

Investing in riparian zone management to reduce erosion from stream channels: how do we evaluate success?

Rebecca Bartley, Seonaid Philip, Anne Henderson and Dan Tindall



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management in the GBR catchments

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ACRONYMS

ASRIS.....	Australian Soil Resource Information System
DEM.....	Digital Elevation Model
DSITI	Department of Science, Information Technology and Innovation
GBR.....	Great Barrier Reef
GBRMPA.....	Great Barrier Reef Marine Park Authority
M&E.....	Monitoring and Evaluation
MW	Mackay Whitsunday
NESP.....	National Environmental Science Programme
UQ	University of Queensland
US.....	United States

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EXECUTIVE SUMMARY

Changes to land use, vegetation and climate in recent centuries, have resulted in stream-bank erosion rates that are considerably higher than natural background levels in many parts of the world. The most common approach used to stabilise stream-banks is riparian vegetation. This is because it is much cheaper than expensive engineering structures, and it has additional ecological benefits. Despite considerable investment in stream restoration using vegetation, we have a limited understanding of the effectiveness of riparian vegetation for reducing stream bank erosion.

Stream-bank erosion can occur 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 and anabranching (forming of a new channel). The form and type of bank erosion can vary within and between catchments draining to the Great Barrier Reef (GBR), but collectively these processes can be considered as channel change.

In this study we collated all of the known data on stream-bank erosion rates (or channel change) for the GBR catchments. Because many existing studies did not specifically evaluate the influence of vegetation, either intact or restored, this study then specifically tested the hypothesis that sites with more riparian vegetation (>75%) will be more stable and undergo less *change in channel width* than sites with less riparian vegetation (<50%). A key assumption used in this approach was that if a change in channel width was detected, then it is very likely that there had been significant stream-bank erosion at the site. If a change in channel width is not detected, it doesn't mean that stream-bank erosion has not occurred, as stream-bank erosion may have occurred within the channel boundary. It simply means that the approach used in this study was too coarse to detect the change. The Fitzroy and Mackay Whitsunday catchments were used as case study sites to test this hypothesis. Historical air photos (~1950 to 2012) were the key technique for measuring changes in channel width. Knowledge of the rates of channel change for sites with and without riparian vegetation provides important baseline data to help evaluate sites that have recently undergone riparian remediated.

The results from the review of stream-bank erosion and channel change in the Great Barrier Reef catchments suggests that rates can vary from 0.01 m to 5 m yr⁻¹ depending on the size of the catchment, the method used to estimate change and the time period of the study. High erosion rates generally occur following major flood events (~5 m yr⁻¹). Outside of these major events, channel erosion in the GBR catchments is relatively low by world standards (0.01 – 0.1 m yr⁻¹).

The results of the aerial photo analysis for the Fitzroy catchment showed that there was no statistically significant change in channel width between sites with good (>75%) and poor (<50%) riparian vegetation ($p = 0.481$). The median change in channel width for control sites with good (>75%) vegetation was 0.0464 m yr⁻¹, and for impacted sites (with <50% vegetation) there was an overall channel contraction of -0.0086 m yr⁻¹.

In the Mackay Whitsunday catchments, there is a weak, but statistically significant difference (at the $p < 0.1$ level) in the change in channel width between the control and impact groups; but the difference is not in the direction that we expected. The median channel change for control sites was 0.061 m yr⁻¹, whereas the impact sites underwent an overall channel

contraction of -0.233 m yr^{-1} . This difference was very biased by the 1960's and 1970's period when the impacted reaches underwent greater channel contraction than the control reaches.

Given that considerable stream-bank erosion (slumping, scouring) can occur on a reach without a measurable change in channel width, the results of this study do not suggest that riparian vegetation is not important or useful for controlling erosion. These results simply say that large scale channel change (expressed as a change in channel width) could not be measured at these sites using aerial photos over the time period studied (~1950 - 2102). There are a number of possible explanations for this result. These include (a) that the aerial photo analysis was too coarse to detect the low rates of annual channel change; (b) that riparian vegetation has a different role depending on the type of channel being assessed; (c) that the impacted sites had already undergone a period of channel expansion when many of the sites were cleared in the late 1800's and early 1900's, and what we have observed in this study is post-disturbance channel contraction; (d) that large infrequent runoff events are a dominant driver of major channel change in these systems, and it may have been more useful to assess channel change following extreme events rather than averaging channel change across decades; and (e) that the large number of weirs and dams in the Fitzroy catchment may have influenced the results by buffering the effect of riparian vegetation on channel change.

Taking into consideration the results from this study, as well as previous discussions on the role of bank erosion in Bartley et al., (2015), the key recommendations from this study are:

- (1) The need to incorporate a 'lag effect' in the models used to evaluate GBR remediation investment. Many of the 'remediation' approaches implemented by the Regional bodies were not directly influencing the amount and extent of riparian vegetation (e.g. fencing or off-site stock watering point). Given the long lag times between fencing and the establishment of riparian vegetation from natural seeding, it is likely to be several years to decades before there is a measurable response from such activities. This has major implications for the Source Catchments modelling as they assign the water quality benefit from a management practice change to the year that the investments occurs (Waters et al., 2013). A lag term that considers the time it takes for the physical water quality benefits to be realised following remediation would provide more realistic estimates of the potential benefit of remediation;
- (2) Riparian vegetation (e.g. ~100 m buffer) is important for stabilising banks, intercepting runoff and ecological function, however, it cannot be used as a Band-Aid solution if the area upstream is void of ground cover. The amount of vegetation (ground cover) upstream will influence the amount of runoff and stream power affecting a stream reach, and so all vegetation upstream of a reach will directly, and indirectly, influence bank stability. Therefore consideration should be given to integrating multiple vegetation metrics for a given site;
- (3) A specific budget (~10%) should be given to formally evaluating the effectiveness of on-ground remediation works, including riparian management, on water quality. This should be done at the investment scale (e.g. reach, paddock scale), using robust measurements that are able to detect changes in erosion (see Bartley et al., 2016b). Evaluation should not rely on modelling alone. Monitoring should also be assessed against reference sites rather than simply tracking change over time at the site restored, and the M&E should be embedded within a robust conceptual and methodological framework.

1. PREFACE

1.1 Background and Context

Stream-bank erosion is estimated to contribute ~30-40% to end of catchment sediment yields in the Great Barrier Reef (GBR) catchments (Wilkinson et al., 2015). However, our understanding of the degree of alteration of stream-bank erosion with the introduction of agriculture, and the success of methods for remediating stream-bank erosion sites (using approaches such as riparian vegetation, fencing and stock removal), is limited. Without a robust understanding of these issues it is difficult to target sites for remediation as well as to evaluate the costs and benefits of undertaking remediation in the riparian zone.

Risk frameworks, previously known as A, B, C, D frameworks, are used to evaluate the influence of improved grazing land management on hillslopes in rangelands, and for nitrogen use in sugarcane. No such risk framework exists for riparian management. Before such a framework can be developed, we need an improved understanding of the rates of stream-bank erosion and channel change we can expect in natural or well managed landscapes. Without such information we don't know what we are trying to restore stream-bank erosion rates to, and if the remediation actions being implemented (e.g. fencing) will be effective at reducing stream-bank erosion.

1.2 Objectives

The original over-arching objectives of this project were to (i) provide new data sets to evaluate the current predicted rates of bank erosion; and (ii) provide more robust benchmarking of future stream-bank remediation interventions. Objective (ii) was addressed in the accompanying report Bartley et al., (2016b). This report tested the hypothesis that sites with more riparian vegetation will be more stable and undergo less *change in channel width* than sites with less riparian vegetation. Historical air photos (~1950 – 2012) were the key instrument for measuring changes in channel width. The Fitzroy and Mackay Whitsunday catchments were used as case study sites to test this hypothesis.

1.3 Contracted deliverables

The specific contracted deliverables for the project are:

1. A report that describes the framework, and test the new data sets and frameworks on two case study catchments (one wet tropical and one dry tropical catchment). *Two reports were delivered:*
 - a) Bartley, R., Philip, S., Henderson, A.E. and Tindall, D., 2016. *Investing in riparian zone management to reduce erosion from stream channels: how do we evaluate success? Report to NESP, Project 1.2a.*
 - b) Bartley, R., Goodwin, N., Henderson, A.E., Hawdon, A., Tindall, D., Wilkinson, S.N. and Baker, B., 2016b. *A comparison of tools for monitoring and evaluating channel change, Report to NESP, Project 1.2b.*
2. A briefing with key DoE staff in Canberra to discuss the implication of the results for evaluating the effectiveness of riparian management at the whole of GBR scale.

Presentations to the DoE staff and regional bodies involved in the study are planned for April/May/June 2016.

3. At least one technical workshop/meeting with the Queensland modelling team to discuss how the results may be integrated into existing modelling frameworks and tools.

A workshop/presentation with the Queensland modelling team will be undertaken at a mutually convenient time in April/May/June 2016.

2. INTRODUCTION

There is continued interest in understanding the source of fine sediments delivered to the Great Barrier Reef (GBR) (Bartley et al., 2014a). Identifying the major sources of fine sediment enables investments in remediation to help reduce the amount of sediment reaching the GBR, and to meet water quality targets (Kroon, 2012). Using fallout radionuclide tracers, channel erosion is considered to represent ~70% of the total fine sediment load delivered to the GBR (Olley et al., 2013; Wilkinson et al., 2013), and ~ 30% is considered to be coming from what is commonly termed 'bank erosion' or the erosion of vertical channel surfaces on rivers and streams. The other 40% is from gully erosion.

Stream-bank (or bank) erosion and lateral channel change are terms used to describe the erosion of the channel boundary in river systems. Bank erosion, in a classic sense, refers to the meander migration of a river across a floodplain (Hooke, 1979). However, lateral channel change in the streams and rivers draining to the Great Barrier Reef (GBR) can occur as a result of meander migration (where there is erosion on the outside, concave bank) (Leonard and Nott, 2015a), channel widening or incision (where there is erosion on both banks) (Bartley et al., 2008), or channel avulsion and anabranching (forming of a new channel) (Amos et al., 2008). Each of these processes has both an erosion and deposition component, although we are primarily interested in erosion processes in this study.

