Stream bank management in the Great Barrier Reef catchments: a handbook

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Executive summary

Context, purpose and methods

The Great Barrier Reef (GBR) is one of Australia’s greatest natural assets and contributes an estimated AUS $5.4 billion per year to the Australian economy. However, the condition of the GBR is declining, and poor water quality from adjacent catchments has been identified as one of the major threats. In response to this threat, the Australian and Queensland Governments developed the Reef Water Quality Protection Plan, with the aim to reverse the decline in catchment water quality. Part of this plan involves prioritising locations for on-ground remediation of diffuse agricultural constituent sources. The main constituents of concern are sediments, nutrients, herbicides and pesticides.

Sub-surface erosion (e.g. gully, streambank and scalded hillslope erosion) has been identified as a major source of the anthropogenic sediment delivery from agricultural areas to the GBR. Streambank erosion, which is one of three processes representing sub-surface erosion, is estimated to contribute ~30-40% to end of catchment sediment yields. Stream bank erosion, meander migration and lateral channel change are terms used to describe the erosion of the channel boundary in river systems. However, our understanding of the degree of alteration of bank erosion with the introduction of agriculture, and the success of methods for remediating bank erosion sites, is limited. Without a robust understanding of these issues it is difficult to target the sites for remediation as well as to evaluate the costs and benefits of undertaking remediation.

This report had five key objectives. Firstly, to review the International literature and identify the key processes driving stream bank erosion. It is considered important to understand the drivers, and not just the symptoms, of stream bank erosion. Secondly, using the SourceCatchment model, which incorporate the key processes driving stream bank erosion, identify the relative risk of stream bank erosion in each of the 47 GBR management units. Thirdly, to discuss some of the issues that should be taken into consideration prior to remediation. These include the available options, effectiveness, time lags, and monitoring and evaluation needs of the remediation. Fourthly, to discuss the potential cost of the remediation, as well as the various options for delivering the funding. Finally, this information is demonstrated on two case study catchments, the Burdekin and Daintree basins.

Key Results and Findings

What is bank erosion?

The dominant controls of bank erosion were identified as stream power, riparian vegetation, bank material and channel confinement. In general, bank erosion in the streams of the GBR occurs as a result of meander migration (where there is erosion on the outside, concave bank), channel widening or incision (where there is erosion on both banks), or channel avulsion (formation of a new channel). Importantly, following bank erosion, the sediment may be deposited (in the channel or on the floodplain) or transported to the marine system. This study presents the results for the exported sediment fractions only. Deposition of the eroded material is not explicitly dealt with in this report. The presence of riparian vegetation on streambanks significantly reduces the likelihood of bank erosion, however, riparian vegetation has a variable influence at different spatial scales and it has different impacts on bank erosion depending upon its position in a catchment. It is also acknowledged that riparian zones have many positive benefits in the landscape, particularly for ecological processes; however, this report focuses specifically on the use of riparian zones for erosion management.
What are the key management units (sub-catchments) for prioritisation?

The lack of measured data on stream bank erosion means that models, such as SourceCatchments, are commonly used to determine the relative contribution of bank erosion in a sediment budget. However, the bank erosion processes modelled in SourceCatchments are a simplification of the often complex bank erosion processes, and therefore the modelled estimates need to be used with a high degree of caution. The modelled outputs are, however, the only tool that provides bank erosion estimates for all of the stream networks in the GBR. Using three different metrics to describe the contribution of sediment delivery to the GBR from bank erosion (i.e. kt/yr, t/ha/yr, % change from pre-European), the modelling results suggest that the Mary and Pioneer Rivers (or management units) should undergo further investigation as bank erosion is predicted to be a major source of sediment in these catchments. The next sub-set of catchments that should be examined in closer detail include the East Burdekin, Lower Burdekin, Herbert, Isaac, Fitzroy, Dawson and O’Connell. Importantly, remediation should not be initiated in any catchment without an evaluation of whether bank erosion is actually a problem in the catchments. Preliminary assessment of some management units suggests that the models may have incorrectly identified some high risk areas. Conversely, some areas not considered to have a high bank erosion risk based on the model, may in-fact have sites suitable for remediation.

What do I need to think about before embarking on remediation?

Prior to undertaking any bank erosion remediation in a catchment, the underlying processes or drivers of the erosion need to be understood. In general, the first rule of remediation is to avoid the damage in the first place. It is easy, quick and cheap to damage natural streams. It is hard, slow and expensive to return them to a (dynamically) stable condition. In most cases, fencing off the riparian zones (and allowing native vegetation regeneration) is going to be the only cost-effective option, and priority should be given to smaller first and second order streams where fencing off is likely to be most effective. Riparian zones have been shown to work best when they are least 1 km in length, when the upstream catchment is in reasonable/good condition, and the riparian zone is a proportion of the mean channel width. Where possible, priority should also be given to ‘connecting’ in-tact riparian zones, rather than establishing a patchwork of isolated riparian zones. Native riparian vegetation has benefits for both mechanical and hydrological processes, and a combination of native woody and grass species are likely to offer the greatest benefit in terms of bank stabilisation. Fencing off and revegetating riparian zones have been shown to be effective in ~10 studies around the world, with sediment erosion, concentrations and/or yield decreasing following remediation by between ~ 30-90%. However, there are almost as many studies suggesting that the remediation was not effective. Importantly, monitoring and evaluation of any remediation is critical to justify the use of Government funding, determine if the remediation is actually improving water quality, but also as a marketing tool to encourage other farmers to undertake remediation.

The message that prevention of erosion is a priority is highlighted when the cost of remediation is considered. Remediation is expensive! Prices will vary between locations, however, general estimates range from ~$16,000 per kilometre for a combination of fencing and associated offsite watering points (where required) in grazed areas, to over $5 million per kilometre for rock revetment of a 6 m high bank. The risks associated with the success of these projects are similar. Lost production and maintenance costs have been taken into consideration when pricing remediation. Once it is decided that remediation is appropriate, there are several approaches available for delivering the funding including regulation, financial incentives and moral suasion. It will be important to consider the investment ratio for funding riparian zones as it un-likely that there will be a private benefit to landholders.
Case Studies: how to identify reaches suitable for remediation within a priority management unit (sub-catchment)

To synthesise this information, a number of case studies (from the Burdekin and Daintree catchments) were presented to demonstrate how an understanding of the drivers of bank erosion can help identify suitable remediation options. In both case studies, results from the SourceCatchments modelling from the GBR catchments were used at the sub-catchment scale to prioritise areas that had higher than expected rates of bank erosion. Example reaches were identified and potential remediation options discussed in light of the biophysical conditions at each site. At the reach scale, other sources of information such as Google Earth and local knowledge were also employed in addition to the modelling. In all case studies, fencing and vegetation management were the only remediation options considered. Engineering structures are discussed as a bank erosion remediation option, however, there needs to be a compelling argument to justify the expense associated with structural remediation. Based on this premise, no examples were found that were suitable for engineering based remediation. A similar approach could be used by Regional bodies to help determine the restoration options at each site.

Application and areas of further research

The results of this project will be useful for Regional NRM groups needing to understand how to prioritise bank erosion remediation projects. A summary of the recommended approach is presented in Table 1. The data sets presented in this report can be deployed within cost-benefit analysis tools (such as INFFER) so that bank erosion remediation can be considered alongside other threats such as gully and hillslope erosion.

Evaluating the impact of land use on bank erosion is challenging in the GBR catchments. This is due to a number of factors. Firstly, the natural rates of bank erosion in these large tropical systems are very variable, therefore the impact of human disturbance is difficult to detect. Secondly, there have been no specific studies investigating the link between land use change and increased rates of bank erosion. Thirdly, the bank erosion rule used in the catchment models does not represent all forms of bank erosion (e.g. avulsion and anabranching systems are not explicitly considered). Therefore it is difficult to use this tool beyond general risk assessments at the sub-catchment scale. Finally, where there is clear evidence for increased bank erosion, there have been no studies to demonstrate the effectiveness of various remediation options on reducing bank erosion and improving water quality delivered to the GBR. Further work in these areas is urgently needed to support and justify future spending on bank remediation.
### Table 1: Synthesis of the approach recommended for management of stream bank erosion in the GBR catchments. Note that this approach may not apply in extreme event conditions (e.g. 1 in 100 year events). Approximate scale references: catchment (~100,000 km²); sub-catchment (~1,000-50,000 km²); reach (~1-10 km)

<table>
<thead>
<tr>
<th>Step</th>
<th>Question</th>
<th>Approach and scale</th>
<th>Tool or technique</th>
<th>Answer or Outcome</th>
<th>Who will do this</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Do you have a bank erosion problem?</td>
<td>As channel erosion is a natural process, it is important to identify that the erosion that is being observed is due to anthropogenic disturbance and not just a natural process of channel evolution. Scale: sub-catchment to catchment</td>
<td>Isotope tracing and/or dating techniques are best suited here. Channel sediments have a different (radionuclide) signature to hillslope sediments. The ratio of this signature may have changed over time, and may be detectable in sediment or coral/marine cores. Catchment models also provide an estimate of the anthropogenic contribution of sediment sources (however, these estimates have not been independently validated). Aerial photo and LiDAR analysis can also be useful in some cases.</td>
<td>If there is no evidence for excess erosion, continue with sustainable management practices (consider protecting the site under Step 5). If there is evidence for excess anthropogenic sediment, move to Step 2.</td>
<td>These are research questions to be undertaken via R&amp;D</td>
</tr>
<tr>
<td>2</td>
<td>Has bank erosion increased everywhere, or are there hotspots?</td>
<td>Identify and prioritise the management units (or sub-catchments) that have excess anthropogenic sediment. Scale: sub-catchment to catchment</td>
<td>At the scale of the GBR, the only practical approach here is to use catchment models. These outputs should be validated against field visits/data where-ever possible. This is because processes such as channel incision (e.g. downstream of dams or near sand extraction) will not be represented in the models.</td>
<td>This will provide a priority list of basins for erosion control.</td>
<td>Provided in Table 2 in this report.</td>
</tr>
<tr>
<td>3</td>
<td>What is the cause of the increased bank erosion?</td>
<td>Bank erosion may increase due to removal of riparian vegetation. It may also increase due to increased stream power following changed hydrology (from agricultural development) upstream. Scale: reach to sub-catchment</td>
<td>Closely assess the site using Google Earth and ancillary data sets to check that there is a good understanding of the erosion processes (described in Section 2). If the riparian zone is non-existent or impaired (e.g. by stock access), it is likely to be the main driver of the bank erosion. If it is in-tact over a large length, then the channel may be incised resulting from downstream or prior disturbance, or excess runoff upstream.</td>
<td>Classify the sites based on the driver of erosion.</td>
<td>Regional bodies in collaboration with research groups. Guidance for this approach provided in this report.</td>
</tr>
<tr>
<td>4</td>
<td>What are the remediation (erosion control) options?</td>
<td>Identify a range of remediation options depending on the main cause of erosion. Scale: reach</td>
<td>If poor riparian vegetation is the main cause of erosion, then fencing and revegetation is an obvious strategy. If the vegetation is in-tact, but the bank is still eroding, then evaluate the impact of land use upstream and downstream. Reducing runoff (e.g. using GLM methods) may be warranted.</td>
<td>Examples of the approach are provided in this report.</td>
<td>Regional bodies in consultation with local advice from soil conservation, agricultural service, revegetation consultants (or equivalent).</td>
</tr>
<tr>
<td>5</td>
<td>Is the remediation cost-effective?</td>
<td>It may be that erosion control is possible (e.g. riparian fencing and revegetation), however, it may not be cost effective. That is, the cost of the works may outweigh the benefits of the work. Scale: reach (linking to sub-catchment)</td>
<td>Evaluate the cost-benefit of each of the options and rank/prioritise sites. It is important that areas that are not currently eroding, but that warrant protection due to the potential for erosion (e.g. high stream power or erodible soils), are included in this assessment. Information on the effectiveness of bank erosion remediation is scarce. Data from a limited number of studies is provided in Table 4.</td>
<td>Prioritise and rank sites within each management unit (sub-catchment). Table 8 in this report provides a more detailed guide to the logic of choosing sites.</td>
<td>Regional bodies as part of the INFER process within the WQIP. Additional data on the effectiveness of remediation options is required (which is in the R&amp;D domain).</td>
</tr>
<tr>
<td>6</td>
<td>Was the remediation effective?</td>
<td>Once the works are implemented, adequate documentation, monitoring and evaluation (M&amp;E) is required to determine if the remediation was effective and by how much. Scale: reach and sub-catchment</td>
<td>There are three types of evaluation/documentation. Determine if: (i) the project was actually implemented according to the plan; (ii) the project met the physical objective (e.g. did riparian cover increase by 50%?) (iii) the project had a positive impact on erosion locally and water quality offsets.</td>
<td>Adequate M&amp;E will provide a better understanding of which approaches are effective at reducing sediment delivery to the GBR.</td>
<td>(i)Landholder and Regional Body (ii) Regional Body or extension officer (iii) Not necessary at all sites, but must occur at ~10% of sites. Should be carried out by R&amp;D organisations in collaboration with Regional bodies.</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Background

The Great Barrier Reef (GBR) is recognised internationally as a place of exceptional biodiversity and as a result it was listed as a World Heritage Area in 1981. The GBR is also one of Australia’s greatest natural assets and contributes an estimated AUS $5.4 billion per year to the Australian economy (Access Economics Pty Ltd, 2009) through tourism and commercial and recreational fishing. Despite the high ecological and economic value, the last decade has seen increased evidence for declining reef health (DeVantier et al., 2006; Cooper et al., 2008; Bruno et al., 2009; De’ath et al., 2009; Fabricius et al., 2010). The declining condition of the GBR is considered to be the result of a combination of factors including over-fishing, coral disease, climate change and poor water quality from agricultural land uses (Hughes et al., 2007; De’ath et al., 2009; Brodie et al., 2012). The specific water quality constituents of concern to marine health are nutrients (nitrogen and phosphorus), chemicals (pesticides) and fine sediment (Fabricius, 2005; Brodie et al., 2008; Wooldridge, 2009).

