F. in Table 1). However its relative contribution to total erosion volume in the MBR is substantially less than in the adjacent Lockyer Creek catchment (Grove et al., 2013).

Saturation of susceptible riverbank sediment has been suggested as a primary driver of this process (Grove et al., 2013; Stout et al., 2018). The generally higher proportion of sand at sites where it occurred (Supplementary materials 8) may have contributed to greater riverbank saturation. If riverbank saturation is the primary driver of this process, these sites only pose a risk to sediment loads in future flood events if the necessary saturation conditions are met.

5.5 Implications for using ecosystem restoration for reducing riverbank erosion and turbidity in drinking water

The benefits provided by riparian vegetation ecosystems were quantified over 1688 observations at a catchment scale (62 km) and confirm that vegetation significantly reduced riverbank erosion along a riparian corridor where land cover was substantially different to natural conditions. It provided the greatest erosion reduction benefits where there was minimal current vegetation cover. The data used to quantify these benefits were associated with a large magnitude flood when flow related forces were high. Vegetation is likely to be more effective at reducing erosion in smaller magnitude events when flow related forces are lower.

The large tree species represented by LWV are likely to be the most appropriate for reducing riverbank erosion and ecosystem restoration in the catchment. Riparian vegetation has evolved over millions of years to survive in, and modify, local geomorphic processes (Corenblit and Steiger, 2009). Therefore the most suitable species for mitigating riverbank erosion are likely to be those present before large scale human settlement, as they have adapted to local conditions (Brooks et al., 2003; Lyons et al., 2000). In many locations, due to the long period of human settlement it is not possible to determine pre-settlement vegetation characteristics (Brierley et al., 2005). However it is possible to determine these species in

Australia due to the relatively recent European settlement. For example historical photos presented in Figure 9 and Kemp et al. (2015) illustrate that densely spaced, large riparian vegetation species were present in the MBR prior to clearing. Weeping Bottlebrush (*Melaleuca viminalis*), River Myrtle (*Waterhousia floribunda*), River oak (*Casuarina cunninghamiana*) and *Eucalyptus* species have characteristics which have allowed them to thrive in the catchment such as the ability of above ground biomass to become prone during floods, extensive surficial root networks, and deep tap roots (Hubble et al., 2010; Jones et al., 1994; Knight, 1999; McCosker, 2000). Revegetation policies should prioritise species suited to the current baseflow rates and largely cleared conditions in the catchment, and allow for succession toward the species assemblages that were historically present (James et al., 2016; McCosker, 2000).

There are increasing calls for riparian vegetation to form part of ecosystem restoration for drinking water quality objectives (Browder et al., 2019; Palmer et al., 2015; UN, 2018). The results presented here highlight that the relationship between vegetation and riverbank erosion varied with process, and that changes to longitudinal coarse sediment connectivity are also likely to be important drivers of the trajectory of river condition. However further work is needed to clarify the effect of other aspects of sediment connectivity, such as the influence of hillslope-channel connectivity and the sediment contributions from tributaries, on the erosion response of the MBR (Lisenby and Fryirs, 2017; Rice, 1999). Sediment connectivity is an important aspect of riparian ecosystems that should be considered in addition to vegetation to improve the design of ecosystem restoration measures. This is likely to be relevant to other water supply catchments which have experienced a range of land use changes, however the relative importance of each factor will vary depending on local characteristics. A greater understanding of these factors would help build knowledge about

the complexity and uncertainty associated with using ecosystem restoration to achieve water quality objectives, and contribute to making these approaches more comparable to engineered water supply solutions.

6 Conclusions

Ecosystem restoration for water quality objectives will be necessary to meet the demand for domestic water in many locations. Effective ecosystem restoration requires evidence of the benefits that ecosystems provide and identification of the drivers of ecosystem deterioration so that measures can be designed which are appropriate for local conditions. We quantified the benefits provided by riparian vegetation ecosystems over 1688 observations at a catchment scale (62 km) and found that the presence of large woody vegetation significantly reduced riverbank erosion, even during a large magnitude flood along a riparian corridor where land cover differed substantially from natural conditions. While large woody vegetation was associated with increased erosion for some processes, these processes made a minimal contribution to total erosion volume. Some larger magnitude instances of erosion are likely to be related to changes in longitudinal coarse sediment connectivity in the catchment. While some of these sites appear to indicate that a local threshold was exceeded, overall the Mid Brisbane River has been remarkably resilient in the face of land use change and flooding. This is fortuitous given the large population who rely on drinking water from this source, and increases the likelihood that the trajectory of river condition observed after the flood could potentially be reversed. The results suggest that while riparian vegetation ecosystems can play a role in reducing contributions to sediment loads from riverbank erosion in the catchment, river rehabilitation efforts must also consider sediment connectivity. These findings can help build knowledge about using ecosystem restoration to achieve water quality objectives and contribute to making these approaches more comparable to engineered water supply solutions.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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McMahon et al (2019) Credit author statement

Joseph M. McMahon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Jon M. Olley:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Andrew P. Brooks:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing - review & editing. **James C.R. Smart:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing - review & editing. **Ben Stewart-Koster:** Validation, Writing - review & editing. **William N. Venables:** Validation. **Graeme Curwen:** Data curation. **Justine Kemp:** Validation, Writing - review & editing. **Morag Stewart:** Investigation, Methodology. **Nina Saxton:** Conceptualization, Investigation, Methodology. **Arman Haddadchi:** Investigation, Methodology. **Justin C. Stout:** Investigation, Methodology.

Graphical abstract

McMahon et al (2019) Highlights

1. 1% increase in vegetation canopy cover reduced riverbank erosion by between 2-3%
2. Changes to longitudinal coarse sediment connectivity also affected riverbank erosion
3. Both drivers need to be addressed for effective ecosystem restoration