It is generally acknowledged that bank erosion and lateral channel change varies with distance down a catchment (Abernethy and Rutherford, 1998), stream power and bankfull discharge (Walker and Rutherford, 1999), bank material and riparian vegetation (De Rose et al., 2005; Constantine et al., 2009; Simon et al., 2014), sediment load (Constantine et al., 2014) as well as the accommodation space or level of channel confinement (e.g. rocky gorge vs alluvial floodplain) (Wilkinson et al., 2009). However, Brookes et al., (2014) concluded that stream power was not a major driver of bank erosion in Queensland rivers, and that in-channel deposition (of coarse bedload) is a better predictor of bank erosion.

Changes to land use, vegetation and climate in recent centuries, have resulted in bank erosion rates that are considerably higher than natural background levels in many parts of the world (Hooke, 1980). Tens of millions of dollars are spent stabilising and restoring stream-banks and riparian areas across the globe in an effort to reduce the amount of sediment delivered to ecologically sensitive receiving waters (Bernhardt et al., 2005; Kondolf et al., 2008; Kurth and Schirmer, 2014; Wohl et al., 2015). Of all the variables that influence bank erosion, the most common factor used to control bank erosion is riparian vegetation. This is because it is much cheaper than expensive engineering structures (Bartley et al., 2015) and has additional ecological benefits (Pusey and Arthington, 2003). Despite this investment, we have a limited understanding of the effectiveness of riparian vegetation on reducing erosion, and if the vegetation is successful, what the erosion rates will be restored to (Morandi et al., 2014).

The presence of riparian vegetation is useful for many types of erosion, but its specific influence may vary with its position in a catchment, and the height of the bank being restored (Abernethy and Rutherford, 1998; Curran and Hession, 2013). 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 and a combination of woody and grass species are likely to offer the greatest benefit in terms of bank stabilisation (Simon and Collison, 2002).

There are numerous studies that have evaluated the effectiveness of riparian vegetation at the reach scale (Gonzalez et al., 2015). Many of these studies look at the effect of riparian vegetation on providing wood for in-stream habitat (Hyatt et al., 2004), on in-stream water quality (Osborne and Kovacic, 1993; McKergow et al., 2004; McKergow et al., 2006) on bank erosion or channel change (Harris and Olson, 1997; Bartley et al., 2008). A recent study by Olley et al., (2015) determined that the sediment yield per unit area from a catchment containing no remnant vegetation is predicted to be between 50 and 200 times that of a fully vegetated channel network. Most of these studies have evaluated the influence of in-tact riparian vegetation. There are no studies, to our knowledge, that have evaluated the effectiveness of improved or remediated riparian zones in the GBR catchments. Changes to the extent of remnant riparian zones have been mapped in the Tully catchment (Pert et al., 2010), however, these changes have not been linked to improvements in bank erosion or water quality.

The current approach used to evaluate the effectiveness of improved riparian vegetation on bank erosion in the GBR catchments is the Source Catchments model (Waters et al., 2013; Wilkinson et al., 2014). This model is also extensively used to evaluate the water quality benefits and costs of remediation (Thorburn and Wilkinson, 2013; Alvarez-Romero et al., 2014; Beher et al., 2016; Kroon et al., 2016). The bank erosion rule within the Source Catchments model provides a useful estimate of bank erosion risk, as it considers many of the factors that control bank erosion rates outlined above. However, the bank erosion rule does not represent all forms of bank erosion (e.g. avulsion and anabranching systems are not explicitly considered). More importantly, there is very little data from the GBR catchments, or tropical northern Australia, that allows an assessment of the accuracy of the modelled bank erosion estimates. Consequently, the use of the model as an evaluation tool for riparian zone investment is limited. Bartley et al., (2015) discussed how best to prioritise stream-bank sites for restoration, however, one of the major limitations in restoration science is knowing what success looks like. Knowledge of historical rates of bank erosion and channel change will provide some context for this assessment, and thus help evaluate the success of investments in riparian remediation.

To fill the gap in our knowledge about the rates of erosion and channel change in the GBR catchments, this study has three specific objectives. These are (i) to review and collate all the current data on bank erosion for the GBR catchments; (ii) using two GBR catchments, evaluate if there is a difference in the rates of change in channel width (as a surrogate for bank erosion) for sites with good (> 75%) and poor (<50%) riparian vegetation. This includes assessing the effects of riparian vegetation independently of the other geomorphic variables controlling channel change (i.e. drainage area as a surrogate for discharge, channel slope and bank material); and (iii) identify where the recent remediation sites sit on this spectrum. For objectives (ii) and (iii), the Fitzroy and Mackay Whitsunday catchments were chosen as case study sites, as they provided information about the recent remediation investments under Reef Trust. In the Mackay Whitsunday catchments, there were also several restoration projects under the systems repair program that were available for assessment (Alluvium, 2014).

There are very few techniques that are useful at capturing channel change over such a large area (~140,000 km² in the case of the Fitzroy), and over a relatively short time frame (< 9 months). Historical aerial photos are commonly used to assess channel change at this scale and were the primary method used in this study (Lawler, 1993). The use of aerial photos to evaluate channel change meant that we were largely restricted to looking at changes in channel width over time. The key assumption here is that if we can detect a change in channel width, then it is very likely that there has been significant bank erosion at the site. If however, we do not detect a change in channel width, it doesn't mean that bank erosion has not occurred. It simply means it has not been significant enough to detect using this approach. For example, studies on the Lockyer River following the major flood events identified millions of tonnes of bank erosion, however, the channel width did not change significantly (Croke et al., 2013; Thompson and Croke, 2013; Thompson et al., 2013). In contrast, the Burnett River showed considerably bank retreat and changes in channel width following the 2011 floods (Simon, 2014). With more time and resources, this study would have first classified the streams in the study catchments, and deployed multiple techniques to assess erosion and channel change for sites with and without riparian vegetation (as discussed in Bartley et al., 2016). Given the time constraints, this study specifically tested the hypothesis that sites with more riparian vegetation will be more stable and undergo less *change in channel width* than sites with less riparian vegetation. Historical air photos (1950 – 2012) were the key instrument for measuring changes in channel width.

3. CASE STUDY CATCHMENTS

Given the relatively short time frames of this project, only one Dry Tropics and one Wet Tropics catchment were assessed. Due to data availability and access, the Fitzroy basin was selected to represent a dry tropical catchment, and the Mackay Whitsunday region represented a Wet Tropical catchment.

3.1 Fitzroy

The Fitzroy River catchment is the largest catchment on the east coast of Australia at ~143,000 km². The Fitzroy region is ~156,000 km² and includes the smaller coastal basins of the Styx, Shoalwater, Waterpark, Calliope and Boyne (Figure 1). A more detailed description of the region can be found in Dougall et al., (2014) and at www.fba.org.au. In summary, the Fitzroy catchment has a sub-tropical and semi-arid climate. Most of the catchment is below 300 m asl and receives annual rainfall of ~600-700 mm. As with most catchments that cross the Great Dividing Range, there is a strong east west rainfall gradient, with rainfall decreasing westward. Rainfall and river flows occur primarily in the wet season (Nov – March), but they are highly variable between years and between different sub-basins.

Most of the Fitzroy basin is underlain by Permo-Triassic sedimentary and volcanic deposits of the Bowen Basin (Amos et al., 2008). The younger geologies include sedimentary deposits in the Surat Basin, basalts in the central catchment and more complex formations in the coastal areas. Due to the diverse geology and hydrology in the catchment, there are over 100 soil types described in the catchment. Cracking clays dominate the cropping areas in the central basin (Carroll et al., 1997; Zund and Finn, 2015). Surface and gully erosion is known to occur on texture contrast (or duplex) soils where hard setting surfaces increase runoff (Ciesiolka, 1987; Hughes et al., 2009b).

The Fitzroy catchment has relatively diverse land use, however cattle grazing is the dominant industry (Figure 2). There are large areas of dryland cropping in the western part of the catchment, largely on basaltic soils which have been identified as a major source of fine sediment delivered to the coast (Douglas et al., 2008). Significant irrigated cropping also occurs around the townships of Emerald, Theodore and Biloela. Mining is also a major industry particularly near Moranbah, Dysart, Blackwater and Moura (Figure 1).

The river channels in the Fitzroy basin have a diverse range of morphologies. Of the 9,600 km of channels (with drainage areas greater than 100 km²), 24 per cent are anabranching (Amos et al., 2009). Almost 60 per cent have a mean floodplain width of over 1 km. The rivers and floodplains have been extensively altered with 57 un-regulated gauges and 39 regulated gauges in the Fitzroy Basin (Sinclair Knight Mertz, 2012). Most of the regulated gauges are in the form of small weirs and dams. The extensive flow regulation has likely altered connectivity between channels and floodplains and the storage of sediment in the river system (Hughes et al., 2009a; Hughes et al., 2009c; Thompson et al., 2011). It is also possible that channel migration and erosion has been influenced by the location of water storages.