Suspended sediment plays an important role in freshwater and marine biogeochemical processes and food webs (Wood and Armitage, 1997; Krumins et al., 2013), however, there is general agreement that increased sediment from agricultural regions is impacting on the GBR (De’ath et al., 2012) and other adjacent habitats such as seagrass beds (Waycott et al., 2005). Prior to remediating the anthropogenic sediment sources, it is necessary to understand the sources, processes and type of sediment being delivered from agricultural regions.

The grazed rangeland catchments in the GBR are considered to be the dominant source of the anthropogenic sediment load to the GBR (Kroon et al., 2012). There are three dominant processes delivering the excess sediment including hillslope, gully and bank erosion. Wind erosion is not considered a major source of sediment to the GBR catchments. For over a decade, hillslope erosion has been considered the dominant process driving sediment delivery in the GBR (Prosser et al., 2001a). However, recent radionuclide tracing studies across Northern Australia suggest that channel (gully, scald and bank) erosion is the dominant source of sediment delivered to marine systems from adjacent catchments (Tims et al., 2010; Hancock et al., 2013; Olley et al., 2013; Wilkinson et al., 2013). Based on these tracing studies, bank erosion is estimated to contribute ~30% of the end of catchment sediment in the large dry tropical streams such as the Burdekin and Fitzroy catchments (Wilkinson et al., 2015) and closer to 40% in the wet tropics streams (Hateley et al., 2014) that do not have extensive gully erosion. However, the proportional contribution from bank erosion can vary spatially within and between catchments, and in many areas it is not clear whether the rate or amount of bank erosion has increased significantly with agricultural development. The specific particle size considered to be of greatest threat to the GBR is the 4-16 µm particle size (fine to very fine silts) that is transported >1 km offshore (Bainbridge et al., 2012).

There is a great deal of knowledge about how to manage hillslope erosion in GBR catchments (e.g. Ash et al., 2001; Silburn et al., 2011). There is, however, little information on how to manage bank erosion in the rivers and streams of the GBR. Even less information is available on the relative costs and benefits of remediating these erosion sources. A companion report (Wilkinson et al., 2015) will deal with issues related specifically to gully erosion. This report will deal specifically with issues related to bank erosion.

1.2 NRM Regions

To deal with the issue of poor water quality from agricultural land use, the Reef Water Quality Protection Plan, and Reef 2050 Long term sustainability plan, involves identifying priority locations for on-
ground investment of remediation options that will result in a reduction of constituent loads to the Great Barrier Reef (GBR). The funding for on-ground remediation works is delivered from Federal and State Government managed programs by the Regional bodies. These Regional bodies represent the five NRM regions in the GBR (Cape York, Wet Tropics, Burdekin, Mackay Whitsundays, Burnett-Mary) (Figure 1). The prioritisation process is largely coordinated as part of the Water Quality Improvement Plans (WQIP) in each of the regions.

To prioritise sites for remediation, Natural Resource Managers must understand the threats they are trying to manage, but increasingly they also need to estimate of the costs and benefits of the remediation in economic terms. This allows for a comparison between competing threats using decision support models (e.g. Hajkowicz et al., 2005; Pannell et al., 2012; Barson et al., 2014).

**Figure 1: Location of GBR Regions and sub-catchments or management units within regions**
1.3 Aims and objectives

The aim of this report is to provide information to technical officers within the Regional bodies as well as to Federal agency staff responsible for the delivery of on-ground remediation programs in the GBR region. This report will:

i. Review the processes driving stream bank erosion (Section 2)

ii. Based on the latest outputs from the Source Catchments model, which represent the key processes driving bank erosion, identify the relative contribution of stream bank erosion across the GBR (Section 3)

iii. Discuss the issues that need to be taken into consideration prior to undertaking remediation. These include the potential remediation options, effectiveness, estimated time lags and monitoring and evaluation needs (Section 4)

iv. Identify which management actions will be most cost-effective in managing bank erosion, and the options for delivering the funding for on-ground management (Section 5)

v. Using the information provided in components (i) to (iv) above, provide examples of how to identify sites for remediation using multiple data sets (Section 6)

The purpose of this report was not to identify specific areas for remediation. Prioritising areas for on-ground works is conducted by the Regional bodies, and bank erosion is only one erosion process that needs to be considered. Instead, this report is to help support and guide the decision makers and managers and help them use scientifically robust information. In many cases, Regional bodies may need to call on expert advice to help with specific activities such as designing remediation activities for a specific site.

It is acknowledged that riparian zones have many positive benefits in the landscape. These include reducing the runoff of sediments (Herron and Hairsine, 1998; McKergrow et al., 2004b; McKergrow et al., 2004a; Parkyn, 2004) and nutrients (Osborne and Kovacic, 1993; Rassam et al., 2006), improving water quality (Olley et al., 2014), providing shade, habitat and temperature control for in-stream ecology (Pusey and Arthington, 2003) and as a wildlife corridor for terrestrial fauna (Martin and McIntye, 2007). Riparian zones provide important ecological functions at local (Bunn et al., 1999) and regional scales (Bardgett et al., 2001; Munro et al., 2007). We acknowledge the multiple benefits of riparian zones in catchments, however, this report will deal specifically with riparian zones in the context of reducing the amount of stream bank erosion delivered to the GBR.

1.4 Contracted deliverables

This report represents the primary deliverable for the Department of Environment project titled ‘A handbook on stream bank management’ (Procurement Number 1314-0625). The aim of this report is to assist in the design of on-ground stream bank stabilisation projects and to help prioritise future research and extension activities. This report will be accompanied by a number of presentations to GBR Regional bodies and Department of Environment staff in Canberra.
2 A review of processes driving bank erosion

2.1 Evaluating the source of sediment: the sediment budget concept

A sediment budget is a method of accounting for the sources and sinks of sediment as it travels from its point of origin to its eventual exit from a drainage basin (Slaymaker, 2006). Sediment budgets for all of the catchments on the GBR coast of Australia have been developed using computer models (McKergow et al., 2005) to help identify the dominant sources of erosion. Using these models, the dominant sources of sediment are bank, hillslope and gully erosion (Figure 2). Ideally modelled results should be supported by data, however, developing sediment budgets from measurements can take years to decades even for very small areas (e.g. Bartley et al., 2007). This report only deals with the bank erosion component of the sediment budget.

Not all sediment that is eroded from a bank is exported to the GBR. Fine sediment (e.g. clays ~4 µm) eroded from streambanks will generally remain in suspension or solution until the runoff event stops. In large tropical monsoonal events, fine sediment is likely to be exported a long way from the original erosion source. Coarser sediment fractions (e.g. 63 µm) may only be transported a short distance from the original erosion location. The specific distances that the sediment will be transported are related to the length and timing of the event and the channel morphology (which dictates opportunities for deposition). Sediment eroded from catchments closer to the coast have a higher chance of being exported to the coast than from areas further inland. The sediment erosion and deposition algorithms used within the modelling frameworks, including the dam trapping algorithm, are described in Wilkinson et al., (2010) and Ellis and Searle (2014), and will not be presented in this report. The bank erosion export values or rankings presented in this report have accounted for deposition within the stream network. Particle size is not specifically considered in the report, and any reference to sediment load is total sediment load (fine + coarse sediment).
2.2 What is bank erosion?

Stream bank erosion is the common term used to describe the erosion of the channel boundary in river systems. Bank erosion and channel change have been studied in considerable detail along many channel reaches around the world, and reviews on this subject can be found in Hooke (1980), Lawler (1993) and Millar (2000). This section will briefly review the key processes driving bank erosion. It is important to understand the processes that drive bank erosion, so that we can understand both the cause (e.g. vegetation removal) and symptoms (e.g. erosion) of channel change. Treating the erosion symptom, without treating the cause, is not an efficient use of resources.

Bank erosion is a natural processes that occurs even in densely forested systems (Rozo et al., 2014) and are integral to the functioning of river ecosystems (Pusey and Arthington, 2003). Bank erosion is a
2.3 How do banks erode?

Stream bank erosion occurs by three mechanisms: mass failure (collapse of stream banks), fluvial scour, or by erosion when the bank is exposed to the air (subaerial erosion) (Abernethy and Rutherfurd, 1998b). In general, bank erosion in the streams of the GBR occurs as a result of meander migration (where there is erosion on the outside, concave bank), channel widening or incision (where there is erosion on both banks), or channel avulsion (formation of a new channel). Each of these processes has both an erosion and deposition component, however, the erosion processes are the main focus of this study.

Depending on the processes driving bank erosion outlined above, there are several physical ways that a bank can erode or fail. Bank erosion in upper reaches is controlled by sub-aerial preparation, in mid-basin reaches by fluvial entrainment, and in the lower reaches by mass failure (Lawler, 1992; Lawler, 1995; Abernethy and Rutherfurd, 1998a). Sub-aerial processes are often viewed as 'preparatory' processes, weakening the bank face prior to fluvial erosion (Couper and Maddock, 2001). Plants interact with and modify sub-aerial processes of streambank erosion by altering bank hydrology, flow hydraulics and bank geotechnical properties (Abernethy and Rutherfurd, 2000a). Fluvial entrainment which includes processes such as meander migration and fluvial scour is an important process contributing to bank erosion (e.g. Martin et al., 1986; Williams, 1986; Nanson and Croke, 1992; Micheli et al., 2004). Mass failure often occurs where bank height exceeds a critical value for the boundary material (Lawler, 1992; Abernethy and Rutherfurd, 1998a), and Simon (2014) determined that banks greater than 26° are more vulnerable to mass failure and erosion on the Burnett River, Queensland. Others authors (e.g. Dapporto et al., 2003) determined that banks erode at slopes considerably steeper than 26°. Hubble et al., (2010) conducted a review which shows that the presence of riparian forest on riverbanks significantly reduces the likelihood of erosion by mass failure due to reinforcement of riverbank soils by tree roots. This results in a narrower channel cross-section in reaches with vegetation.

2.4 What are the drivers of bank erosion?

Stream banks erode because the forces applied to particles and aggregates of sediment exceed the forces resisting movement. The forces applied to sediment are gravity (pulling particles and aggregates down) and the force of water flowing down or across the bank (fluvial scour). The factors that increase the resistance of stream banks to these forces include the size of the particles, the cohesion of the sediment (produced by the clay in the banks), the matrix suction of the banks by water, and the 'apparent' cohesion provided by the roots of vegetation. Vegetation can also directly protect the banks from the force of flowing water. Thus, if transporting forces exceed resisting forces, the bank erodes.

Erosion rates will be increased if force is increased and resistance reduced. By understanding the distribution of force and resistance in streams we will be better able to manage erosion. Many of these force and resistance factors vary systematically through a river system, producing distinct patterns of erosion. For example, Walker and Rutherfurd (1999) and Rutherfurd (2000) conducted a global review of river bend migration data and determined that stream power and bankfull discharge were the most important predictors of bank erosion for rivers. Further work suggested that the bank material and riparian vegetation was also an important source of information required to predict bank erosion (De Rose et al., 2005), as was the accommodation space or level of channel confinement (e.g. rocky gorge vs alluvial floodplain) (Wilkinson et al., 2009). These factors were used to drive the bank erosion equation that is...
currently used to predict bank erosion in the GBR catchments (See Section 3), and will be discussed in more detail in the sections below.

### 2.4.1 STREAM SIZE

The best predictor of erosion rates (expressed as the volume of sediment released) is stream size. Larger streams tend to erode more quickly than smaller streams in absolute terms. That is, they produce more sediment per unit length of stream. This is because the height of the stream banks increases downstream, and because the overall energy of the stream tends to increase downstream (toward some peak).

### 2.4.2 STREAM POWER

Stream power is a measure of the force applied to a stream boundary, and hence is a useful indicator of bank erosion rate (Knighton, 1999). Total stream power per unit channel length \((W \ m^{-1})\) is defined using Equation 1 and specific stream power \((W \ m^{-2})\) is given by Equation 2 where \(\gamma\) is the density of water \((N \ m^3)\), \(Q\) is the bank full flow/discharge \((m^3/s)\), \(S_l\) is the energy slope \((m/m)\) and \(w\) is channel width \((m)\).

\[
\Omega = \gamma Q S_l
\]

Equation 1

\[
\omega = \frac{\Omega}{w}
\]

Equation 2

Stream power is considered an important influence over bank erosion rates due to its direct impact on channel form (Knighton, 1999; Thompson and Croke, 2013) as well as the more indirect influence on riparian vegetation (Bendix, 1999). Some studies have identified threshold stream powers (e.g. 100 N/m2 or 300 W/m2) that relate to catastrophic geomorphic change (Magilligan, 1992), however, in non-catastrophic conditions, bank erosion is controlled by a range of factors such as channel gradient, meander curvature and bank resistance (Hooke, 2007). Due to the interaction of stream power with these other variables, simple thresholds linking bank erosion to gradient or stream power are often difficult to detect (Hooke, 2007; Stacey and Rutherfurd, 2007).

### 2.4.3 VEGETATION

A major focus of bank erosion research has been the link between bank erosion and riparian vegetation. Beeson and Doyle (1995) found that bends without riparian vegetation were 30 times more likely to undergo major bank erosion than non-vegetated bends and Smith (1976) found that in cool environments with aggrading river conditions ‘heavily’ vegetated banks were 20,000 times more resistant to erosion than non-vegetated banks. Micheli et al., (2004) did a comparison of migration rates and bank erodibilities between 1949 and 1997 on the Sacramento River (USA) and found that reaches bordered by agriculture were 80 to 150% more erodible than reaches flanked by riparian forest. In Australia, Brooks and Brierley (2002) found channel erosion rates as low as 5 mm a\(^{-1}\) on the Thurra River in Victoria, and they attributed the lateral stability to the extensive woody debris on both the floodplain and in the channel.

Despite the obvious importance of riparian vegetation in controlling bank erosion, Rutherfurd (2000) documented that even heavily forested catchments can undergo catastrophic widening and channel change (e.g. the Avon and Bellingen Rivers, Australia) and Nanson and Hickin (1986) determined that for 18 Canadian rivers, bank vegetation has little significant effect in controlling channel migration.