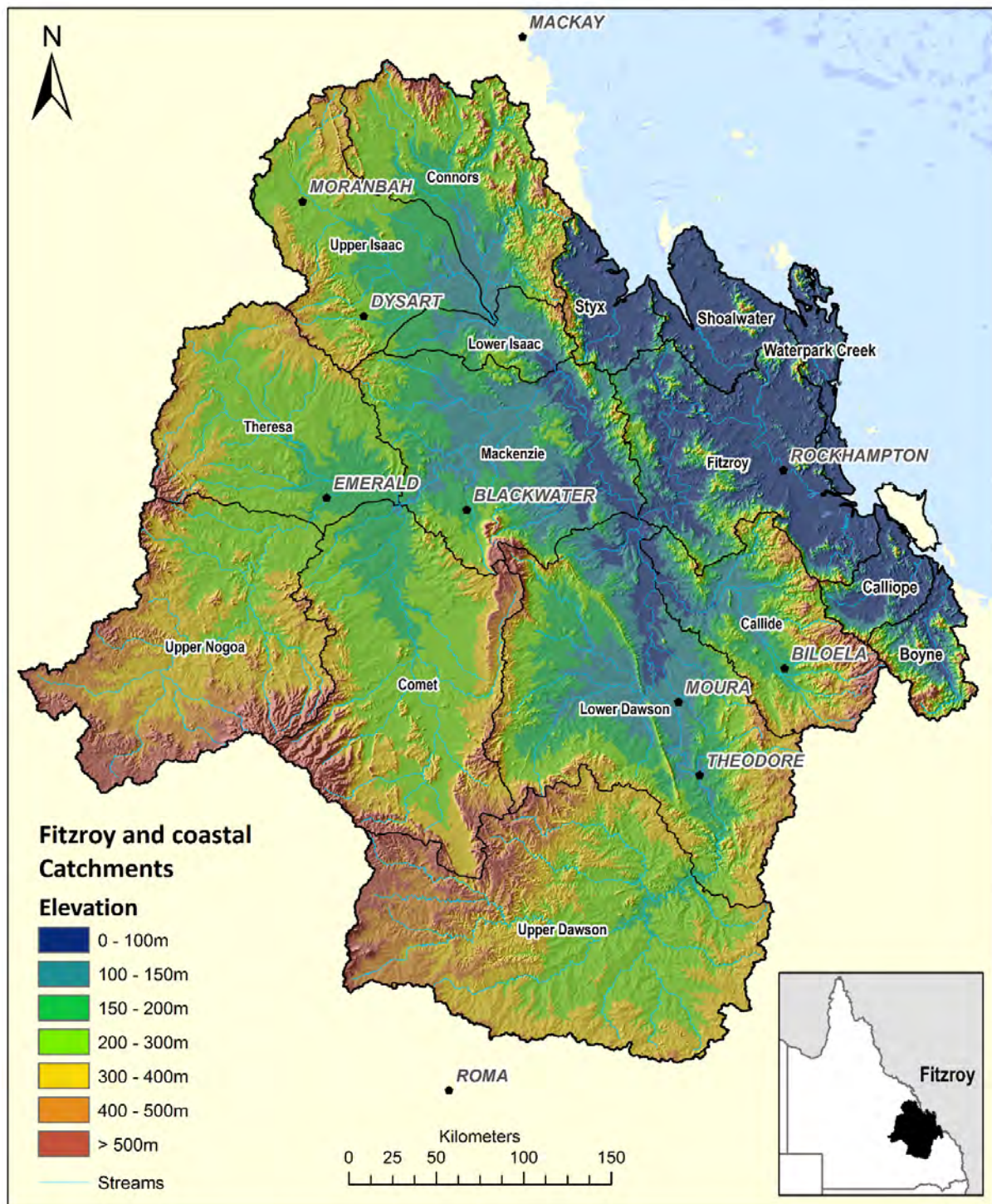


Figure 1: Fitzroy Region showing Fitzroy Catchment and sub-basins, also includes the smaller coastal basins of the Styx, Shoalwater, Waterpark, Calliope and Boyne.



Figure 2: Major Land uses of Fitzroy and coastal catchments.

3.2 Mackay Whitsunday

The Mackay Whitsunday region covers ~9,100 km² and stretches for ~300 km along the coast between the towns of Clairview and Bowen (~300 km). The Whitsunday Islands group is situated off the coast between Bowen and Mackay (Figure 3). The rivers in this region include the Pioneer, Proserpine, O'Connell and Plane Creek basins. This project focuses specifically on remediation sites on the O'Connell River system, however, control sites from adjacent basins were also included in the study. A detailed description of the catchments can be found in Packett et al., (2014). In summary, the region has a tropical savannah (Aw) climate in the northern parts (Proserpine region), and temperate (Cwa) in southern areas under the Koppen–Geiger classification system (Peel et al., 2007). Average annual rainfall varies from ~1000 mm per year in the western regions to ~1800 mm per year in the east, with most of the rainfall and runoff occurring between December and March (Packett et al., 2014).

The geology and landforms in the region are complex with all catchments having their headwaters in the Great Dividing Range which has historically been the site of faulting, volcanism and uplift. The rivers flow off the range, and onto the coastal plain, where there is a range of soil types from cracking clays and texture contrast soils in the western regions, to alluvial plains with clay loams, sandy and acid sulphate soils in the east (Packett et al., 2014).

The land use in the region is dominated by sugar cane (~20%) on the floodplains, and cattle grazing (~44%) and Conservation and forestry (28%) dominating the steeper western upland areas. There are two storages with > 10,000 ML capacity (Peter Faust Dam and Teemburra Dam) and several smaller weirs in the region (Figure 4). A more detailed description of the catchment and its ecological assets can be found in the Great Barrier Reef Marine Park Authority (2013) report.

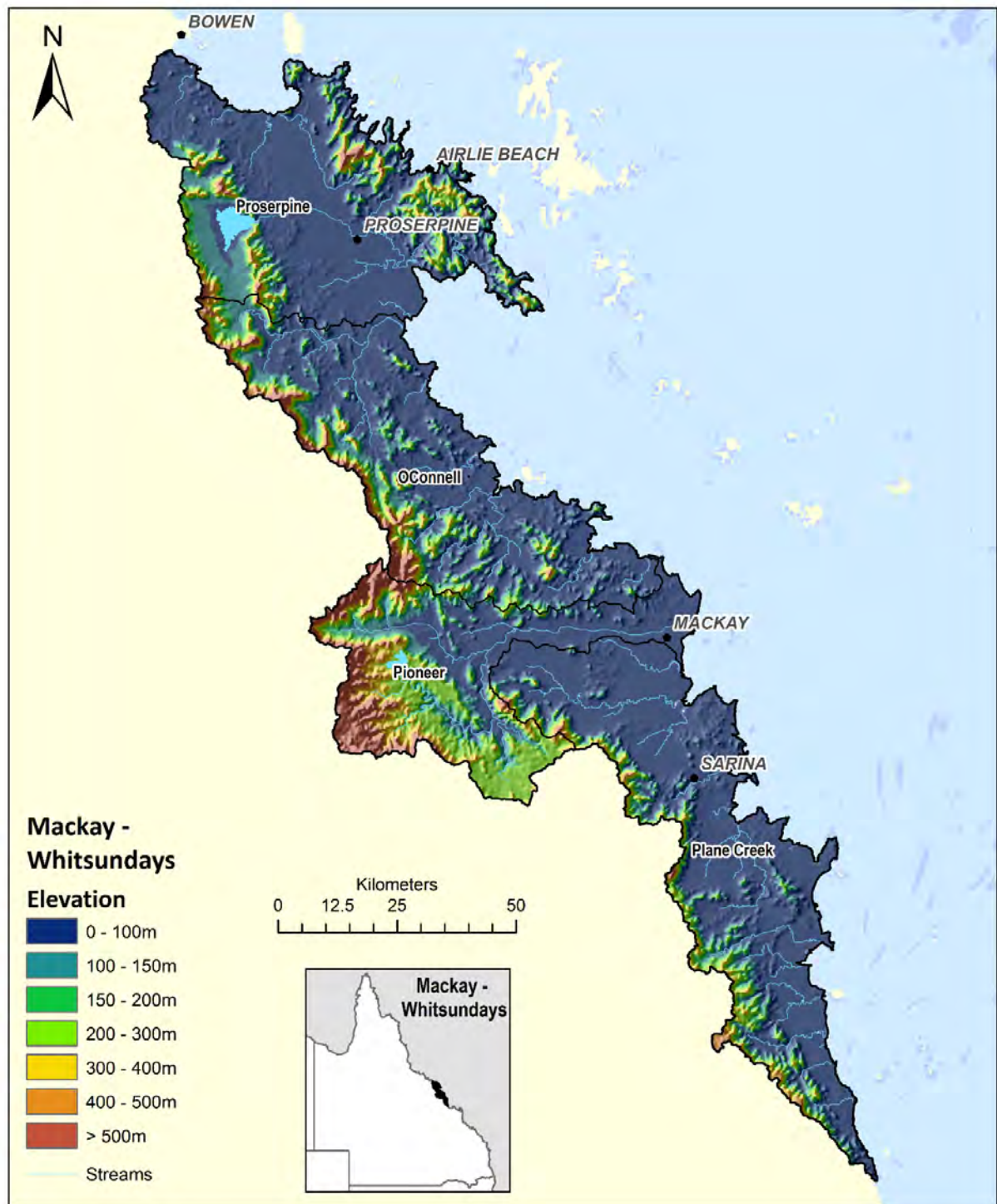


Figure 3: Mackay Whitsundays region showing the major sub-basins of the Proserpine, O'Connell, Pioneer and Plane Creek.

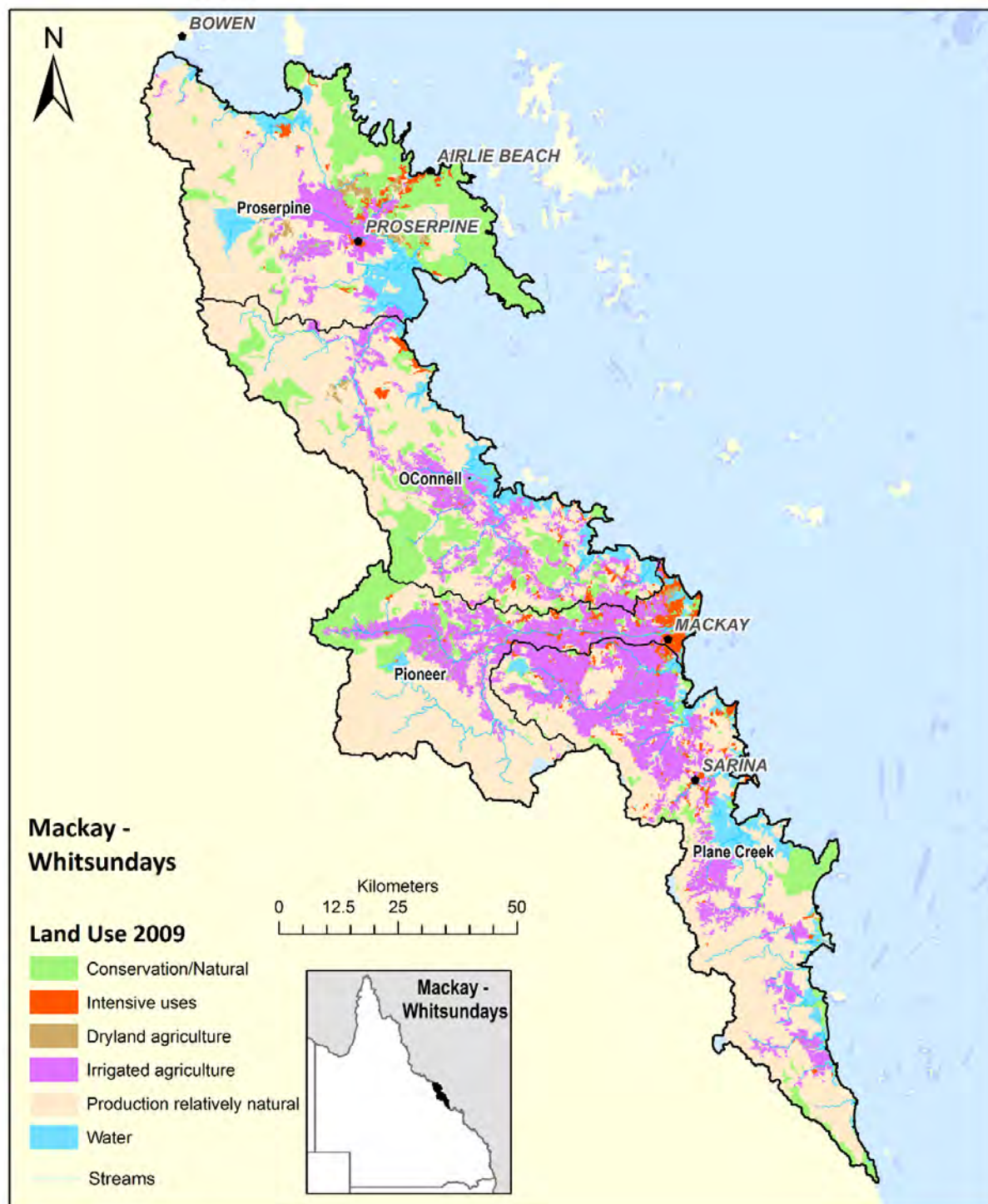


Figure 4: Major land uses of the Mackay Whitsundays region.

4. METHODS

4.1 Review of existing studies

Prior to undertaking an assessment of the historical changes in channel width for the Fitzroy and Mackay Whitsunday catchments, a literature review of existing studies of bank erosion and channel change in the GBR catchments was undertaken. Given the interest and investment in riparian remediation projects in the GBR catchments, it is interesting to note there have been relatively few studies that have measured the rates of bank erosion or channel change. A summary of known and available studies, the methods used and median or mean channel erosion rates are presented in Section 5.1.

4.2 Case studies: site selection

The Fitzroy Basin Association and the Mackay Whitsunday Regional body (Reef Catchments) provided a list of recent riparian remediation sites that were undertaken using funding from the Reef Trust on-ground investments (<http://www.environment.gov.au/marine/gbr/reef-trust>) or the Systems Repair program (Reef Water Quality Protection Plan Secretariat, 2014). The remediation projects were undertaken prior to 2015 and involved a range of activities including fencing riparian areas, providing off-river stock watering access in the case of the Fitzroy, and channel realignment, remediation and re-vegetation in the O'Connell (Alluvium, 2014). This project was not designed to evaluate the process by which the sites were chosen for remediation. Instead, this project was to evaluate if there was a difference in channel width for sites with good (>75%) riparian vegetation and poor (<50%) riparian vegetation over the historical air photo record. The remediated sites were also evaluated using this approach. Using the list of riparian remediation sites provided by the Regional bodies, five sites were chosen in both the Fitzroy and Mackay Whitsunday catchments. It was not possible to evaluate all sites, as some sites were on streams too small to be measured on the aerial photos. Generally streams with a catchment area less than 50 km² were not suitable for this approach.

To evaluate where the remediation sites were on the bank erosion spectrum, we also identified control sites that had good levels of riparian vegetation, and impacted sites with low levels of riparian vegetation. The stream links used to define a reach were based on the Source Catchments node link network (Dougall et al., 2014; Packett et al., 2014). The actual proportion of riparian vegetation was derived using remote sensing (see Section 4.4) and expressed an average for the stream link (see Figure 5). The aerial photos used to assess changes in channel width often only covered a proportion of the stream link (Figure 5), but due to time limitations, the % of riparian vegetation estimated for that reach was also used to represent the % of riparian vegetation for the aerial photo.

There is very little research detailing what amount of riparian cover a reach should have to reduce channel erosion. Brookes et al., (2014) identified 70% as an important threshold for woody riparian vegetation that is likely to help reduce the rate of bank erosion in Queensland rivers. Therefore control sites were selected that had greater than 70% riparian vegetation in the 100 m buffer from the stream network. It was more difficult to set a threshold for impacted sites. The initial selection of reaches to represent 'impacted' sites were based on sites with low amounts (<25%) of riparian vegetation using Google Earth, but because the stream links

used to derive the % vegetation were often longer than the reach length evaluated using aerial photos (see Figure 5), the final % riparian vegetation value reported with each link is often much higher, and closer to 50% in some cases (see Table 1 and Table 2). Therefore a threshold of 50% riparian vegetation cover was used to identify impacted reaches.

Where possible, the sites were chosen from a range of sub-basins within the Fitzroy catchment to provide a representative sample of geomorphic characteristics (drainage area, stream slope, geology etc) (Table 1 and Figure 6). Only three control and impact sites were chosen in the Mackay Whitsunday as it is a much smaller area (Table 2 and Figure 7). Where possible, control and impact sites were located as close as possible to the remediation site, however, when comparable sites could not be found, alternative sites were sort. In the Mackay Whitsunday (MW) region insufficient control and impact sites could be found in the O'Connell catchment, and therefore the whole MW region was included. The specific location (latitude and longitude) of each remediation site is not listed for privacy reasons, however, the general distribution of sites is shown in Figure 6 and Figure 7.

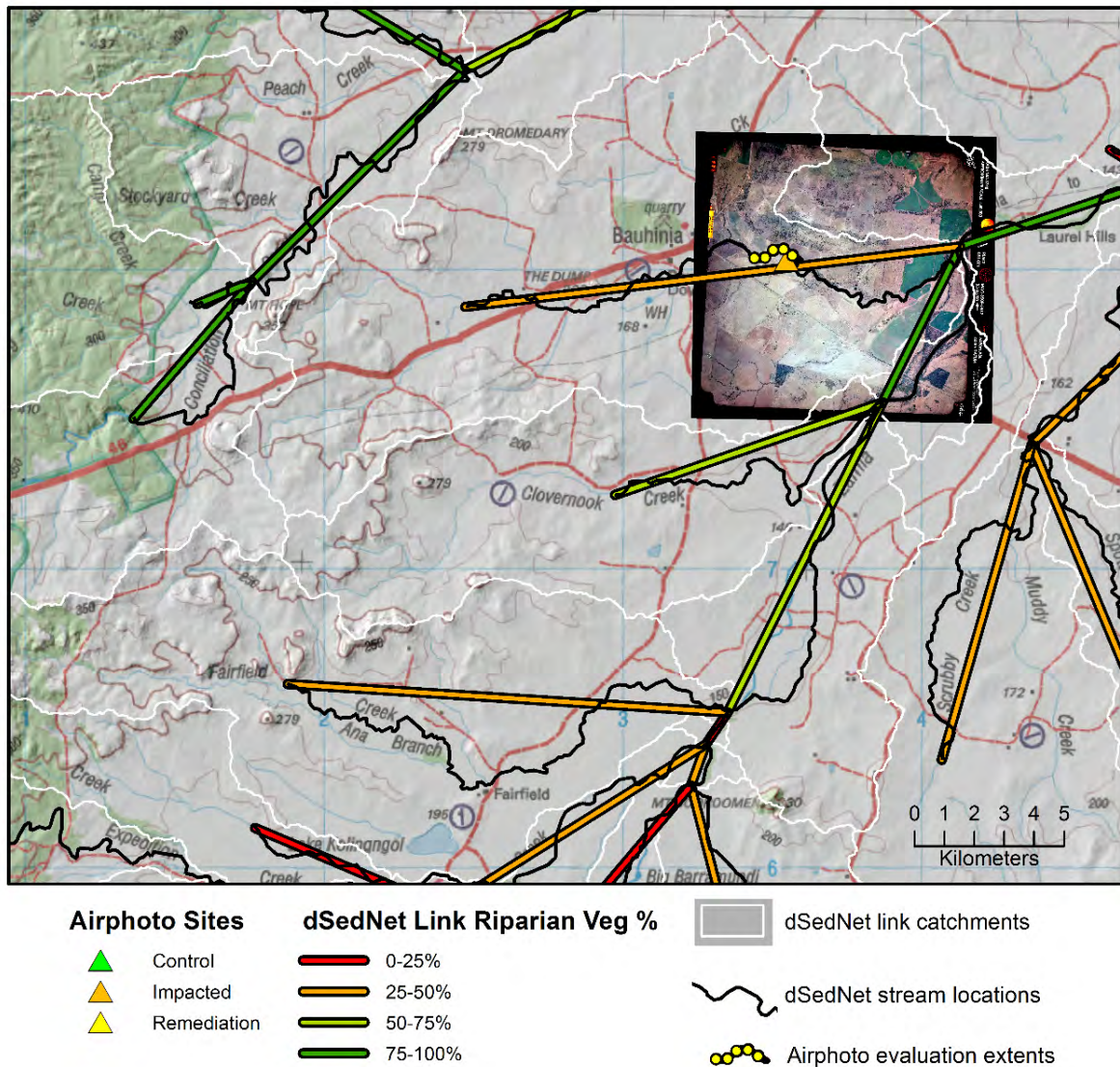


Figure 5: An example of the stream reach as represented by the Source Catchments stream node link network. The aerial photos often covered only a proportion of the stream reach length, however, the % riparian vegetation from the entire link was used to represent the % riparian vegetation in the photos. In this case, the % riparian vegetation for this air photo site is 25-50%.