Riparian vegetation also has different influences at different spatial scales (Curran and Hesssion, 2013), and it has different impacts on stream processes depending upon its position down a catchment (Abernethy and Rutherfurd, 1998a). The presence of riparian vegetation is useful for all types of erosion, but its specific influence may vary within the catchment. For example, in headwater areas, trees can
provide woody debris in the channel that increases the hydraulic resistance of the channel and banks. In middle reaches, the main role of riparian vegetation is to strengthen the bank substrate by tree roots. In lower reaches, where channels are often wider and banks higher, vegetation maintains steeper bank geometries. Riparian vegetation has benefits for both mechanical and hydrological processes as well as local climate and a combination of woody and grass species are likely to offer the greatest benefit in terms of bank stabilisation (Simon and Collison, 2002).

2.4.4 RIVER PLANFORM AND CONFINEMENT

The ability of a river to migrate into its surrounding landscape is an important factor for understanding the bank erosion potential of a river (Lawler, 1993; Ebisemiju, 1994; Hooke, 1995b; Gilvear et al., 2000; Ashworth and Lewin, 2012; Rozo et al., 2014). Confined or bedrock controlled channels are less likely to have high bank erosion compared to alluvial reaches with a large accommodation space. Estimates of channel confinement can be derived from digital terrain products such as MrVBF (multi-resolution valley bottom flatness) (Gallant and Dowling, 2003). This data set can help identify valley bottoms, where rivers are more likely to actively erode in deposited alluvium. It is important to note, however, that these data sets may be too coarse in some settings, and are best used at regional scales.

Many Australian rivers do not necessarily have ‘classic’ floodplain morphology, or where there are floodplains, they are relatively inactive and rarely inundated (e.g. Amos et al., 2009). In many large rivers, it is the bench features, that sit within the macro-channel, that are most active in terms of lateral erosion (Hughes et al., 2009) (see Figure 3).

Meander wavelength (or channel sinuosity), is a geomorphic planform feature of river systems that will influence the rate of channel migration (Hasfurther, 1985) and thus bank erosion. Hickin and Nanson (1975) showed that the rate of channel migration rapidly declines for bends where the ratio of radius of curvature to channel width is greater or less than 3.0. A number of studies found that rates of bank erosion varied with stages of meander development, being greatest in the middle stages of evolution and decreasing with increased sinuosity and concave bench formation (Nanson and Hickin, 1986; Hooke, 1987; Hooke and Redmond, 1992; Hooke, 1995a; Gilvear et al., 2000).
Figure 3: An example of bank erosion occurring on an inset channel bench in Keelbottom Creek (Burdekin catchment) that sits within the larger stable macro-channel.

2.4.5 BANK MATERIAL

A number of studies have found that bank erosion rate is strongly related to the grain size of the sediments (e.g. Nanson and Hickin, 1986) and the percentage of silt and clay in the banks (e.g. Hooke, 1979). Information about the resistance of eroding bank material (e.g. sediment texture and particle size) is considered important for predicting bank erosion as well as understanding the options for remediation (Walker and Rutherfurd, 1999). Predicting soil attributes accurately across large areas (i.e. 430,000 km$^2$) is challenging, however, digital soil mapping (DSM) techniques are improving our ability to map soil attributes across large areas with quantified uncertainty (e.g. Thomas et al., Accepted).

2.5 Has bank erosion changed due to land use in the GBR catchments?

There have been no studies that have specifically investigated changes in bank erosion rates for different land use, and there have been relatively few studies of bank erosion in tropical regions of Northern Australia, including the GBR catchments.

It is reasonable to suggest that where there has been a change in riparian vegetation and/or runoff that bank erosion rates are likely to have increased. This assumption is supported by a study conducted in the Daintree catchment that demonstrated that erosion rates on banks with riparian vegetation were 6.5 times (or 85%) lower than on sites without riparian vegetation (Bartley et al., 2008). However, the influence
of increased runoff and its effect on bank erosion is much harder to detect. For example, studies of streamflow records (1920-2007) using pre and post clearing river flow data in the Upper Burdekin suggest that there has been an increase in event storm flow during large rainfall events following land clearing (Peña-Arancibia et al., 2012), which would suggest larger stream powers and thus higher bank erosion. However, a study by Bainbridge (2004) over a similar time period, estimated that the Upper Burdekin has some of the lowest bank erosion rates in the world (0.03% of channel width). The Upper Burdekin river experiences extreme discharges due to the monsoonal climate (Fielding and Alexander, 1996), and given that the channel is locally incised into Palaeozoic bedrock (Wohl, 1992), the channel is naturally able to accommodate very large flow events. Therefore although within channel benches may be eroded periodically (e.g. Figure 3), the change in runoff due to land use has not been significant enough to detect an increase in bank erosion of the macro-channel. It is also possible that this change is significant, but there is a time lag between the land use change and the system response, and the channel has yet to express this change in the form of excess erosion.

There is evidence to suggest that bank erosion rates in tropical rivers vary widely. For example, the highest meander migration rates in Australia have been measured on the Daly River in the monsoonal tropics (~20 m of migration per year between 1969 and 1983) (Vertessy, 1990). Importantly, the Daly River has relatively low land use intensification (compared to Southern Australia), so these high rates are likely to be natural and related to the naturally high runoff in this catchment. Conversely, Saynor et al., (2006) determined that bank erosion in the Alligator Rivers region was more active on smaller headwater channels, and less significant on larger channels. The most significant bank erosion in the GBR catchments appears to be related to extreme events, and channel incision, such as in the Burnett Mary region in 2011 and 2013 (Simon et al., 2014).

In summary, bank erosion rates can vary considerably within and between catchments. Bank erosion is likely to be higher on sites without riparian vegetation, however, other factors such as stream size, location, geomorphic structure and discharge are also important.

**Key points**

- Based on a global review of river bend migration data, stream power, riparian vegetation, bank material and level of channel confinement are considered the most important attributes for predicting bank erosion.
- Bank erosion in upper reaches is dominated by sub-aerial preparation, in mid-basin reaches by fluvial entrainment or meander migration, and in the lower reaches by mass failure.
- Riparian vegetation has different influences at different spatial scales and it has different impacts on stream processes depending upon its position down a catchment.
- The presence of riparian vegetation on stream banks significantly reduces the likelihood of erosion by mass failure due to reinforcement of stream bank soils by tree roots.
- There have been no studies that have specifically investigated changes in bank erosion rates for different land use in Northern Australia, and existing bank erosion studies suggest that natural bank erosion rates vary widely.
3 The pattern of stream bank erosion in the GBR catchment

Now that we have discussed the processes that control bank erosion, we can identify the pattern of bank erosion in the catchments of the GBR. The catchment area draining to the GBR is ~430,000 km², and bank erosion rates have been measured on a very small proportion of this area (discussed in 2.5). As it is impractical to obtain long term measured estimates of bank erosion or channel change on even a small percentage of the stream network, we need an alternative approach for assessing bank erosion risk. Models that encompass many of the processes driving bank erosion (described in Section 2.4), are commonly used to determine the relative contribution of bank erosion and identify areas that may be susceptible to higher than natural rates of bank erosion. It is important to be aware, however, that models are a representation of reality and they don’t necessarily consider all of the processes that may contribute to bank erosion or effectively accommodate all of the site specific attributes.

3.1 Modelling approaches used to identify bank erosion

3.1.1 CATCHMENT SCALE

Over the last decade, the main model that has been used to estimate bank erosion rates in the GBR catchments is the eSourceCatchments model (Waters and Carroll, 2013; Dougall et al., 2014) which is a derivative of the SedNet model (Prosser et al., 2001b; McKergow et al., 2005; Wilkinson et al., 2009; Wilkinson et al., 2010). The bank erosion equation in the SedNet model was based on the empirical relationships presented in Walker and Rutherfurd (1999) and Rutherfurd (2000) that used meander migration rate as a surrogate for bank erosion (as discussed in Section 2.4) (De Rose et al., 2005). The SourceCatchments model calculates a mean annual rate of bank erosion (t/yr) as a function of riparian vegetation extent, bank erodibility and retreat rate (see Appendix A). Mean annual bank erosion is then disaggregated as a function of the daily flow (Appendix A). The bank erosion rule in the SedNet model represents bank erosion as a process of meander migration, and the inclusion of the stream power term also accommodates potential lateral incision (De Rose et al., 2005). However, bank erosion that occurs as channel avulsion or anabranching (which is often found in the smaller tidal systems adjacent to the coast) is not currently included.

The original purpose of the models were to look at the general patterns of sediment erosion, transport and deposition between catchments at the National scale (Prosser et al., 2001c). Based on the interaction of various processes driving bank erosion (as discussed in Section 2), it is acknowledged that these models (and the equations within) only provide an estimate of the relative risk of bank erosion occurring in any one reach or sub-catchment. There is the potential for large systematic errors without sufficient model calibration (De Rose et al., 2005). The size of the model links, and the scale of the data used to drive the models, can result in a high level of uncertainty at the reach scale (e.g. Bartley et al., 2008). In addition, the models provide a reach averaged estimate and don’t consider the explicit erosion process (e.g. incision vs meander migration) that can often vary within a reach, and even vary on different banks within the same reach. Despite the limitations at the reach scale, the models provide the best available approach for evaluating the relative contribution of bank erosion to the sediment budget at large (whole) catchment scales.
3.1.2 REACH SCALE

Once a region or sub-catchment has been identified as having a high (potential) rate of bank erosion, higher resolution reach scale models may be required to provide more specific estimates of the influence of vegetation and soil geotechnical properties on the bank erosion process. There are several reach scale models available for this purpose. For example Abernethy and Rutherfurd (2000a) used the physically based slope stability model GWEDGEM to assess the geotechnical properties of native Australian riparian trees on bank stability. Simon et al., (2014) used BSTEM (Bank-Stability and Toe-Erosion Model) to evaluate the contribution of bank erosion from the Burnett River catchment. Internationally, RIVMOD has been adapted to evaluate channel width increases (Carroll et al., 2004) and most recently Parker et al., (2014) developed a reach-based, stream power balance approach for predicting river channel adjustment. This approach is most similar the current SourceCatchments model, however, it is applied to stream reaches with a much higher resolution (~50 m spacing) and thus more intensive data requirements.

Each of these models generally require site specific data inputs related to the soil properties, flow velocities and local bank and vegetation morphology. They are therefore best targeted to specific reaches where there is a need to know more about the reach specific bank erosion properties (Frothingham, 2008). However, even with high resolution local field data, these models are still unable to accurately predict bank retreat and failure in all cases (Midgley et al., 2012). Again, this is likely due to the complex interaction of a range of processes controlling bank erosion in space and time.

3.2 Modelled bank erosion risk in the GBR catchments

Based on the result of the SourceCatchments modelling (undertaken by Queensland State Government, see Dougall et al., 2014), the contribution of bank erosion for each of the major sub-catchments or management units is presented as kilotonnes per year (Figure 5) and tonnes per hectare per year (Figure 6). Each of these figures also show the estimated increase in bank erosion since agricultural development (as a %). These results are summarised in Table 2 for the top 10 management units in each category. Three different metrics were used to assess the contribution from bank erosion (kt/yr, t/ha/yr and % increase). When the management units (or sub-catchments) appeared in the group for all three metrics, it was given a red status (e.g. Mary and Pioneer catchments). When a basin appeared in two groups, it was given orange status; and when it appeared in only one group, it was given green status (see Table 2).

Importantly, these rankings DO NOT provide a directive or justification for on-ground remediation. Instead, they provide a list of catchments that should undergo further assessment according to the processes outlined in Section 4. This simple analysis suggests that the Mary and Pioneer management units should under-go further investigation. According to the modelled bank erosion estimates, the Mary and Pioneer sub-catchments are likely to have elevated bank erosion rates. The East Burdekin, Lower Burdekin, Herbert, Isaac, Fitzroy, Dawson and O’Connell would also warrant further investigation.

Without further more detailed investigation, it is possible that funding could be misspent in areas that don’t actually have significant bank erosion. For example, a quick assessment of the East Burdekin River downstream of the Burdekin Falls Dam (BFD) suggests that this is a bedrock gorge with very little manageable bank erosion. The area receives very high discharges, and the channel has incised into the bedrock in this area (Wohl, 1990) (Figure 4). It is likely that the high modelled discharges are driving the high bank erosion rates for this management unit, however, in reality there are few opportunities to manage bank erosion at this site. Conversely, the Paradise Dam on the Burnett River has been shown to have adverse impacts on bank erosion rates downstream (Simon, 2014). Therefore alluvial reaches downstream of large impoundments should also be a focus of further investigation.
Table 2: Priority management units for further investigation (not remediation). Management units in each column are ranked from highest to lowest (sediment delivery from bank erosion) for each metric. Catchments in red are considered the highest priority for further investigation; then range and then green. See text above for explanation of colour scheme.

<table>
<thead>
<tr>
<th>Priority management units based on total sediment delivery (kt/y)</th>
<th>Priority management units based on unit area sediment delivery (t/ha/y)</th>
<th>Priority management units based on % increase since agricultural development</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Burdekin</td>
<td>East Burdekin</td>
<td>Boyne</td>
</tr>
<tr>
<td>Lower Burdekin</td>
<td>Pioneer</td>
<td>Styx</td>
</tr>
<tr>
<td>Mary</td>
<td>Lower Burdekin</td>
<td>Shoalwater</td>
</tr>
<tr>
<td>Herbert</td>
<td>Mulgrave-Russell</td>
<td>O’Connell</td>
</tr>
<tr>
<td>Upper Burdekin</td>
<td>O’Connell</td>
<td>Fitzroy</td>
</tr>
<tr>
<td>Isaac</td>
<td>Mary</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Pioneer</td>
<td>Herbert</td>
<td>Comet</td>
</tr>
<tr>
<td>Fitzroy</td>
<td>Johnstone</td>
<td>Mary</td>
</tr>
<tr>
<td>Bowen-Bogie</td>
<td>Don</td>
<td>Isaac</td>
</tr>
<tr>
<td>Dawson</td>
<td>Tully</td>
<td>Dawson</td>
</tr>
</tbody>
</table>

Figure 4: A reach downstream of Burdekin Falls Dam identified by the models as having high bank erosion risk, but in reality the channel is incised into a bedrock Gorge with little obvious bank erosion.
Figure 5: Exported sediment contributions from bank erosion in each management unit within the GBR (Kt/y), with % increase from pre-development conditions in brackets.
Figure 6: Exported sediment contributions from bank erosion in each management unit within the GBR (t/ha/y), with % increase from pre-development conditions in brackets.
Key points

- Models are commonly used to determine the relative contribution of bank erosion, however, models are a representation of reality and there is a high degree of uncertainty when used at the reach scale.