4.3 Channel condition characteristics

To enable the assessment of the effectiveness of riparian vegetation on channel change, the geomorphic conditions for each sample group (control and impact) needed to be as similar as possible to allow for an assessment of the influence of riparian vegetation. At each reach, three variables that are known to influence bank erosion and channel change were calculated. These included (i) upstream catchment area, which is a surrogate for discharge or flow; (ii) average channel slope, which is a surrogate for stream power; and (iii) the % of fine sediment (<63 μm) in the bank material. There was insufficient time or resources in this project to collect data on these variables, therefore the Source Catchments input data were used. Readers are encouraged to access these reports for detailed methods (Dougall et al.,

2014; Packett et al., 2014), but in brief, the catchment area and slope data were generated from the 100 m hydrologically enforced DEM using a 30 km² threshold, and the % fine sediment was based on the ASRIS soil layer data adjacent to the stream link. Metrics for the Fitzroy catchment are presented in Table 1, and the Mackay Whitsundays in Table 2.

4.4 Vegetation mapping

The riparian vegetation mapping used in this study was the Queensland Government Reef catchments riparian data layer (Queensland Government, 2014). In brief, the riparian forest data layer represents foliage projective cover, and is created using a range of Landsat satellite imagery (1984 – 2013), which has a spatial resolution of 30 m. The riparian area is defined as a 100 m buffer based on the Australian Hydrological Geospatial Fabric drainage layer (version 2.1.1). Scarth et al., (2008) has estimated that a foliage projected cover of 11 % is equivalent to ~ 20% crown cover, and the prediction errors are within ~11 % (Kitchen et al., 2010). Ground cover (grasses) are not included in the riparian forest layer. For each stream link on the 1:250 k drainage network, the riparian zone is assigned a % of riparian vegetation between 0 and 100%. The % of riparian vegetation attributed to each site is shown in Table 1 for the Fitzroy catchment and Table 2 for Mackay Whitsundays.

Table 1: Description of selected Control, Impact and Remediation reaches in the Fitzroy catchment

Catchment and sub-catchment	Reach number	Drainage area (km ²)	Slope (%)	Bank material (% fines <63 µm)	% riparian vegetation
Control sites	1	52,370	0.02	76	81
	2	752	0.06	35	96
	3	50,730	0.06	61	78
	4	630	0.23	55	95
	5	1,480	0.04	53	92
Impact sites	1	205	0.14	80	39
	2	260	0.06	71	46
	3	125	0.26	79	31
	4	78	0.20	81	49
	5	133,800	0.03	40	41
Remediation sites	1	6,230	0.05	82	46
	2	133,790	0.03	40	41
	3	2,210	0.07	81	62
	4	10,900	0.07	80	60
	5	820	0.14	83	71

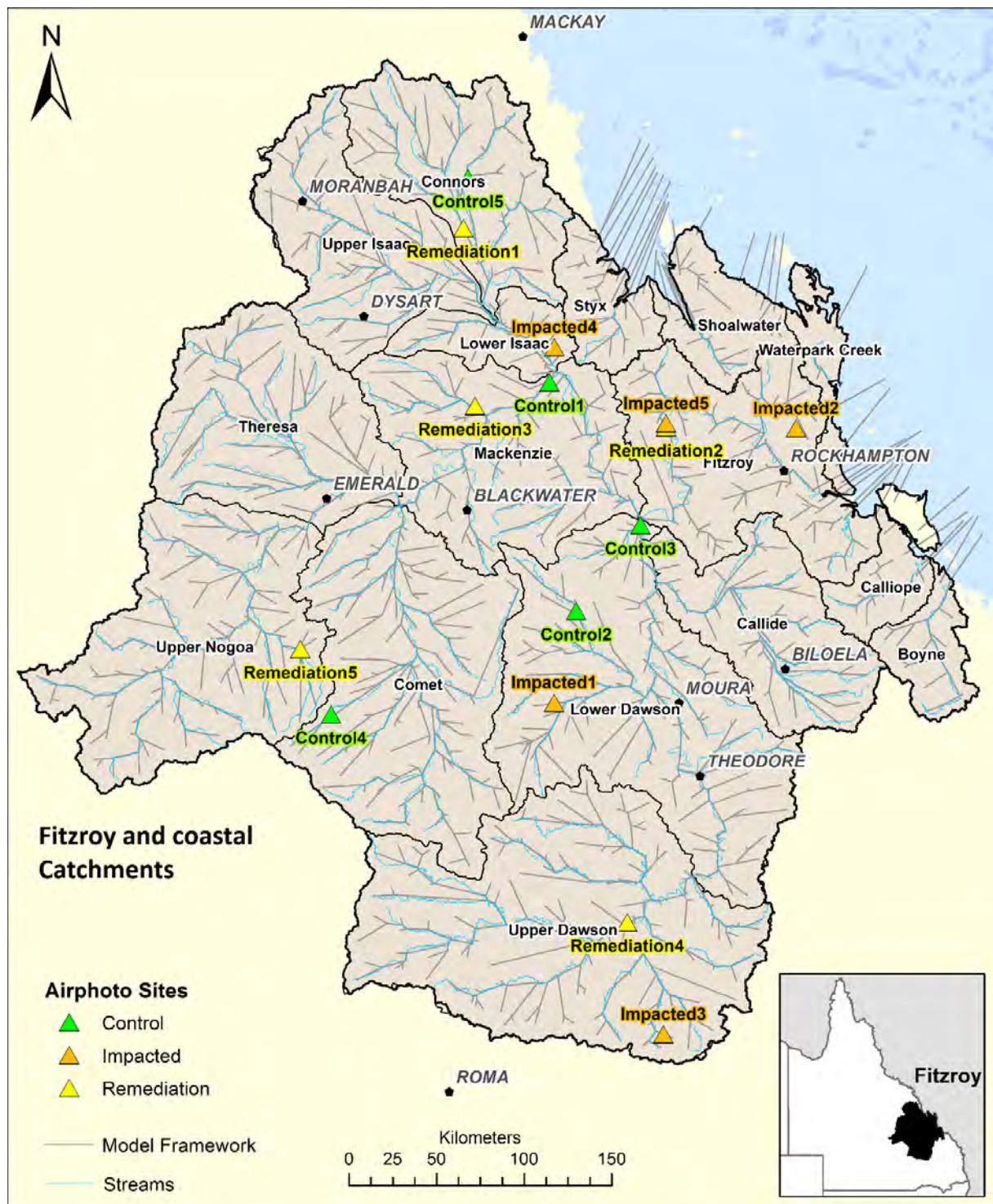


Figure 6: Location map of control, impacted and remediation sites in the Fitzroy catchment

Table 2: Description of selected Control, Impacted and Remediation reaches in the Mackay Whitsunday catchment

Catchment and sub-catchment	Reach number	Drainage area (km ²)	Slope (%)	Bank material (% fines <63 µm)	% riparian vegetation
Control sites	1	102	0.04	64	79
	2	124	0.45	422	84
	3	392	0.1	47	52
Impacted sites	1	342	0.12	35	39
	2	835	0.18	48	47
	3	1,492	0.03	46	49*
Remediation sites	1	222	0.18	42	51
	2	222	0.18	42	51
	3	222	0.18	42	51
	4	106	0.47	48	69
	5	99	0.18	49	63
	6**	373	0.12	47	47

*The % riparian vegetation for this reach was computed at >50%, however, this was considered to be distorted by areas of high cover up and downstream of the specific site evaluated using the aerial photos. Riparian vegetation at the specific site where the photos were assessed was considered to be <30% cover, however, a nominal value of 49% was set in the table for consistency with other sites. ** this was a late addition to the assessment and not included in the statistical analysis