- The bank erosion process modelled using SourceCatchments is an estimate of the potential contribution from bank erosion. Banks can also erode from channel avulsion, sand and gravel extraction and downstream of dams. These processes are not currently explicitly represented in the models.

- An evaluation of modelled bank erosion risk across the entire GBR region suggests that the Mary River and Pioneer sub-catchments (or management units) should undergo further investigation as the models suggest it is likely that bank erosion is a major source of sediment in these catchments. The next sub-set of catchments that should be examined in closer detail include the East Burdekin, Lower Burdekin, Herbert, Isaac, Fitzroy, Dawson and O’Connell.

- Importantly, remediation should not be initiated in any catchment without further evaluation that bank erosion is actually a problem in the catchments. Preliminary assessment of some management units suggests that the models may have incorrectly identified some high risk areas. Conversely, some areas not considered to have a high bank erosion risk based on the model, may in-fact have sites suitable for remediation.
4 Remediation approach, options and effectiveness

Section 2 discussed the processes driving bank erosion and Section 3 describes which of the GBR catchments are likely to have the greatest prevalence of bank erosion. This section now discusses some of the issues that should be considered prior to remediation of riparian areas. There is an enormous amount of literature and guides on ‘how to do’ river restoration (e.g. Newbury and Gaboury, 1993; Rosgen, 1994; Raine and Gardener, 1995; Rutherfurd et al., 2000; Lovett and Price, 2001; Bennett et al., 2002). This section provides an overview of these processes only, and readers are encouraged to consult the general rehabilitation literature for more detail.

4.1 Considerations for remediation

The first rule of rehabilitation is to avoid the damage in the first place (Bernhardt and Palmer, 2011). “It is easy, quick and cheap to damage natural streams. It is hard, slow and expensive to return them to their original condition. Usually, we are not capable of returning anything approaching the subtlety and complexity of the natural system. For this reason, the highest priority for stream rehabilitators is to avoid further damage to streams especially streams that remain in good condition” (Rutherfurd et al., 2000).

Once vulnerable intact areas have been protected, prior to embarking on any active remediation works, it is important to decide if remediation is actually necessary (Holl and Aide, 2011). This is because there are numerous examples of ecosystems recovering over a period of decades without human intervention (Jones and Schmitz, 2009). Deciding not to actively remediate an area does carry large uncertainties, and it is best used when there is evidence that other streams in the same region have recovered naturally (Smith and Turrini-Smith, 1997). However, given the scarcity of monitoring data available from large and expensive remediation activities (e.g. Table 4), the ‘do nothing’ approach would carry no additional risk in many circumstances. An example of a do-nothing case may be where there is local evidence of bank erosion, but the evidence that the bank erosion has significantly changed due to human land use is poor (i.e. it may be located on a large meander bend with high stream powers).

If you decide that remediation is necessary, it is important to understand how much your river has changed over time (Piegay et al., 2005) and the amount of sediment that bank erosion is currently contributing to end of catchment sediment budgets (Bartley et al., 2007; Palmer et al., 2014). The underlying processes or causes governing the erosion need to be understood to ensure that restoration projects meet their goals, and adverse effects are prevented (Feld et al., 2011; Schirmer et al., 2014). As well as understanding the processes occurring at the site to be restored, it is critical that this information is evaluated within a whole of system or catchment context as several studies have demonstrated that site-scale restoration measures are likely to be unsuccessful if the sub-catchment physical habitat upstream is degraded (Feld et al., 2011; Sheldon et al., 2012; Lorenz and Feld, 2013).

Finally, resources should preferentially be allocated to sites where ecosystems are sufficiently resilient, but where degradation or the landscape context is inhibiting natural recovery, rather than sites which are likely to recover with no or minimal intervention (Holl and Aide, 2011).
4.2 Know your catchment – is there a bank erosion problem?

Before embarking on any restoration, it is critical to ask a number of questions to help determine if you (a) have a bank erosion problem and (b) what some of the options are for remediation. It is important to note that these questions may be outside of the domain expertise of many regional catchment groups, and require relatively sophisticated research approaches (e.g. sediment tracing and dating) to unravel some of these questions. In most cases, experts would be required to address these questions, however, they are an important first step in understanding if there is a bank erosion problem, and they are therefore discussed in this section (see also Table 1).

Has the stream actually changed since European settlement? i.e. is there more erosion than expected?

It is acknowledged that certain conditions (e.g. high slope, high rainfall, low vegetation, geology and soil type) will produce higher sediment yields from catchments even in the absence of agricultural land use change. Without an understanding of the natural susceptibility of a catchment to erosion, remediation resources may be incorrectly allocated to areas that appear to be producing high sediment yields, when in fact they have landscape attributes that generate large volumes of sediment even in the absence of agriculture. For example, recent tracing studies suggest that sub-surface erosion is a dominant source of sediment to the GBR (Hancock et al., 2013; Wilkinson et al., 2013), however, the ratio of sediment from sub-surface erosion is similar for sites with very different management histories (Wilkinson et al., 2013). Therefore it is not clear whether the rate or amount of bank erosion has increased significantly since European settlement, and it is possible that channel erosion has always been the dominant source of sediment in some areas; even in the absence of agriculture. Undertaking a large bank erosion restoration campaign would not be sensible in areas that have naturally high rates of bank erosion.

When there is evidence for anthropogenically caused erosion, what has changed (e.g. land-use, riparian vegetation, runoff)?

It is important to get a better understanding of the factors that are driving the high erosion so you can treat the cause as well as symptoms. It is important to isolate the factors that management can control (e.g. vegetation) versus factors that are largely out of management control (e.g. channel slope). To help understand the processes driving bank erosion in your catchment, it is useful to map information such as stream power, vegetation, sinuosity, floodplain location and width, bed and bank material attributes (e.g. particle size). In some cases, regional scale data will be sufficient. In other cases, local data will need to be collected (e.g. Bartley et al., 2008). If available, it is also useful to have metrics such as stream order (noting that often the small headwater streams are not included in these analyses). In some areas high resolution LiDAR data may be available. If LiDAR is available, it would be useful to map channel width, bank slopes and width-depth ratios. An understanding of the flood frequency, and specifically the recurrence interval of the

---

**Box 1: Further reading**

bankfull event, will also be useful for estimating project risk. For example, if a site to be remediated is going to have active revegetation planted along the bank, the vegetation will have a better chance of success if the bankfull recurrence interval is greater than 5 years. This would mean a higher probability of time between events for juvenile vegetation to establish.

4.3 Remediation options

4.3.1 REDUCING RUNOFF

As described in Section 4, remediating isolated sections of stream bank are not going to effective, or as effective, if the upstream areas are highly disturbed. This is because stream power is one of the most significant factors driving bank erosion rates. Runoff is a component of stream power, and therefore reducing the amount of runoff and stream power at a given site, will, in theory, reduce the amount and rates of bank erosion at high risk sites. It will also improve the success of any remediation. Runoff, or the amount of water that runs over the surface and into rivers following rainfall events, will generally be higher in areas that have been disturbed and have low vegetation than in areas that are in good condition (Bartley et al., 2006; Thornton et al., 2007).

Despite our understanding of the effects of clearing vegetation, there have been very few studies that have evaluated the effectiveness of increasing or enhancing the amount of vegetation cover on catchment run-off (Wilcox et al., 2008; Bartley et al., 2014). Studies in the Burdekin and adjacent Fitzroy watersheds have found that increasing ground cover generally increases the amount of rainfall required to initiate runoff (Connolly et al., 1997; Bartley et al., 2010) and reduces peak discharges (Ciesiolka, 1987). Extrapolation of such data using water balance modelling suggests that the most effective revegetation strategy, in terms of runoff reduction, was to increase cover levels modestly across the whole watershed rather than to revegetate small areas intensively (Connolly et al., 1997). Although the measurable effect of improved vegetation on stream runoff will be challenging to quantify in tropical systems (Cook et al., 2011), it should be considered as a first step in improving bank erosion rates within a catchment.

4.3.2 PASSIVE FENCING

Due to the large size, limited access, and remoteness of many catchments draining to the GBR, it is likely that fencing off of riparian areas, and removing stock access, will be the only economically viable option for many sites. In practice, however, these same factors will also make fencing more difficult and costly.

In riparian zones, grazing decreases erosional resistance by reducing vegetation and exposing more vulnerable substrate (Trimble and Mendel, 1995). Studies by Robertson and Rowling (2000) demonstrated that seedlings and saplings of dominant Eucalyptus tree species were up to three orders of magnitude more abundant in areas with no stock access, and the biomass of groundcover plants was an order of magnitude greater in areas with no stock access. This suggests that natural regeneration of native vegetation is possible once cattle are removed by fencing off riparian zones. There is also evidence from streams in the Wet Tropics of Australia that considerable natural revegetation can occur with changes to farming practices. For example, reduced burning of sugarcane has reduced wildfire outbreaks and resulted in a net increase of riparian forest vegetation of 22 ha in the Mossman Catchment between 1944 and 2000 (Lawson et al., 2007).

Riparian fencing on its own, without active revegetation, has been shown to reduce stream suspended sediment (SS) loads by ~40% (Owens et al., 1996). The sediment reductions appear to be due to decreased stream bank erosion. Generally, once cattle are excluded from riparian areas there is a rapid transition from a wide, shallow stream with an unstable bed and heavily grazed and trampled banks, to a
stream with more stable, vegetated banks (Howard-Williams and Pickmere, 2010). Grazing has a greater potential to cause damage in the smaller streams simply because of low stream banks and shallow depths, and animals have easier access at many points (Williamson et al., 1992). On larger channels, with more active meandering, and higher steeper banks, fencing off a riparian zone has comparatively little benefit because any grazing effects are rapidly overtaken by channel migration (Williamson et al., 1992). However, the higher steeper banks may contribute more sediment per unit length, and although cattle may not directly impact the banks, they would indirectly influence vegetation establishment, which is important for root reinforcement.

It is difficult to be prescriptive about how wide a riparian buffer should be at any one site. Some studies suggest research needs to focus on buffer widths that are within the range that landowners are likely to "give up" in the name of water quality protection (Lyons et al., 2000). However, this approach may not reach the ecologically acceptable water quality targets required by the GBR (Kroon et al., 2014b). A review by Parkyn (2004) suggest that grass buffer strips of ~30 m will be effective at removing pollutants (sediments and nutrients from adjacent agricultural lands), however, the width required to reduce active channel erosion is generally considered a function of potential meander migration (Walker and Rutherfurd, 1999). Using the approach presented in Abernethy and Rutherfurd (1999; 2000b) that assumes a channels migrate at ~1.6% of channel width per year, it is possible to come up with a rough guide for the width of an effective riparian buffer (Equation 1). Importantly, this estimate is based on data from around the world, but is biased towards temperate systems. Tropical systems are likely to have higher natural migration rates (e.g. Vertessy, 1990), and therefore more information on channel migration rates in tropics systems would help refine this approach for tropical systems. Examples of how this metric can be applied will be presented in Section 6.

\[
1.6\% \times \text{mean channel width (m)} \times \text{tree establishment rate (years)}
\]

Alternative guides to riparian zone buffer width are presented in Lovett and Price (2001) that suggest that riparian width should be scaled to stream order in rangeland areas, and between 25-50 m wide in cropping regions (Table 3). Other studies that have evaluated effectiveness of riparian restoration suggest that sites > 1 km length were most effective (Feld et al., 2011). Other important considerations for all fencing projects include stock access, feral animal (pig) damage, weed maintenance and flood management. It is not an option to ‘fence and forget’ riparian zones. They will require active maintenance and management.

<table>
<thead>
<tr>
<th>Stream order</th>
<th>Recommended riparian buffer width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streams in sugar growing areas</td>
<td>25</td>
</tr>
<tr>
<td>Rivers in sugar growing areas</td>
<td>50</td>
</tr>
<tr>
<td>1-2</td>
<td>50</td>
</tr>
<tr>
<td>3-4</td>
<td>100</td>
</tr>
<tr>
<td>5-6</td>
<td>200</td>
</tr>
</tbody>
</table>

### 4.3.3 RE-VEGETATION OF RIPARIAN ZONES

In some areas, it may be important to fence off a riparian zone and actively revegetate the site rather than wait for natural revegetation. This may be suitable in severely degraded riparian zones where
there is likely to be a low natural seed base, areas where specific tree species are required for multiple riparian zone benefit (e.g. wildlife habitat corridor) or where erosion is relatively rapid and active revegetation is likely to have benefits sooner than natural vegetation regeneration.

Legacy effects of past vegetation can continue to influence water quality for many years or decades and control the potential level and timing of water quality improvement after vegetation is restored. However, the degree to which stream water quality can be managed through the management of riparian vegetation remains to be clarified in many areas (Dosskey et al., 2010). Those studies that have quantitative data on the effectiveness of riparian zones suggest that fencing off and actively revegetating streams can reduce sediment yields by up to 80% (Line et al., 2000) and in a study by McKergow et al., (2003) by as much as 90%.

In terms of prioritising areas for active revegetation a conceptual modelling exercise by Parkyn et al., (2005) shows that riparian tree planting programmes should commence in the headwaters and progress downstream to avoid nutrient yield increases. Significant sediment yield from bank stored sediment of small streams can be expected until the channel reaches the more stable, original channel width, but progressive planting may decrease the peak loads of sediment.

A number of important factors should be considered in the rehabilitation of riparian vegetation to achieve worthwhile results. These include flood disturbance, vegetation zonation, vegetation succession, substrate composition, corridor planting width, planting techniques, native plant regeneration, LWD recruitment and adaptive ecosystem management (Webb and Erskine, 2003). In many areas a combination of trees and grass is considered optimal as they both play different but complimentary roles. For example, grassy vegetation in riparian zones is generally better than trees at assimilating phosphorus (Lyons et al., 2000), however, the root reinforcement properties of large trees are important for reducing bank failure (Abernethy and Rutherfurd, 1998b).

There is very little quantitative evidence describing the risks associated with re-vegetation, however, an understanding of the flood frequency of a given site is most likely the best indicator of potential revegetation success. Determining the flood frequency of a site can be undertaken using sophisticated hydraulic modelling if there are stream gauges near the reach (Thompson and Croke, 2013), or it could be as simple as asking the local landholder how often their paddock goes under water. If a site is regularly inundated, the chance of tube-stock and seedlings being stripped out by flood events is high. However, in severely eroded areas, flooding should not preclude the remediation of banks using vegetation, as there are many successful stories of vegetation taking hold even despite flood impact (e.g. Watson, 2009).

Tree density often peaks 15–25 years after restoration and active management of the riparian zone such as weed control should occur for at least 10 years following initial setup (Lennox et al., 2011). Local expert knowledge should be sort when establishing a riparian zone (Schirmer and Field, 2000; Dixon et al., 2005) and there are a lot of resources available to guide managers in this area (see Box 1).

Importantly, there is considerable evidence that riparian zones will not significantly reduce nutrient loads to streams (Line et al., 2000; McKergow et al., 2003), and in many cases nutrient yields, particularly nitrogen, will actually increase following re-establishment of a riparian zone over time (Howard-Williams and Pickmere, 2010; Connor et al., 2013).

4.3.4 ENGINEERING MODIFICATION

In many parts of the world, considerable resources have been spent trying to stabilise stream banks (Figure 7). In many cases, these are adjacent to bridges, roads and dams where the costs can be justified based on the value of the asset they are trying to protect. There are, however, very few publications that have appropriately evaluated the success of these expensive restoration options (Bernhardt et al., 2005). More recent studies suggest given sufficient time restoration activities such as channel re-alignment and grade control structures have been shown to meet their goals of channel stabilisation and erosion reduction (Buchanan et al., 2014). However, other studies have shown that the introduction of large woody
debris, boulders and gravel are often likely to be swamped by larger-scale geomorphological and physico-chemical effects (Feld et al., 2011).

Importantly, if expensive engineering works are to be undertaken at a site there needs to be sufficient evidence that the erosion rates are:

- considerably higher than would be expected under natural conditions;
- a major threat to an asset of significant value (e.g. highway bridge); and
- that fencing off and vegetation regeneration is not going to reduce the erosion rate significantly or quickly enough.

In all cases much higher resolution information about bank properties and hydraulic conditions at the site should be undertaken to ensure that the engineering modifications will last (Frothingham, 2008; Simon et al., 2014).

Figure 7: Examples of active hydraulic engineering structures being installed in the Murrumbidgee River (left) and near Armidale, NSW (right)

4.4 Remediation effectiveness (benefits) and time lags

There is a plethora of research documenting how beneficial riparian vegetation is for a range of processes (as documented in Section 2.4.3). There are also numerous websites dedicated to documenting progress on restoration activities (e.g. http://www.riparian.net.au/ and http://www.globalrestorationnetwork.org/). Despite the wealth of anecdotal evidence demonstrating the benefits of reinstating riparian zones, there are comparatively few studies that have quantitatively evaluated the effectiveness of increasing or returning vegetation to riparian zones on bank erosion rates. Table 4 presents a summary of available published peer reviewed studies that have documented the response of bank remediation on sediment yields, water quality or erosion rates from around the world. The table also lists the length of the study which can be used as a surrogate estimate of the time lag of effectiveness.

It is important to note that 5 of the 12 studies did not result in improved sediment yields, water quality or reduced erosion following remediation. In fact for some studies, particularly those that only ran for short time frames (~3 years), there was an increase in sediment yields following remediation (e.g. Marsh et al., 2004). This highlights the importance of preventing erosion, as once systems have changed, it is very difficult in many situations to reduce erosion rates. Where there was quantitative evidence for improved water quality and riparian condition following remediation, the response time was quite variable, ranging between 2-18 years.
It is also important to note that to achieve the improvements suggested in these studies, stock would have to be removed/excluded from the riparian zone for long periods of time. As landholders often graze these areas during drought, it is unlikely that riparian zones would have full cattle exclusion in all areas. Therefore these values should be used conservatively when estimating the potential benefit of riparian vegetation and bank remediation.
Table 4: Synthesis of channel bank remediation studies and the measured response. Studies in green had a positive response to remediation (e.g. bank erosion decreased or water quality improved). Examples in orange text did not demonstrate an improvement following remediation.

<table>
<thead>
<tr>
<th>Country</th>
<th>River</th>
<th>Type of management used to control bank erosion</th>
<th>Response following riparian improvement</th>
<th>Time frame of study</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Echidna Creek, SE Queensland</td>
<td>Trees</td>
<td>100% increase in suspended sediment yield</td>
<td>3 years</td>
<td>Marsh et al., (2004)</td>
</tr>
<tr>
<td>Australia</td>
<td>East Gippsland, Victoria</td>
<td>Trees</td>
<td>80% decrease in channel erosion</td>
<td>13-18 years</td>
<td>Hardie et al., (2012)</td>
</tr>
<tr>
<td>Australia</td>
<td>Albany, Western Australia</td>
<td>Trees</td>
<td>Reduced suspended sediment loads by 90%</td>
<td>6 years</td>
<td>McKergow et al., (2003)</td>
</tr>
<tr>
<td>UK</td>
<td>Narrator Brook, Dartmoor</td>
<td>Re-forestation</td>
<td>Increased active bank erosion, channel widths and bedload</td>
<td>50 years</td>
<td>Murgatroyd and Ternan (1983)</td>
</tr>
<tr>
<td>Denmark</td>
<td>River Skjern</td>
<td>Re-instated meanders in a previously channelized reach</td>
<td>The net result is a slightly wider and shallower river in 2011 than in 2001. There was large variation in bank retreat among transects and average bank retreat for left banks was 39 cm and 68 cm for right banks. This corresponds to a forecasted bank retreat of 3.9 m for left banks and 6.8 m for right banks over a 100 years period.</td>
<td>10 years</td>
<td>Kristensen et al., (2014)</td>
</tr>
<tr>
<td>USA</td>
<td>North Carolina</td>
<td>Livestock exclusion from streams and active tree revegetation</td>
<td>82% reduction in sediment loads, 33% reductions in nitrate/nitrite</td>
<td>2-3 years</td>
<td>Line et al., (2000)</td>
</tr>
<tr>
<td>USA</td>
<td>Ohio</td>
<td>Stream fencing and stock removal</td>
<td>With the cattle fenced out of the stream, the annual sediment concentration decreased by more than 50% and the amount of soil lost decreased by 40%. Average annual soil losses were reduced from 2.5 to 1.4 Mg/ha.</td>
<td>5 years</td>
<td>Owens et al., (1996)</td>
</tr>
<tr>
<td>USA</td>
<td>Pennsylvania</td>
<td>Fencing, stock removal, natural vegetation colonisation</td>
<td>Suspended sediments decreased by 47-87%</td>
<td>12 years</td>
<td>Carline and Walsh (2007)</td>
</tr>
<tr>
<td>USA</td>
<td>Vermont</td>
<td>Revegetation with trees</td>
<td>Between 1966 and 2004, reforested reaches widened at an average rate of 4.1 cm/year. This was attributed to a post-clearing morphological trajectory of widening and deepening</td>
<td>40 years</td>
<td>McBride et al., (2010)</td>
</tr>
<tr>
<td>USA</td>
<td>California</td>
<td>Riparian restoration with trees</td>
<td>Fine sediment and embeddement of stream channel substrate did not change indicating that these metrics may be linked to watershed processes operating at spatial scales larger than those of the typical revegetation project site.</td>
<td>0-39 years</td>
<td>Lennox et al., (2011)</td>
</tr>
<tr>
<td>USA</td>
<td>Iowa</td>
<td>Riparian forest buffers and grass filters</td>
<td>Bank retreat rates reduced by 36-87% following exclusion of livestock from grassed riparian zones, and by 59-91% following establishment of riparian forest buffers</td>
<td>3 years</td>
<td>Zaimes et al., (2008) cited in Thorburn and Wilkinson (2013)</td>
</tr>
</tbody>
</table>
4.5 Monitoring and evaluation

To determine if the restoration project is actually successful and achieved its intended goals, appropriate monitoring is required (Feld et al., 2011). Evaluation is critical to justify the use of Government funding, but also as a marketing tool to encourage other farmers to undertake remediation. A review of stream restoration projects in the US found that only 10% of projects indicated that any form of assessment or monitoring occurred. Most of these ~3700 projects were not designed to evaluate consequences of restoration activities or to disseminate monitoring results (Bernhardt et al., 2005).

It is important that any monitoring and reporting program is developed in the context of an adaptive process that is clearly linked to identified values and objectives, is informed by rigorous science, guides management actions and is responsive to changing perceptions and values of stakeholders (Bunn et al., 2010). A understanding of the expectations and attitudes of the landholders that are likely to be affected from any restoration decisions would also be sensible if there is going to be significant changes to privately managed land (Flick et al., 2010).

It is suggested that a range of quantitative metrics are collected for each project. These include information on the:

(i) Operational success of the project
   a. Did the project do what they say they would do (e.g. 5 km of fencing was paid for, and 5 km of fencing was installed)?

(ii) Social-economic success of the project
   a. What were the real costs of the project? Did it cost more/less than expected?
   b. How did the project change the landholders understanding of erosion control?

(iii) Physical and ecological water quality response
   a. Was there an improvement in measured water quality? Did bank erosion decline following remediation?

Component (iii) is often the hardest to measure as it may take considerable resources and time (as described in Section 4.4). Due to the cost, it would not be feasible to undertake a detailed monitoring and evaluation program on all remediation sites, however, there are currently no known M&E sites that are measuring the water quality response of improved land management in the GBR catchments. This means that recommendations may be being made that are not effective at reducing sediment yield, and thus Government and landholder resources are being wasted. Conversely, certain remediation options may be extremely effective, however, there is no data to support this, and therefore it is difficult to get uptake from other landholders.

Having long term water quality monitoring sites are ideal (e.g. Bartley et al., 2014), however, there are other approaches available to help determine if remediation has had an impact. For example, Buchanan et al., (2014) and Skidmore et al., (2001) suggest there are three principle restoration design frameworks that can be used to evaluate restoration effectiveness. These include an:

(1) Analog approach which adopts templates from historic or adjacent reference channel characteristics with the assumption of equilibrium between channel/catchment form and hydrologic and sediment inputs;

(2) Empirical approach which uses equations that relate various channel/catchment characteristics derived from regionalized or universal data, also with the assumption of equilibrium

(3) Analytical approach which applies hydraulic models and sediment transport relations to derive equilibrium conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium with existing or predicted sediment and hydrologic inputs.
Key points

- The underlying processes or causes governing the erosion need to be understood to ensure that restoration projects meet their goals, and adverse effects are prevented;

- The first rule of remediation is to avoid the damage in the first place. It is easy, quick and cheap to damage natural streams. It is hard, slow and expensive to return them to their original condition;

- Priority consideration should be given to smaller first and second order streams where fencing off is likely to be most effective:

- Riparian widths should be ~1.6% × mean channel width (m) × tree establishment rate (years) or if the channel is not actively migrating, then it should be a function of stream order;

- Riparian zones have been shown to work best when they are least 1 km in length and when the upstream catchment is in reasonable/good condition;

- Riparian vegetation has benefits for both mechanical and hydrological processes, and a combination of woody and grass species are likely to offer the greatest benefit in terms of bank stabilisation;

- Fencing off and revegetating riparian zones have been shown to be effective at <10 studies around the world, with improvements to sediment erosion, concentrations and/or yield in the order of 30-90%. However, there are almost as many studies suggesting that the remediation was not effective.

- Monitoring and evaluation is critical to (i) ensure that recommendations being made are actually effective at reducing sediment yield (ii) to justify the use of Government funding (iii) as a communication and marketing tool to encourage other farmers to undertake remediation.
5 Costs of remediation

Once it has been identified that bank erosion is an issue and an effective remediation option is available, it is wise to understand whether the cost of the remediation is commensurate with the benefits of the remediation. Several tools are available to Natural Resource Managers that provide an estimate of the cost and benefit of the projects in economic terms, and allow a comparison between competing threats (e.g. Hajkowicz et al., 2005; Pannell et al., 2012; Barson et al., 2014).

The INFFER™ tool is being used by all GBR catchment Regional Bodies as part of their Water Quality Improvement Plan (WQIP) process (http://www.inffer.com.au/) (Pannell et al., 2012). The WQIP’s are the main mechanism for evaluating and prioritising remediation works within each Region. To successfully implement the INFFER model requires a relatively high level of understanding of the erosion threat (e.g. bank erosion) and where that fits within the bigger picture of catchment remediation. This was discussed in Section 4.1 and 4.2. It also requires an understanding of the various options for remediation (Section 4.3), the likely costs, the likely effectiveness, time lags and risks associated with these activities (Section 4.4) and a discussion of the monitoring and evaluation considerations (Section 4.5). This section will discuss the potential cost of the remediation, and the various options for delivering the remediation funding.