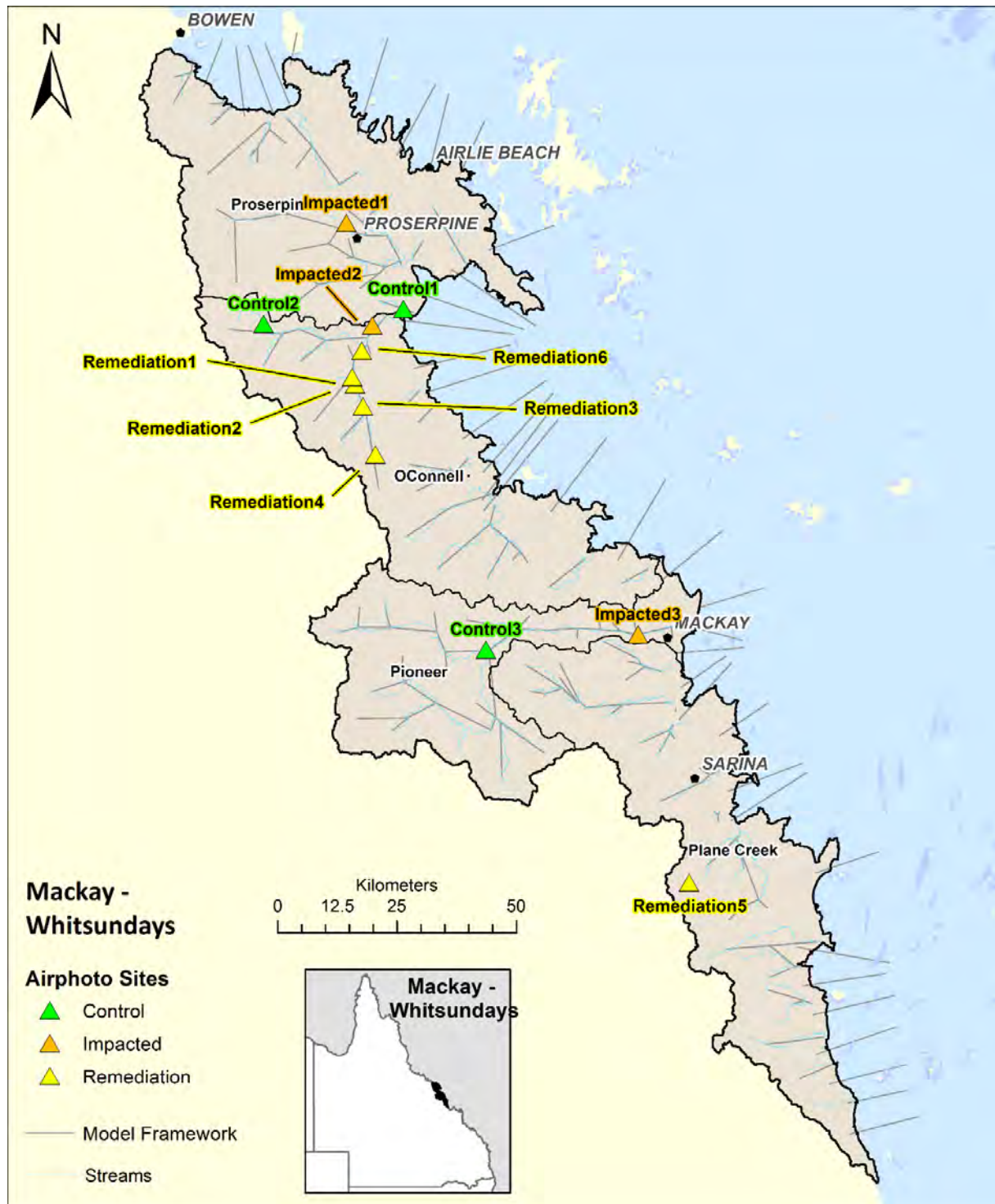


Figure 7: Location map of control, impacted and remediation sites in the Mackay Whitsunday catchment

4.5 Aerial photo interpretation and analysis

At each of the reaches chosen (Control, Impact or Remediated) a time sequence of aerial photos from the Queensland Government historical photo archive were collated. Representative photos from each decade spanning from ~1950 to 2012 were assessed for their suitability (i.e. image quality). Not all reaches had suitable photos from every decade (see Appendix A). Each photo was then rectified to the SPOT 2012 image using the

Quantum GIS software geo-referencing plugin. The rectification process used a minimum of 7 points per photo. This approach also calculates the error between photos (based on the nearest neighbour resampling method). The projection was GDA 1994 Australia Albers Central Meridian.

Following rectification, a representative reach length of ~1.6km in the Fitzroy catchment and ~800m in the Mackay Whitsundays were defined. Within each reach, five cross-sections were selected at ~400 m and ~200 m intervals for the Fitzroy and MW catchments, respectively. The width of the channel (from bank top to bank top) was recorded at the exact same position for each cross-section in each photo year. Control points for the cross sections were digitised along the drainage line on both the right and left high bank. It is acknowledged that assessing bank top on aerial photos is challenging, and there are a number of sources of potential error using this method, including photo distortion and measurement error (Bartley et al., 2008). To allow and correct for distortion errors from the aerial photos, cross-sections at the edges of aerial photos were avoided. Other studies have suggested that the error to do with photogrammetry and mapping is in the order of 3–4% (Hooke and Redmond, 1989) and up to 17% (Williams et al., 1979). Operator consistency was maintained by having only one person undertake the aerial photo interpretation. It was determined that streams with a width of <30 m were unsuitable for this technique, and therefore sites were biased to larger streams.

4.6 Data analysis

There were two steps involved in the data analysis. Firstly, Sigmaplot (version 12.5) was used to determine if there was any statistical difference between the control and impact groups in terms of their channel condition characteristics including upstream catchment area, average channel slope and % of fine sediment in the bank material. The assumption is that there is no significant difference between any of these attributes between the two groups, and that only the % of riparian vegetation is significantly different. This then allows for any difference in channel change to be directly attributable to the presence of riparian vegetation. Two tailed T-tests were used when the data were normally distributed and Mann-Whitney Rank Sum Tests when the data were not.

The second data analysis approach was used to assess the change in channel width (m yr^{-1}) between photo years with the hypothesis that sites with greater riparian vegetation will show less change in channel width (as a surrogate for erosion) than sites with less riparian vegetation. All the aerial photo measurements were collated in MS Access. Absolute channel widths are presented in Appendix A, and only the change in channel width from the previous photo period is presented in the main body of the report. Data analysis of statistical changes in channel width were undertaken using Sigmaplot (version 12.5). Mann-Whitney Rank Sum Tests, a non-parametric approach, were used to test for significance between groups and air photo periods.

Given the relatively small sample sizes, large spatial scale and level of uncertainty in many of the data inputs in this study (e.g. remotely sensed vegetation data and DEM derived channel slopes), a more conservative significance value of 10% or 0.1 was considered appropriate in this study. This increases the chance of committing a type I error (Zar, 1996), [which is incorrectly attributing a statistical difference in the analysis that is not real], however, this is considered appropriate given the data involved.

5. RESULTS

5.1 Synthesis of bank erosion rates in the GBR

To quantify the effectiveness of riparian remediation, it is important to first know what the relative rates of channel erosion are for different rivers in the GBR catchment. Studies of bank erosion and channel change following catastrophic floods (e.g. >1 in 100 year recurrence interval), such as that on the Burnett River in 2011, demonstrate that erosion rates can be as high as $\sim 5 \text{ m yr}^{-1}$ on the main river channel (Table 3). However, most studies of bank erosion or channel change in the rivers draining to the GBR have shown much lower rates of channel change in the order of $< 1 \text{ m yr}^{-1}$, and commonly lower than 0.1 m yr^{-1} in the drier catchments (Table 3). A range of different methods were used to derive these rates, including erosion pins, historical aerial photos and LiDAR, and the definitions of bank morphology also vary between the studies. Not all of the studies actually quantify the condition of the riparian zone where the erosion measurements were taken. This makes direct comparison of the rates between the studies difficult. Nonetheless, this synthesis does provide a summary of known studies in the GBR catchments, and provides some baseline data against which remediation evaluation can initially be evaluated. Interestingly, bank erosion rates following major flooding can be high ($\sim 5 \text{ m yr}^{-1}$), otherwise bank erosion on the GBR rivers are relatively low by world standards (Hooke, 1980).

Table 3: Summary of bank erosion rates measured in GBR catchments. Catchments listed from north to south.

Catchment	River	Approximate catchment size (km ²)	Estimated rates of channel erosion and change (m yr ⁻¹)	Method or approach used	Reference
Daintree	Daintree River	~1320 km ²	~0.74 (± 0.47) m yr ⁻¹ , which is equivalent to ~0.8% yr ⁻¹ change in channel width	Repeat cross-section surveys over 3 wet seasons	Bartley et al., (2008)
Mulgrave	Mulgrave River	~798 km ²	Estimated that <6% of the total length of the Mulgrave River had undergone measurable channel movement since European settlement	Changes in the river's planform characteristics were identified using historic parish maps and aerial photographs	Leonard and Nott (2015b)
Burdekin	Upper Burdekin River	~30,000 km ²	0.073 m yr ⁻¹ , which is ~0.03% of channel width	Aerial photos over a 40 year period linked to cross-sectional surveys of the Upper Burdekin channel	Bainbridge (2004)
Burdekin	Weany Creek	~14 km ²	0.034 m yr ⁻¹	Erosion pins and repeat cross-section surveys over 3 years (during a drought)	Bartley et al., (2007).
Fitzroy	Various	140,000 km ²	0.046 m yr ⁻¹	Based on changes in channel width between ~1950 and 2012 at 5 control reaches, 15 cross-sections (with >50% riparian vegetation)	This study
Mackay-Whitsundays	O'Connell River	~856 km ²	0.001 to 0.1 m yr ⁻¹ .	Repeat LiDAR over a 54 km stretch of the main channel	Brookes et al (2014)
Mackay Whitsundays	Various	~9,100 km ²	0.061 m yr ⁻¹	Based on changes in channel width between ~1950 and 2012 at 5 control reaches, 15 cross-sections (with >50% riparian vegetation)	This study
Burnett River	Burnett River	~32,220 km ²	0.74 – 5.75 m yr ⁻¹ (2.94 – 23.0 m between 2009 and 2013)	Bank retreat calculated from aerial photography 2009 to 2013. A catastrophic flood (>1 in 100 year recurrence interval) occurred in 2011.	Simon et al., (2014)

5.2 Fitzroy

A comparison between the control and impact groups in the Fitzroy catchment determined that there was no statistical difference between upstream catchment area ($p = 0.151$), average channel slope ($p = 0.378$) and % of fine sediment in the bank material ($p = 0.206$). However, given the low number of sites ($n = 5$) in each sample, caution must be used in over-interpreting these results. There was, however, a significant difference between the % of riparian vegetation for the control and impact groups ($p < 0.001$). This then allows us to attribute any significant difference in channel change to the presence or absence of riparian vegetation.

When all of the channel change data are combined together into the control and impact groups, there is no statistically significant difference in the change in channel width between sites with good ($>75\%$) and poor ($<50\%$) riparian vegetation ($p = 0.481$). The median channel change (m yr^{-1}) for control sites with good ($>75\%$) vegetation was an average channel expansion of 0.0464 m yr^{-1} and for impacted sites with poor ($<50\%$) vegetation there was an overall channel contraction of $-0.0086 \text{ m yr}^{-1}$ (Table 4). The original channel width data for each photo year is presented in Appendix A.