5.1 Bank erosion remediation costs

The cost associated with bank erosion remediation does vary slightly between regions in the GBR. Table 5 provides an estimate for each of the primary remediation options which was based on conversations with staff at several of the GBR Regional bodies (specifically BMRG, Terrain, NQ Dry Tropics and FBA) and published estimates from the region (e.g. Lovett and Price, 2001). The costs can be adjusted if local prices vary considerably. It is assumed that for each of more expensive options (e.g. bank battering and toe revetment) that fencing off and revegetation will also occur to provide additional support to the site in terms of long term tree root reinforcement. This extra vegetation is important insurance as Miller and Kochel (2013) found that 50% of engineered structures (e.g. grade control structures and bendaway weirs) showed signs of impairment after 5 years.
Table 5: Estimated costs of bank erosion remediation options assuming a 6 m high bank with a 1 km long, 100 m wide riparian buffer (~10 ha) on a property in B condition.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Costs</th>
<th>Fence off, natural vegetation regeneration and paddock management</th>
<th>Fence off and active revegetation</th>
<th>Bank battering</th>
<th>Rip-rap or rock revetment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fencing</td>
<td>$5000/km</td>
<td>$5000</td>
<td>$5000</td>
<td>$5000</td>
<td>$5000</td>
</tr>
<tr>
<td>Production loss (assuming highly productive treed land from Table 6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A condition land</td>
<td>$387/ha</td>
<td>$3870</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B condition land</td>
<td>$203/ha</td>
<td>$2030</td>
<td>$2030</td>
<td>$2030</td>
<td>$2030</td>
</tr>
<tr>
<td>C condition land</td>
<td>$100/ha</td>
<td>$1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-site watering</td>
<td>Tank $2500</td>
<td>$8700</td>
<td>$8700</td>
<td>$8700</td>
<td>$8700</td>
</tr>
<tr>
<td></td>
<td>Trough $1200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polypipe $5000/km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance (floods/pigs/weeds)(^a)</td>
<td>$250/annum</td>
<td>$250</td>
<td>$250</td>
<td>$250</td>
<td>$250</td>
</tr>
<tr>
<td>Revegetation(^b)</td>
<td>$27,900/km</td>
<td></td>
<td>$27,900</td>
<td>$27,900</td>
<td>$27,900</td>
</tr>
<tr>
<td>Bank battering (generally for banks &gt;26(^c))</td>
<td>$100,000/km</td>
<td></td>
<td>$100,000</td>
<td></td>
<td>$100,000</td>
</tr>
<tr>
<td>Rock-revetment for toes of bank (~6 m high)</td>
<td>$5000/m</td>
<td></td>
<td></td>
<td></td>
<td>$5,000,000</td>
</tr>
<tr>
<td></td>
<td>or $5000000/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (per km)</td>
<td>$15,980</td>
<td>$43,880</td>
<td>$143,880</td>
<td>$5,143,880</td>
<td></td>
</tr>
<tr>
<td>Risks</td>
<td>Low</td>
<td>Depends of frequency of overbank events</td>
<td>Depends of frequency of overbank events</td>
<td>Moderate (~50%) loss over 5 years</td>
<td></td>
</tr>
</tbody>
</table>

Revegetation data was adjusted for inflation i.e. cost in 2001 estimated at $2010 per 100 m is ~$2790 per 100 m in 2013.
### Table 6: Loss of future income (Net Present Value/ha over 20 years) if grazing completely excluded from different condition land (based on Star and Edwards, 2013)

<table>
<thead>
<tr>
<th>Condition Description</th>
<th>A condition</th>
<th>B condition</th>
<th>C condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly productive units - treed (e.g. equivalent to Black Basalt in Burdekin)</td>
<td>$469</td>
<td>$275</td>
<td>$150</td>
</tr>
<tr>
<td>Highly productive units - treed</td>
<td>$387</td>
<td>$203</td>
<td>$110</td>
</tr>
<tr>
<td>Coolibah floodplains - treed</td>
<td>$65</td>
<td>$29</td>
<td>$6</td>
</tr>
<tr>
<td>Coolibah floodplains - cleared</td>
<td>$6</td>
<td>$0</td>
<td>$0</td>
</tr>
</tbody>
</table>
5.2 Funding delivery mechanism

The INFFER process identifies five classes of adoption of works and actions from highly attractive to highly negative. Highly attractive suggests that the practice is likely to be taken up without incentives while highly negative indicates works/actions would not be adopted without ongoing payments or strongly-enforced regulations. As INFFER suggests practice adoption is influenced by a range of factors which include costs but also factors such as riskiness, complexity, compatibility, observability, social pressures and other factors. These factors will apply to different landholders to different extents and so adoption or the response to mechanisms promoting adoption is unlikely to be smooth or continuous across landscapes and constituencies.¹

Table 7 provides an indication of the types of mechanisms that can be used to support practice change. Different mechanisms promote change in different ways. Financial incentives are useful in overcoming constraints such as cost and some aspects of risk. Moral suasion is useful in addressing factors such as social pressures. Extension and information approaches may be useful in addressing complexity. The heterogeneous nature of the feasible remediation options, barriers to adoption and effectiveness of different mechanisms in overcoming them tends to suggest that a mix of mechanisms will be required to achieve high levels of uptake. Often cost is seen as a limiting factor, at least in the sense that if there is a cost barrier this must be overcome or at least addressed before other mechanisms are likely to be effective. Because of the heterogeneity in some aspects of the system, the delivery mechanisms will usually need to be designed to allocate scarce resources towards those spatial locations that are likely to deliver the greatest benefit for the resources available.

Note that we have clearly stated resources here rather than costs – although direct payment approaches such as grants will likely mean greater costs and thus greater pressures for cost effective allocation. In this line of thinking conservation tenders and similar highly targeted approaches offer opportunities to target payments to those practice changes and landholders who are able to make the greatest reduction per unit of scarce dollars available. Such approaches need to be supported by targeted extension and information campaigns that support the desired outcomes. There will also often be an opportunity for different schemes to be effective in isolation. As an example consider a region where some landholders have stable banks due to past management while others are impacted by significant erosion. A dual purpose extension campaign may support practices that maintain bank stability while emphasising the importance of taking action to improve stability in erosive settings (potentially backed by incentives to support these potentially expensive actions). Similarly program design and implementation pathways should always identify and target the binding constraints to changing management. For example, if labour availability is the critical limit then any approach requiring additional labour from landholders will fail.

Regardless of the funding mechanism employed, there is unlikely to be a net private benefit to creating riparian buffer zones in agricultural systems. Lost production and maintenance costs (e.g. weeds/pigs) were considered in the overall cost of creating a riparian zone (Table 5). However, this compensation is unlikely to off-set the full implementation cost and maintenance for managing riparian zones (e.g. fixing fences during flooding). Therefore we doubt there will be a significant private benefit to landholders. Essentially, if there was a significant net private benefit to the landholder, they would undertake the fencing themselves now, without any financial contribution from the Government. Landholder driven riparian zones are not common in many areas, suggesting that managing riparian zones and the subsequent reduction in bank erosion along rivers is going to need considerable government investment.

¹ Caution should be exercised in arguing for required actions in highly heterogeneous settings because of either the potential for very high costs to some landholders, the very low benefits that may be delivered from some locations or both.

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Table 7: Mechanisms available to address stream bank erosion

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Motivation</th>
<th>Example of type of policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required actions (Regulatory based measures)</td>
<td>Prohibition via regulation</td>
<td>No grazing allowed on river frontage of stream order X or higher</td>
</tr>
<tr>
<td></td>
<td>Regulation with flexibility</td>
<td>Targets set (e.g. for riparian vegetation) but with flexibility allowed for meeting target</td>
</tr>
<tr>
<td>Financial incentives</td>
<td>Flat rate grants</td>
<td>Fixed grants such as a per kilometer fencing grant.</td>
</tr>
<tr>
<td></td>
<td>Cost share grants</td>
<td>Grants limited to a maximum proportion of total proponent costs.</td>
</tr>
<tr>
<td></td>
<td>Flexible grants</td>
<td>Grants that are not fixed in relation to inputs or costs (but may still have a maximum).</td>
</tr>
<tr>
<td></td>
<td>Cost reducing financial assistance</td>
<td>Rebates, local government rate rebates and similar</td>
</tr>
<tr>
<td>Non payment-based Incentive</td>
<td>Information advice &amp; support</td>
<td>Advice and assistance such as BMPs, farm planning and design support for remediation actions.</td>
</tr>
<tr>
<td></td>
<td>Security / protection of actions</td>
<td>Conservation covenants to protect actions into the future.</td>
</tr>
<tr>
<td>Moral Suasion</td>
<td>Consumer generated</td>
<td>Certification of sustainable production or similar such as “Reef Protection Certified”</td>
</tr>
<tr>
<td></td>
<td>Promotion, awards and similar</td>
<td>Reef Safe farming awards or other similar promotions.</td>
</tr>
</tbody>
</table>

5.3 Synthesis

Based on the literature presented in Section 2, and the knowledge of the relative costs associated with remediation (Section 4), there are essentially five options for remediation of erosion sources which are outlined in Table 8.
Table 8: The five options for bank remediation in the GBR catchments. This table should be used by NRM groups when trying to prioritise sites in conjunction with Table 1.

<table>
<thead>
<tr>
<th>Option</th>
<th>Issue</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>If there is no evidence for excess anthropogenic erosion and no obvious threat</td>
<td>Continue to use sustainable management practices</td>
</tr>
<tr>
<td>2</td>
<td>If there is no erosion, but the threat is identifiable</td>
<td>Address the threat if it is cost effective</td>
</tr>
<tr>
<td>3</td>
<td>There is evidence of erosion, but it appears that it will recovery on its own (self remediate)</td>
<td>Address the threat (if cost effective) but do not actively remediate, allow for natural repair</td>
</tr>
<tr>
<td>4</td>
<td>There is evidence of erosion and it is not remediating on its own</td>
<td>Address the threat and remediate the site</td>
</tr>
<tr>
<td>5</td>
<td>There is evidence of erosion and it is not remediating on its own</td>
<td>In some rare circumstances it may be appropriate and cost effective to remediate the site but not the threat (e.g. bank erosion near a major road or railway bridge caused by increased runoff from land use change upstream)</td>
</tr>
</tbody>
</table>

Key points

- Remediation is expensive. Prices will vary between locations, however, general estimates range from ~$16,000 per kilometre for fencing to over $5 million per kilometre for revetment of a 6 m high bank. The risks associated with the success of these projects are similar.
- It is important to take lost production and maintenance costs into consideration when costing remediation.
- Once it is decided that remediation is appropriate, there are several approaches available for delivering the funding including regulation, financial incentives and moral suasion.
- Overall, there are five general bank remediation options ranging from (1) do nothing if there is no erosion and no obvious threat, (2) addressing the threat if erosion is present and it is cost effective, (3) addressing the threat if erosion is present and it is cost effective, but do not actively remediate, allow for natural system repair, (4) if there is evidence of erosion and it is not remediating on its own, address the threat and remediate the site and (5) In some circumstances it may be appropriate and cost effective to remediate the site but not the threat (e.g. bank erosion near a major road or railway bridge caused by increased runoff from land use change upstream)
- It will be important to consider the investment ratio for funding riparian zones as it un-likely that there will be a private benefit to landholders
6 Case studies

In this section we will use the information provided in the above sections and apply it to two case study catchments that have very different physiographic, climatic and land use settings: the Burdekin and Daintree catchments. We chose the Burdekin catchment, as it was identified as having high bank erosion risk in Section 3.2. The Daintree catchment was not identified as high risk catchment in Section 3.2, however, it provided a case study at the other end of the land use disturbance spectrum (as 95% of the catchment is under forest). It could therefore be used to demonstrate some of the other principles discussed in this report (e.g. protect in-tact areas first). It also highlighted some of the challenges when using the catchment models in smaller management units.

We will not undertake a full cost benefit analysis as bank erosion as a threat is not likely to be considered on its own. Instead, we will give you some examples of how a Regional Body may use existing information to make decisions about where bank remediation is appropriate and some of the considerations in that process.

6.1 Case Study 1: Burdekin Catchment

The Burdekin watershed is ~130,000 km² and drains into the Great Barrier Reef Lagoon south of Townsville on the east coast of Australia (Figure 9). It is the largest contributor of anthropogenic derived fine sediment to the GBR lagoon (Kroon et al., 2012). It has an annual average rainfall of 727 mm and the largest mean annual runoff of any of the GBR watersheds at 10.29 \times 10^6 ML (Furnas, 2003). The rainfall and runoff regime is highly variable in both space and time (Petheram et al., 2008; Rustomji et al., 2009) with rainfall generally higher near the coast (often >2000 mm) than in western areas (<600 mm). The Burdekin has highly pronounced wet and dry seasons on an annual time scale, and long periods of below average rainfall can be punctuated with tropical depressions that can bring >1000 mm of rainfall in a few weeks. The Burdekin region (as presented in the Reef catchment modelling) is composed of 10 sub-watershed areas including the Upper Burdekin (~29% of the total area), Cape River (~14%), Belyando (~25%) and Suttor sub-watersheds (~13%) all above the Burdekin Falls Dam (BFD). The Bowen-Bogie sub-watershed (~8%), Lower Burdekin (4%) and East Burdekin (~2%) are below the Burdekin Falls Dam. The recent model runs also include the Black (~1%), Ross (1%) and the Don (~2%) sub-catchments. Examples of the different types of bank erosion observed in the Burdekin catchment are shown in Figure 8.

Figure 8: Examples of bank erosion in the Burdekin catchment (left) a first order tributary stream (right) the main channel of the Burdekin River near Basalt National Park.
Figure 9: WQIP Management Units or sub-catchments of the Burdekin. Location of case studies A, B and C are shown for reference.
6.1.1 IS THERE A BANK EROSION PROBLEM?

Based on the modelling work presented in Dougall et al., (2014) the model results were interrogated at sub-catchment or management unit scale to determine the amount of sediment currently predicted to be coming from channel bank erosion (Figure 10), and how much the amount of bank erosion has changed since pre-development conditions (Figure 11 and Figure 12). Note that units of t/ha, rather than t/km were used so that it is possible to compare between erosion types (gully, bank and hillslope erosion).

These results suggests that the East Burdekin, Lower Burdekin and Upper Burdekin all have >30% of the total load contributed from bank erosion (Figure 10). The Don and Bowen-Bogie have >10% sediment contribution from bank erosion. All other catchments have less than 10% contribution from bank erosion. The results also suggest that the catchments that have >10% contribution from bank erosion (East Burdekin, Lower Burdekin, Bowen-Bogie, Don and Upper Burdekin) are also where there is a much higher contribution of sediment from bank erosion compared to pre-European conditions (Figure 11 and Figure 12).

![Figure 10: Proportion of predicted gully, bank and hillslope erosion contributing to sediment export from each sub-basin in the Burdekin catchment (based on Source Catchments model outputs)](image-url)
6.1.2 UNDERSTAND THE PROCESSES

The key processes driving bank erosion were discussed in Section 2.4. In many cases, Regional bodies will have the in-house skills to evaluate these data and processes. In other cases, expert advice may be required. Maps of stream power (Figure 13a), current riparian vegetation (Figure 13b), bank material (Figure 14a) and channel plan-form (Figure 14b) are provided here to show the spatial representation of these factors across the Burdekin catchment. The aim of presenting these data in this form is to look at large scale variation is the processes driving erosion. The absolute values presented for any one reach or
link should not be taken at face value, instead the mapping should be used to compare relative values between sites (e.g. high vs low stream power).