The analysis suggests that the only time that there was a significant difference ($p = 0.018$) in channel width change between control and impacted sites is from the 1960's to 1970's when the control sites actually had a median channel expansion of 0.0378 m yr^{-1} , whereas the Impacted sites with $<25\%$ vegetation, actually underwent channel contraction of -0.140 m yr^{-1} (Table 5; Figure 9). Overall, there is very little difference in the change in channel width between control and impacted sites, and therefore our hypothesis that sites with more riparian vegetation would undergo less channel expansion was rejected (Figure 8). Given there is no significant difference between control and impact sites, comparison with remediated sites is somewhat redundant.

It was not possible to present images of all the aerial photos used in this report. Instead, examples for a control, impacted and remediation site from the Fitzroy catchment are shown Figure 10 to Figure 12. Despite the control site (Figure 10) having an average of 95% riparian vegetation the channel underwent an average of 0.43 m yr^{-1} of channel expansion between 1971 and 2012. Four out of five control reaches underwent channel expansion, and only one reach underwent channel contraction. The impacted site example (Figure 11), has $\sim 31\%$ riparian vegetation but has undergone $\sim 0.46 \text{ m yr}^{-1}$ of channel contraction (as opposed to expansion or erosion), between 1983 and 2012 which suggests that the period of channel expansion, possibly caused by a lack of riparian vegetation, may have occurred prior to first aerial photo in 1962. The remediation site (Figure 12) appears to have been relatively stable with only 0.08 m yr^{-1} of channel expansion between 1957 and 2012. The implications of these results will be discussed in more detail in Section 6.

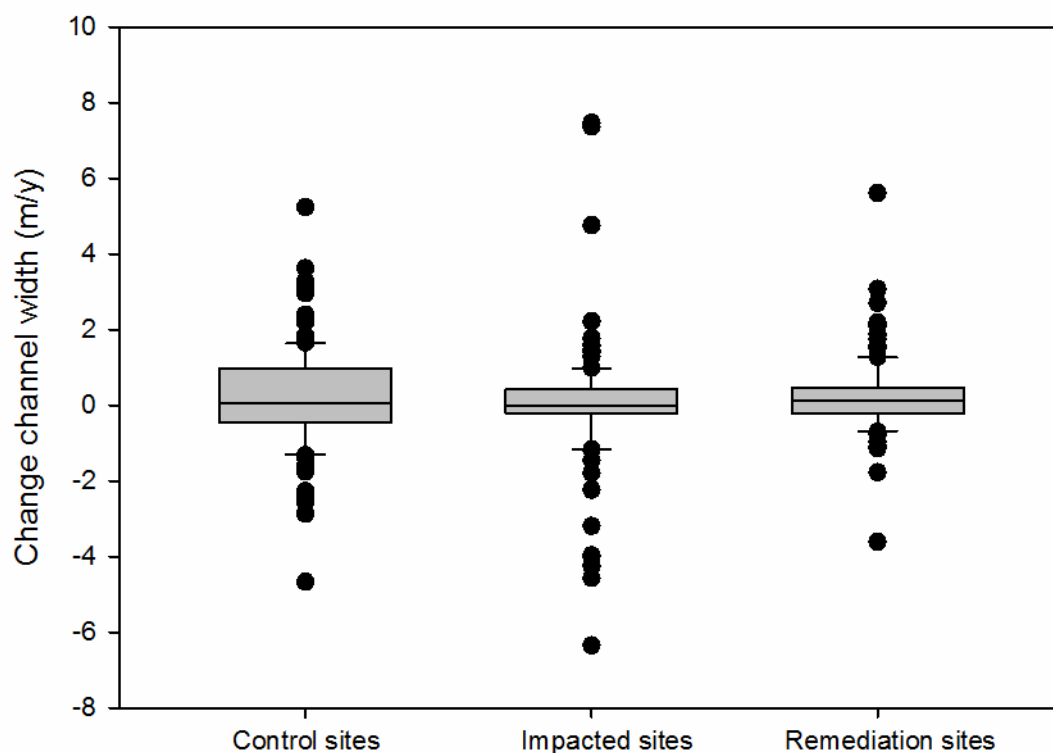


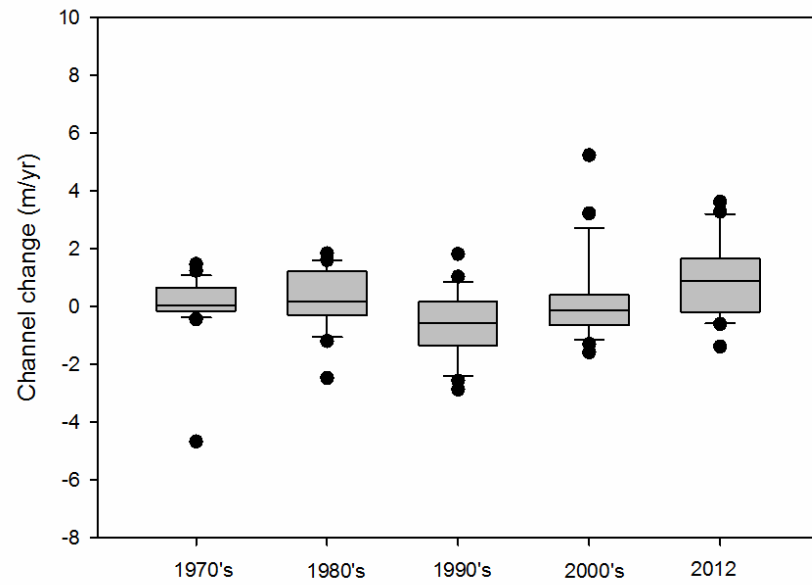
Figure 8: Comparison of all control, impacted and remediation sites (independent of photo year) for the Fitzroy catchment

Table 4: Comparison of median channel width change rates (m yr^{-1}) between control (>75% riparian vegetation), impact (<50 % riparian vegetation) and remediated sites in the Fitzroy catchment. Positive values = channel expansion and negative values = channel contraction.

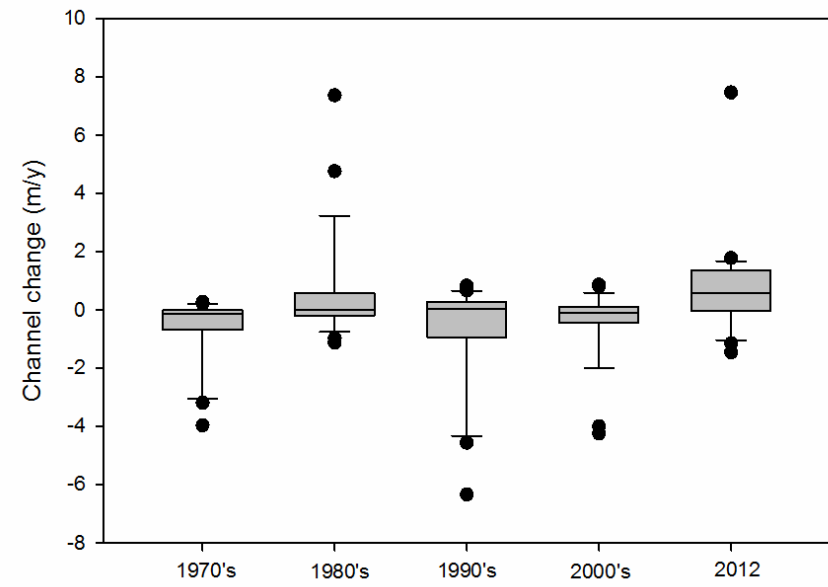
Group	Sample size (no. of cross- sections)	Median change in channel width (m yr^{-1})	25 th percentile change in channel width (m yr^{-1})	75 th percentile change in channel width (m yr^{-1})
Control	125	0.0464	-0.441	0.968
Impact	120	-0.0086	-0.225	0.423
Remediated	136	0.129	-0.231	0.483

Table 5: Comparison of Control and Impact sites between aerial photo years (decades) for the Fitzroy catchment.
Positive values = channel expansion and negative values = channel contraction. Significant differences highlighted in bold and italics.

Year	Site	Median channel width change (m yr ⁻¹)	Significance (p value)
1960's- 1970's	Control	0.222	<i>0.018</i>
	Impact	-0.140	
1970's- 1980's	Control	0.176	0.793
	Impact	-0.005	
1980's -1990's	Control	-0.555	0.288
	Impact	0.0325	
1990's- 2000's	Control	-0.132	1.0
	Impact	-0.0860	
2000 -2012	Control	0.893	0.384
	Impact	0.562	



(A)



(B)

Figure 9: Comparison of changes in channel width of (A) control and (B) impacted sites for the Fitzroy catchment.



Figure 10: An example of a control site (~95% riparian vegetation) on the Fitzroy River (Control site 4).



Figure 11: An example of an impacted site (~31% riparian vegetation) on the Fitzroy River (Impact site 3).



Figure 12: An example of a remediated site (~71% riparian vegetation) on the Fitzroy River (Remediation site 5).

5.3 Mackay Whitsunday

A comparison of the control and impact groups in the Mackay Whitsunday catchment identified no statistical difference between upstream catchment area ($p = 0.119$), average channel slope ($p = 0.554$) and % of fine sediment in the bank material ($p = 0.372$). There was, however, a significant difference (using the $p < 0.1$ threshold) between the % of riparian vegetation for the control and impact groups ($p = 0.065$). This then allows us to attribute any significant difference in channel change to the presence or absence of riparian vegetation. In the Mackay Whitsunday catchments, when all of the channel change data are grouped together, there is a weak, but statistically significant difference ($p = 0.074$) in the change in channel width between the control and impact groups. But the significant difference is not in the direction that we expected. Interestingly, the median channel change (m yr^{-1}) for control sites was 0.061 m yr^{-1} suggesting that, on average, the control channels had widened by $\sim 6 \text{ mm}$ per year, whereas the impact sites underwent an overall contraction of -0.233 m yr^{-1} (Table 6). This difference was very biased by the 1960's and 1970's period when the impacted reaches underwent greater channel contraction than the control reaches (Table 7).