The greatest amount of change in riparian vegetation (tree) cover is predicted for the Belyando and Suttor sub-catchments (Figure 13b), however, because these areas have relatively flat terrain with very low channel slopes, the stream powers are very low (Figure 13a). This results in very low contributions from bank erosion (Figure 10 and Figure 11).

As well as evaluating the spatial variation in the processes driving bank erosion, an assessment of the channel in each of the priority sub-basins was undertaken in Google Earth. Based on this assessment, there is very little evidence of excessive bank erosion in the East Burdekin catchment. It is likely that the high stream powers from the Burdekin Falls dam have given this site a distorted result for this sub-catchment. Most of the reach is bedrock controlled (evident by the bedrock located on the banks and bed of the river) and well vegetated. There is evidence of alluvial gully erosion at the junction of the Burdekin and Bowen River systems, however, this is not classic bank erosion (i.e. has not resulted from lateral channel migration), and should be treated as alluvial gully erosion.

An assessment of the Bowen-Broken system found a similar result with very little evidence of high rates of bank erosion. Most of the channel was reasonably well vegetated on both sides of the river. There is some evidence of severe bank erosion (i.e. steep, bare banks with pipe erosion) at a number of mine sites in the upper section of the Little Bowen catchment, and there is considerable severe gully (badlands) erosion in the Little Bowen. However, it seems that gully erosion, rather than stream bank erosion, is likely to be the dominant source of channel erosion in this catchment.
Figure 13: Distribution of (a) stream power and (b) riparian vegetation across the Burdekin catchment (Source: Dougall et al., 2014)
Figure 14: Distribution of (a) soil clay content (Source: TERN soils mapping) and (b) channel sinuosity across the Burdekin catchment (Source/method: Appendix B)
Figure 15: (a) Digital Elevation Model (DEM) Distribution and (b) MrVBF (valley bottom flatness) for the Burdekin Catchment
6.1.3 ASSESS RESTORATION OPTIONS, COSTS AND BENEFITS

In this section we have selected three example sites to help demonstrate how you might use the information in this report. The location of each of these examples is shown on Figure 9, and the results are summarised in Table 9.

Example A

Issue:
The site has high stream power (Figure 13a) and the riparian vegetation mapping suggests that the vegetation is not necessarily in pristine condition (Figure 13b) and therefore it may be vulnerable and warrant protection. The site has a moderate level of sinuosity (Figure 14a) and local site assessment shows that it is on the outside of an actively migrating bend. The MrVBF maps suggest that the reach is set within a minor floodplain reach, and therefore there is capacity for the channel to migrate laterally.

Checks:
Based on measurements conducted in Google earth, the channel is ~365 m wide at the apex of this bend (Figure 16). Equation 3 was used to determine the appropriate width of the riparian zone assuming that the time for tree to reach maturity is ~20 years (semi-arid environment). Based on this approach, the riparian zone should be ~120 m in this reach [1.6% × mean channel width (m) × tree establishment rate (years) = 0.016 ×~365 ×~20 = 116 m].

Action
Given the riparian zone is already ~125 m along most of this reach, the recommendation would be to fence off the riparian zone to protect it from future erosion. It would be good to extend the fencing on the right bank in the downstream direction so that natural vegetation regeneration may occur in areas where the riparian zone is not at least 120 m wide. Given this site is upstream of Basalt National Park, it would have the added benefit of providing a riparian wildlife corridor to the downstream National Park. It is obvious in Figure 16 that the river has meandered across this area in the past. This is most likely due to the basalt flows that occurred in this area between 0.13-8 million years ago (Wyatt and Webb, 1970). The current Burdekin channel is relatively stable in this area (Bainbridge, 2004), and therefore fencing is considered an appropriate option at this site.
Example B

*Issue:*

The site has high stream power (Figure 13a) and the riparian vegetation mapping suggests that the vegetation is low to poor (Figure 13b). This reach also has moderate sinuosity values (Figure 14a) and the MrVBF maps suggest that the reach is set within an un-confined floodplain reach, and therefore there is capacity for the channel to migrate laterally. As a result the bank here that is there is vulnerable to further meander migration and channel erosion.

*Checks:*

Based on some measurements on Google earth, the channel is ~710 m wide at the apex of this bend. To check what the riparian width should be Equation 3 was employed and the riparian zone should be ~230 m in this reach \[1.6\% \times \text{mean channel width (m)} \times \text{tree establishment rate (years)} = 0.016 \times 710 \times 20 = 227 \text{ m}\].

*Action*

Given the riparian zone is ~95 m along most of the right bank on this reach, the recommendation would be to enhance the riparian zone in this area to provide additional structural support to the bank via tree roots. This will reduce the chance of erosion from lateral migration and mass failure. It would be suitable to widen the riparian zone, fence it off and actively plant local tree and grass species from the region. There will be costs related to lost production which should be considered in this case study. This will occur as a consequence of taking some land out of cane production and installing a riparian zone.

Figure 16: High risk area on Upper Burdekin identified for protection. Fencing off and natural regeneration is recommended.
Example C

Issue:
This site is a tributary in the Don River catchment which has moderate stream power (Figure 13a) and the riparian vegetation mapping suggests that the vegetation is moderate (Figure 13b), however, Google Earth mapping confirms that the riparian vegetation is poor. The site also has a high sinuosity (Figure 14a) and is on the outside of an actively migrating bend. The MrVBF maps suggest that the reach is located at the break point between the uplands and the lower alluvial floodplain setting. Therefore there is capacity for the channel to migrate laterally.

Checks:
Based on measurements in Google earth, the channel is ~50 m wide at the apex of this bend. To check what the riparian width should be Equation 3 was used to determine that the riparian zone should be ~16 m in this reach [1.6% × mean channel width (m) × tree establishment rate (years) = 0.016×~50×~20 = 16 m].

Action
Given the riparian zone is non-existent along many sections of this reach, it is recommended that an active vegetation regeneration program be initiated. This would include fencing off both sides of the river for up to 20 m width (or more where possible). The reaches should be ~1 km in length. Some reaches may be appropriate for natural vegetation regeneration. Other areas, particularly on the outside of bends, should be actively re-vegetated using local plant species.
Figure 18: Tributary in the Don River catchment that is recommended for fencing off and a combination of active and passive vegetation re-generation.
Table 9: Potential benefits (in the INFFER scheme benefits are rated between 0-1). In this table we have estimated benefits as a % reduction to sediment yield. The % likely reduction ranges are conservative estimates based on Table 4.

<table>
<thead>
<tr>
<th>Example</th>
<th>Location</th>
<th>Option</th>
<th>Estimated cost per kilometre (from Table 5)</th>
<th>% likely reduction range (from Table 4)</th>
<th>Timeframe</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Upper Burdekin</td>
<td>Fence off and allow natural regeneration of vegetation</td>
<td>$15,980</td>
<td>90%</td>
<td>~5 years</td>
<td>Low</td>
</tr>
<tr>
<td>B</td>
<td>Lower Burdekin</td>
<td>Fence off and actively revegetate</td>
<td>$43,880</td>
<td>40-50% (large river)</td>
<td>~2-18 years</td>
<td>Medium (floods, land tenure, cropping)</td>
</tr>
<tr>
<td>C</td>
<td>Don River</td>
<td>Fence off and actively revegetate</td>
<td>$43,880</td>
<td>50-60% (small tributary)</td>
<td>~2-18 years</td>
<td>Medium (revegetation during dry periods risky)</td>
</tr>
</tbody>
</table>
6.2 Case Study 2: Daintree Catchment

The Daintree River catchment is ~1320 km², and flows from the Great Dividing Range at an elevation of ~1300 m into the Coral Sea. Ninety-five percent of the catchment is undeveloped forest or wetland, 87% of which is classed as World Heritage Area forest and National Park. About 63% of the forest is classified as rainforest and 24% is a combination of wet and dry sclerophyll forest. The geology comprises predominantly igneous and sedimentary rocks and the headwaters are steep and inaccessible with channel gradients up to 10%. The average rainfall for the area is ~2500 mm, although this is measured on the floodplain and rainfall in the ungauged steep upper catchments is likely to be considerably higher. Although the Daintree catchment is 95% forest, there are some significant bank erosion hot spot areas in the more developed floodplain reaches (see Figure 19).

Several studies have assessed the riparian condition of streams in the Daintree catchment including a study by Russell et al (1998) that mapped the condition of riparian areas, and more recently Kroon et al (2014a) evaluated the quality and condition of the riparian zone for all Wet Tropics streams, including the Daintree River and its tributaries. Each of the studies highlighted that Stuart Creek, a major tributary of the Daintree River, is an area of low riparian vegetation (see Figure 20).

Figure 19: Examples of bank erosion on the Daintree River in the cleared floodplain (or coastal sub-catchment) reach
Figure 20: WQIP Management Units or sub-catchments of the Daintree catchment
6.2.1 IS THERE A BANK EROSION PROBLEM?

Based on the modelling work presented in Hateley et al., (2014) the models were interrogated at sub-catchment (Figure 20) to determine the amount of sediment currently predicted to be coming from channel bank erosion (Figure 21), and how much the amount of bank erosion has changed since pre-development conditions (Figure 22).

Unfortunately, there appears to have been different generations of models used to estimate the current and pre-development scenarios in the Wet Tropics (Report card 3 vs Report Card 4/5) and the results suggest that there is no difference in the bank erosion rate between current and pre-development conditions in Stuart Creek, Coastal and North coast sub-catchments (Figure 20 and Figure 22). There has been clearing, agricultural development and alterations to the riparian zone in each of these sub-catchments. The only sub-catchment that showed any significant increase in bank erosion contribution with agricultural development is the South Coast or Saltwater Creek catchment. A large part of the floodplain is cleared in this catchment for agriculture, however, the riparian zones are in better condition in Saltwater Creek than in Stewart Creek (Figure 23). The models also suggest bank erosion has increased slightly since pre-development in the highly forested Inland sub-catchments (Figure 21 and Figure 22).

Based on these somewhat spurious results, the models will not be used further to prioritise sites for remediation. Instead, local knowledge and other information that involved local field assessment will be utilised (Russell et al., 1998; Bartley et al., 2008; Kroon et al., 2014a).

![Figure 21: Proportion of gully, bank and hillslope erosion contributing to sediment export from each sub-basin in the Daintree catchment (Source: Hateley et al., 2014)](image)
**Figure 22:** showing difference in bank erosion contribution between sub-catchments

**Figure 23:** Well vegetated riparian zones in Saltwater Creek (top) and less well vegetated riparian zones in Stewart Creek (bottom)
6.2.2 UNDERSTAND THE PROCESSES

The key processes driving bank erosion were discussed in Section 2.4. Maps of stream power (Figure 24a), current riparian vegetation (Figure 24b), bank material (Figure 25a) and channel plan-form (Figure 25b) for the Daintree catchment are provided here to show the spatial representation of these factors across the catchment. The aim of presenting these data in this form is to look at large scale variation in the processes driving erosion. The absolute values presented for any one reach or link should not be taken at face value, instead the mapping should be used to compare relative values between sites (e.g. High vs Low stream power).
Figure 24: Distribution of (a) stream power and (b) riparian vegetation across the Daintree catchment (Source: Hateley et al., 2014)
Figure 25: Distribution of (a) soil clay context (Source: TERN soils mapping) and (b) sinuosity across the Daintree catchment (Source/method: Appendix B)
Figure 26: (a) Digital Elevation Model (DEM) and (b) MrVBF (valley bottom flatness) for the Daintree Catchment
6.2.3 ASSESS RESTORATION OPTIONS, COSTS AND BENEFITS

In this section we have selected three example sites to help demonstrate how you might use the information in this report. The location of each of these examples is shown on Figure 20, and the results are summarised in Table 10.

Example A

Issue:
The site has high stream power (Figure 24a) and the riparian vegetation mapping suggests that the vegetation is low to poor (Figure 24b). This reach also has moderate to high sinuosity values (Figure 25a) and the MrVBF maps suggest that the reach is set within a highly active floodplain, and therefore there is capacity for the channel to migrate laterally (Figure 25b). As a result the bank here that is there is vulnerable to erosion.

Checks:
The Google Earth imagery shows that this site is on the in-side bend of a meander and is regularly subject to over-bank flow (note the sand deposits and back-channel swaps on the point bar). Riparian restoration was attempted at this site (on the right bank adjacent to the red line), however, most of the planted seedlings have since been stripped out by flood waters moving across this channel bar.

Action
Given the frequency of over-bank flooding in this area (at least annually) it is not recommended to attempt further revegetation of this site. There is an extremely high risk that the remediation will fail (see Figure 29a).

Figure 27: Lower Burdekin site with high stream power and low veg
Example B

**Issue:**
This reach is upstream of Daintree village and has moderate to high stream powers (Figure 24a) and the riparian vegetation mapping suggests that the vegetation is low to poor (Figure 24b), however, actual assessment of the reach shows several in-tact riparian areas. Although this reach is relatively straight, it forms the approach of a meander bend that has high sinuosity (Figure 25a) and the MrVBF maps shows that the reach is located within an unconstrained floodplain section. Therefore there is capacity for the channel to migrate laterally (Figure 25b), and the bank is vulnerable to further erosion. An example of the mass failure bank erosion occurring along this stretch of river is shown in Figure 29b.

**Checks:**
Based on measurements in Google earth, the channel is ~80 m wide at each of the ‘red line’ sites along this stretch of the Daintree River. To check what the riparian width should be Equation 3 was used to determine that the riparian zone should be ~25 m in this reach [1.6% × mean channel width (m) × tree establishment rate (years) = 0.016×~80×~20 = 25 m].

**Action**
The riparian zone is very thin or non-existent at several sites along this reach, however, there are dense stands of riparian vegetation upstream of each of the sites, it is recommended that the in-tact sites are fenced off and protected and the un-vegetated sites should be fenced off to allow natural seed generation to revegetate these sites. The frequency of flooding is likely to be an issue prohibiting fencing in this area, so some novel forms of fencing may need to be trialled (e.g. fences that lie down during floods).

![Figure 28: The main channel of the Daintree River upstream of Daintree village](image-url)
Figure 29: (a) Photo from the flood-runner downstream of Daintree village showing flood debris deposited in this section of the river, suggesting that immature saplings may struggle to withstand regular flooding in this area and (b) example of ‘mass failure’ bank erosion upstream of Daintree village that would benefit from root-reinforcement from riparian vegetation.

Example C

**Issue:**
The site has high stream power (Figure 13a) and the riparian vegetation mapping suggests that the vegetation is not necessarily in pristine condition (Figure 13b) and therefore it may be vulnerable and warrant protection. The site has a moderate level of sinuosity (Figure 14a) and local site assessment shows that it is on the outside of an actively migrating bend. The MrVBF maps suggest that the reach is set within a minor floodplain reach, and therefore there is capacity for the channel to migrate laterally.

**Checks:**
Based on measurements in Google earth, the channel is ~15 m wide at the apex of this bend. To check what the riparian width should be Equation 3 is used assuming that the time for tree to reach maturity is ~20 years (tropical environment subject to frequent flooding). Based on this approach, the riparian zone should be ~5 m in this reach [1.6% × mean channel width (m) × tree establishment rate (years) = 0.016 ×~15 ×~20 = 4.8 m].

**Action**
Given there is no riparian zone along most of this reach, the recommendation would be to fence off the riparian zone for at least 5 m on either side of the channel and undertake a combination of natural vegetation regeneration and active planting, particularly on the more active outside bends. It is acknowledged that there is an element of risk with this recommendation as the channel is obviously highly sinuous. However, in these higher order streams, it is likely that some of the meandering is being exacerbated by the lack of riparian vegetation in this catchment.
Table 10: Synthesis of the metrics for the bank erosion remediation examples on the Daintree catchment. The % likely reduction ranges are conservative estimates based on Table 4

<table>
<thead>
<tr>
<th>Example</th>
<th>Location</th>
<th>Option</th>
<th>Estimated cost (from Table 5)</th>
<th>% likely reduction range (from Table 4)</th>
<th>Timeframe</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Daintree River (below village)</td>
<td>Don’t touch – risk of remediation failure due to flooding too high</td>
<td></td>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>B</td>
<td>Daintree River (above village)</td>
<td>Protect in-tact areas and fence off and allow natural vegetation regeneration in adjacent reaches</td>
<td>$15,980</td>
<td>40-50% (large river)</td>
<td>~2-18 years</td>
<td>Medium (floods, pigs)</td>
</tr>
<tr>
<td>C</td>
<td>Stuart Creek</td>
<td>Fence off and actively revegetate</td>
<td>$43,880</td>
<td>50-60% (small tributary)</td>
<td>~2-18 years</td>
<td>Medium (floods, pigs)</td>
</tr>
</tbody>
</table>
7 Discussion

For successful remediation of erosion sources, it is critical to understand the key drivers of the erosion, so that both the causes and symptoms of the erosion can be appropriately treated. This report presented a review of the key processes driving bank erosion, and then discussed how knowledge of these processes can help identify suitable sites for remediation in two very different GBR catchments (Burdekin and Daintree).

Three dominant forms of remediation were proposed and discussed. These included fencing off and allowing natural (passive) vegetation regeneration, fencing off and active re-vegetation of the site, and engineering modifications. The choice of remediation option is dependent on the causes of erosion and the likely costs - of lost production to landholders, of remediation activities, and of future effectiveness and maintenance.

A number of case studies were presented to demonstrate how to link an understanding of erosion drivers, processes and remediation options together. In both case studies, fencing and vegetation management were the only remediation options considered. Engineering structures are discussed as a bank erosion remediation option, however, there needs to be a compelling erosion and economic argument to justify the expense, and high risk, associated with structural remediation. There may be exceptions for flood recovery (e.g. Bundaberg) and asset protection projects. Based on this premise, no examples were found that were suitable for engineering based remediation.

In both case studies, catchment modelling was used at the sub-catchment scale to prioritise sites that had higher than expected rates of bank erosion based on a prediction of pre-development or pre-agricultural bank erosion rates. In the Burdekin catchment case study, 5 sub-catchments were assessed further, however, two out of the five catchments were not found to have the level of bank erosion predicted by the models. In the other catchments, evidence of bank erosion was identified using Google Earth, however, in general there was not extensive evidence for excessive bank erosion in rangeland catchments. This is because many of the riparian zones are still in relatively good condition (compared to streams on the coastal floodplains or in Southern Australia). The model results were found not to be as useful in the Daintree catchment due to potential anomalies between predicted bank erosion rates for current and pre-development conditions.

Areas that have high stream power and low levels of riparian vegetation are vulnerable to high rates of bank erosion. This is most commonly found in the cropped coastal catchments that have extensively altered riparian zones. In cropping areas (e.g. sugar cane regions) there is considerable opportunity for improvement in riparian widths and extent, however, it is likely that a shift in land tenure or policy will be required before there will be significant change in these areas. It is argued that additional research is required to demonstrate that bank erosion rates have changed significantly as a result of agricultural development prior to any policy change in this area. Such research will also be useful for guiding remediation recommendations (e.g. riparian buffer width requirements in tropical rivers).

Channel or sub-surface erosion has been identified as the dominant erosion source in sediment budgets conducted in the GBR catchments (e.g. Wilkinson et al., 2013), however, it is likely that gully erosion dominates the sub-surface erosion in the semi-arid catchments (Burdekin, Fitzroy and Cape York) and bank erosion is the dominant source in low-land floodplain reaches and Wet tropics catchments.
7.1 Areas of further research

There are several potential areas of further research related to understanding the contribution from bank erosion. These include:

- **A re-assessment of the models currently used to predict bank erosion in the GBR catchments.** It has been suggested that tropical rivers that have a strongly seasonal discharge variations, and large sand sediment loads, may not fit well with existing geomorphic or sedimentological models of erosion and channel change (Gupta and Dutt, 1989). Therefore is timely to review the bank erosion models to see if they are representing the key bank erosion process in the GBR region.

- **Studies of how bank erosion has adjusted to changes in land use.** This would provide important base-line information that would help evaluate the significance of bank erosion in GBR catchments. It would also provide an understanding of the natural rates of bank erosion so that metrics of channel change are available against which to evaluate bank remediation projects.

- **A better understanding of the particle size contribution from bank erosion.** There is very little data about the particle size composition of channel banks. It is likely that many of the banks are composed of coarse, sandy material that will not contribute significant amounts of sediment to the GBR. Priority should be given to banks that are eroding into fine (<4 µm) material.

- **A better quantification of bank heights and angles.** LiDAR data is now available in most coastal areas and could be used to help identify high, steep banks, particularly in floodplain regions. This would greatly help with identification of at risk stream bank erosion sites.

- **Evaluate the role of re-vegetation on channel banks.** There is evidence to support using riparian vegetation to reduce bank erosion on actively meandering channels. However, there is no information on the effectiveness of riparian vegetation for incising streams or avulsive channels. For example, the Burnett and Mary rivers are prone to bank erosion by channel incision and widening. It would be interesting to run models such as BSTEM (Simon et al., 2014) and assume that the riparian zones were fully vegetated and then compare the bank erosion rates to their current (un-vegetated) condition. This would provide important quantitative estimates of the effectiveness of riparian vegetation.
References


Appendix A


---------------

Mean Annual Bank Erosion (t/y) is calculated by:

\[
\text{MABE (t/y)} = \text{Retreat Rate (m/y)} \times \text{Mass Conversion} \times \text{Bank Erodibility}
\]

Retreat Rate (m/y) is calculated by:

\[
\text{RR (m/y)} = k \times \rho_w \times g \times S_i \times Q_{bf} \times M_f
\]

Where:

- \(k\) is bank erosion ‘calibration’ coefficient (0.00004 by default)
- \(\rho_w\) is density of water (1000 g/m\(^3\))
- \(g\) is acceleration due to gravity (m/s\(^2\))
- \(S_i\) is the river bed slope (m/m)
- \(Q_{bf}\) is the bank full flow/discharge (m\(^3\)/s)
- \(M_f\) is the bank erosion management factor, a linear multiplier allowing modellers to adjust retreat rate according to implied management actions.

Mass Conversion (to ultimately convert Retreat Rate to a Mass) is calculated by:

\[
\text{MC} = \rho_s \times h \times L_i
\]

Where:

- \(\rho_s\) is sediment dry bulk density (t/m\(^3\))
- \(h\) is bank height (m), the ‘bank’ being that which the modeller considers the erosion contributing feature (not necessarily ‘channel’ height or depth).
- \(L_i\) is length of river represented by the link (m)

Bank Erodibility is calculated by:

\[
\text{BE} = (1 - \text{MIN}(\text{RipVeg, MaxVegEffectiveness})) \times \text{SoilErod}
\]

Where:

- \(\text{RipVeg}\) is the proportion of intact riparian vegetation (1 for complete coverage, 0 for none)
- \(\text{MaxVegEffectiveness}\) is a ‘cap’ on the effectiveness of the riparian vegetation
- \(\text{SoilErod}\) is the erodibility of the soil material adjacent to the stream (0 for rock, 1 for erodible soil)

Mean Annual Bank Erosion (MABE) is disaggregated to a daily load using a Link Discharge Factor, which is the relationship of daily outflow to long term average daily flow, and a constant:

\[
\text{Daily Bank Erosion (kg)} = (1-\text{MIN}(\text{RipVeg, MaxVegEffectiveness})) \times \text{SoilErod}
\]
Where:

\[ \text{MABE} \text{ is Mean Annual Bank Erosion (t/y)} \]
\[ \text{LDF} \text{ is Link Discharge Factor} \]

Link Discharge Factor is calculated on a daily basis according to:

\[
\text{LDF} = \frac{\sum_{i=1}^{n} Q_i^b}{n \sum_{i=1}^{n} Q_i^b}
\]

Where:

\[ Q_i \] is the daily flow rate (m³/s)
\[ n \] is the number of days in the long term historical daily flow record
\[ b \] is the adjustable Daily Flow Power Factor, default 1.4

The Daily Bank Erosion (kg) load is then apportioned to Fine and Coarse Sediment according to the supplied fine particle proportion (clay + silt).

According to Dougall et al., (2014) the SedNet Stream Fine Sediment model calculates a mean annual rate of fine streambank erosion in (t/yr) and there are several raster data layers and parameter values that populate this model. The same DEM used to generate subcatchments is used to generate the stream network. A value used to determine the ‘ephemeral streams upslope area threshold’ is also required, and is equal to the value used to create the subcatchment map, which in Burdekin region was 50 km². Floodplain area and extent was used to calculate a floodplain factor (potential for bank erosion) and for deposition (loss). The floodplain input layer was determined by using the Queensland Herbarium pre-clearing vegetation data and extracting the land zone 3 (alluvium) codes. The Queensland 2007 Foliage Projective Cover (FPC) layer was used to represent the proportion of riparian vegetation. Riparian vegetation was clipped out using the buffered 100 m stream network raster. A value of 12% was used for the FPC threshold for riparian vegetation. A 20% canopy cover is equivalent to 12% riparian veg cover and this threshold discriminates between woody and non-woody veg and we assumed that the non-woody FPC cover (below 12%) is not effective in reducing streambank erosion (Department of Natural Resources and Mines 2003).

Streambank soil erodibility accounts for exposure of rocks resulting in only a percentage of the length of the streambank being erodible material, decaying to zero when floodplain width is zero. The steps below were followed to create a spatially variable streambank soil erodibility layer with its value increasing linearly from 0% to 100% as floodplain width increases from zero to a cut-off value. It is assumed that once floodplain width exceeds the cut-off value, the streambank will be completely erodible (i.e. streambank erodibility = 100%). The cut-off value used was 100 m. Streambank soil erodibility (%) = MIN(100, 100/cut-off*FPW), where: FPW is floodplain width (m) and cut-off is the cut-off floodplain width (m). Surface clay and silt values taken from the ASRIS database were added together to create Burdekin NRM region clay and silt percentage layer. ‘No data’ values were changed to the median value. Using the raster data layers described above, SedNet Stream Fine Sediment model calculates eight raster data sets that are used in the parameterisation process. The calculated rasters are: slope (%), flow direction, contributing area (similar to flow accumulation in a GIS environment), ephemeral streams, stream order, stream confluences, main channel, and stream buffers. Variable bank height and width functions were incorporated in the model to replace the default Dynamic SedNet fixed stream bank height and width values. Bank height and width parameters were developed from local gauging station data. Regression relationships were determined between point observations of channel width and upstream area.
Appendix B

Steps for calculating Sinuosity in ArcGIS

1. Fill the DEM and then calculate grids of flow direction and flow accumulation.

   Use Arc Toolbox > Spatial Analyst Tools > Hydrology tool

2. Create a stream raster (1 for stream, null for not) from the flow accumulation grid

   Arc Toolbox > Spatial Analyst Tools > Conditional > Set Null – e.g. for a 50km² minimum catchment area stream network from the 30 m resolution SRTM DEM-H, SETNULL for FLOWACC < 55555 else 1

3. Convert the stream grid to stream lines

   Arc Toolbox > Spatial Analyst Tools > Hydrology Tools > Stream to Feature

4. For each stream line segment, estimate the sinuosity

   Sinuosity Index = Actual path / shortest path

   where

   - Actual Path is the total length of the stream line segment

     Arc Toolbox > Data Management Tools > Features > Add Geometry Attributes

   - Shortest path is the straight line distance between the start and end points of the stream line segment.

     There are python codes to extract start and end nodes (as points) at the ESRI forum (http://forums.esri.com/Thread.aspx?c=93&f=1729&t=281984). These points can be converted to straight lines using Arc Toolbox > Data Management Tools > Features > Points to Line (use the ArcID field as the “Line Field”). Use Toolbox > Data Management Tools > Features > Add Geometry Attributes to calculate length. Then join the straight line attribute table to the stream lines attribute table using theArcID field. Sinuosity can then be added as a calculated field to the stream lines shapefile.

The Sinuosity Index ranges between 1 and its theoretical maximum of infinity. It is commonly below 2 for natural river systems, but can higher where sinuosity is high. Large Indices may anomalously occur on longer reaches, where the river “sweeps” around natural barriers (due to topographic features). Thus there may be a benefit in splitting long stream lines into smaller reaches before calculating sinuosity.