In addition to there being an overall significant difference between control and impacted reaches in terms of channel change, there was also a significant difference between the 1950's and 1960's when the control sites actually had a median channel expansion of 0.0378 m yr^{-1} , compared to the impacted sites that actually underwent channel contraction of -0.140 m yr^{-1} (Table 7). In the decades representing the 1970's, 1980's and 2000's, the vegetated control sites all were significantly ($p < 0.1$) more stable and underwent less channel expansion than the less vegetated sites. The 1990's was relatively stable for both control and impacted sites (Table 7). Given that the significant differences between control and impact sites were not necessarily what we were expecting for these streams, a comparison with remediated sites becomes somewhat redundant.

Figure 15 to Figure 17 provide examples of the change in channel location and planform, for a control, impacted and remediation site. In the control site example (Figure 15), the channel appears is relatively stable due the confinement of the channel within the valley walls, and although the right bank is extensively vegetated, the amount of vegetation on the left bank, particularly adjacent to the large bend at the centre of the photo, has decreased considerably between 1970 and 2012. The impacted site example (Figure 16) is set amongst an extensively cropped area and the remnant riparian zone is very narrow. The macro-channel has remained rather stable between 1961 and 2012 despite the reduction in riparian vegetation. However, the wetted perimeter, that includes mid-channel bars and sand deposits, has moved considerably over the air photo period. This lateral within channel movement is considered a natural process, and occurs on well vegetated rivers, and does not represent bank erosion or channel change. The final example is the most interesting (Figure 17). Using repeat LiDAR from 2010 and 2014, and subsequent DEM's of difference, this site was identified as having recently undergone $\sim 100,000 \text{ m}^3$ of bank erosion (Figure 18)(Alluvium, 2014). In response to the Alluvium study, Reef catchments undertook remediation to stabilise this site and reduce erosion. This was conducted using log groins and bank re-shaping (Figure 19). The aerial photo analysis undertaken in this study has been able to provide a longer term context (~ 50 year period) to compare to the four years of LiDAR channel change data. What the aerial photos show is that the main channel (or thalweg) was on the left side of the macro-channel in 1961 and there was a minor secondary flood-runner on the right had side of the channel. It appears that the minor flood- runner on the right

increased in size and capacity in the 1970's and 1980's, and then a complete channel avulsion of the thalweg has occurred sometime between 2004 and 2009 (see Figure 17). The right hand channel has since enlarged and is now the obvious main channel in 2012. Overall, the channel at this site has expanded an average of $\sim 1.45 \text{ m yr}^{-1}$ over the last 50 years, which is ~ 24 times higher than the median rate for the control sites in the MW region (Table 6). This assessment helps justify the need for remediation at this site; however, there is an urgent need to evaluate the cost-effectiveness of these engineered remediation projects versus cheaper fencing and revegetation options. International studies suggest that in-stream structures often fail in dynamic and mobile river settings (Miller and Kochel, 2013). The implications of these results will be discussed in more detail in Section 6.

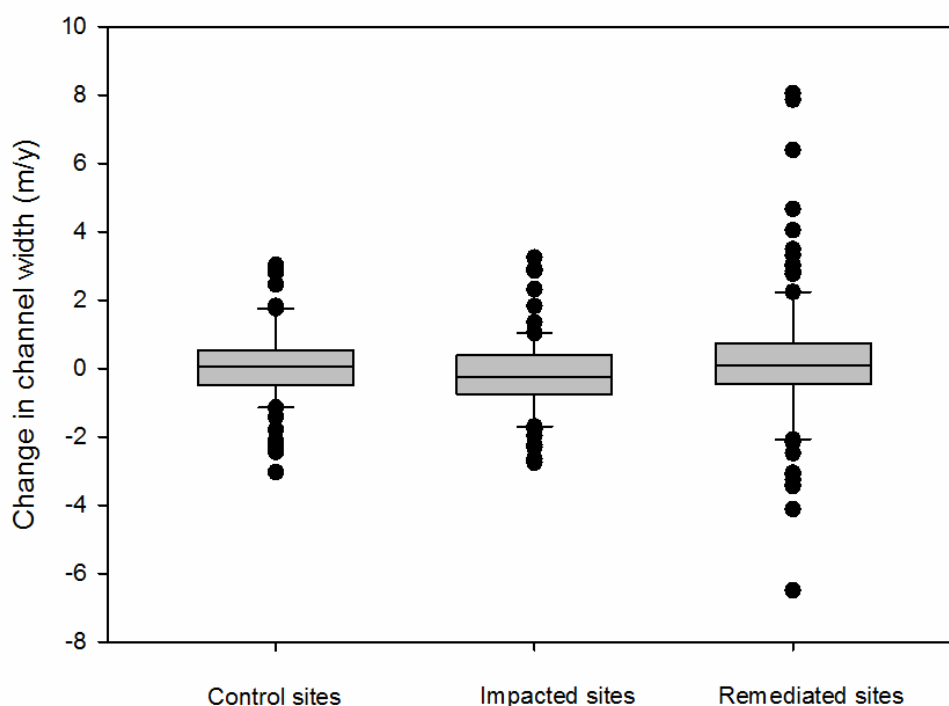


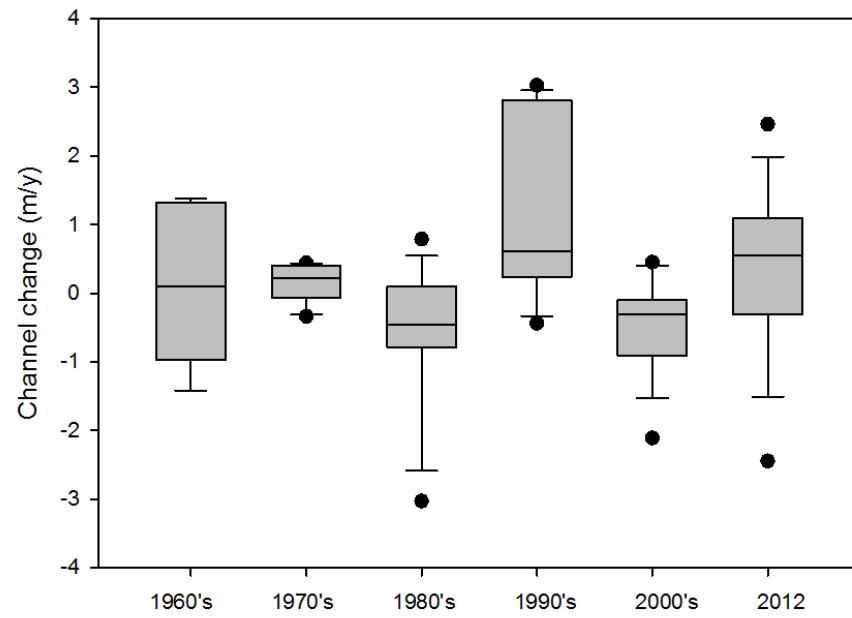
Figure 13: Comparison of all control, impacted and remediated sites for the Mackay Whitsunday catchment.

Table 6: Comparison of median channel change rates (m yr^{-1}) between control ($>75\%$ riparian vegetation), impact ($<50\%$ riparian vegetation) and remediated sites in the Mackay Whitsunday. Positive values = channel expansion and negative values = channel contraction.

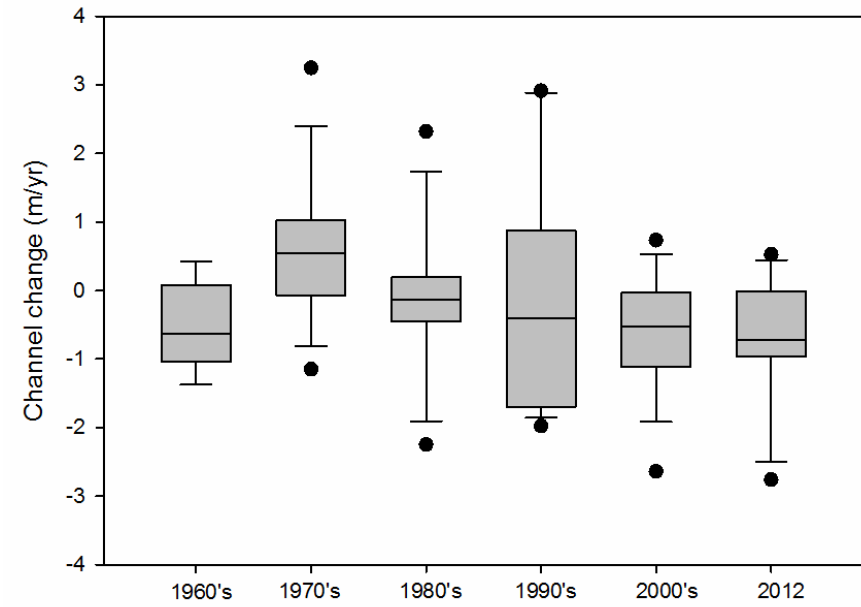
Group	Sample size (no. of cross- sections)	Median change in channel width (m yr^{-1})	25 th percentile change in channel width (m yr^{-1})	75 th percentile change in channel width (m yr^{-1})
Control	80	0.0608	-0.496	0.545
Impact	80	-0.233	-0.758	0.397
Remediated	130	0.107	-0.461	0.744

Table 7: Comparison of Control and Impact sites between aerial photo years (decades) for the Mackay Whitsunday catchments. Positive values = channel expansion and negative values = channel contraction. Significant differences highlighted in bold and italics.

Year	Site	Median channel change (m/yr)	Significance (<i>p</i> value)
1950-1960's	Control	0.0933	0.421
	Impact	-0.626	
1960's- 1970's	Control	0.551	<i>0.029</i>
	Impact	-0.0754	
1970's- 1980's	Control	-0.134	<i>0.094</i>
	Impact	0.137	
1980's -1990's	Control	-0.040	<i>0.009</i>
	Impact	1.059	
1990's- 2000's	Control	-0.523	0.315
	Impact	-0.855	
2000 -2012	Control	-0.720	<i>0.009</i>
	Impact	0.247	



(A)



(B)

Figure 14: Comparison of changes in channel width of (A) control and (B) impacted sites for the Mackay Whitsunday catchments.

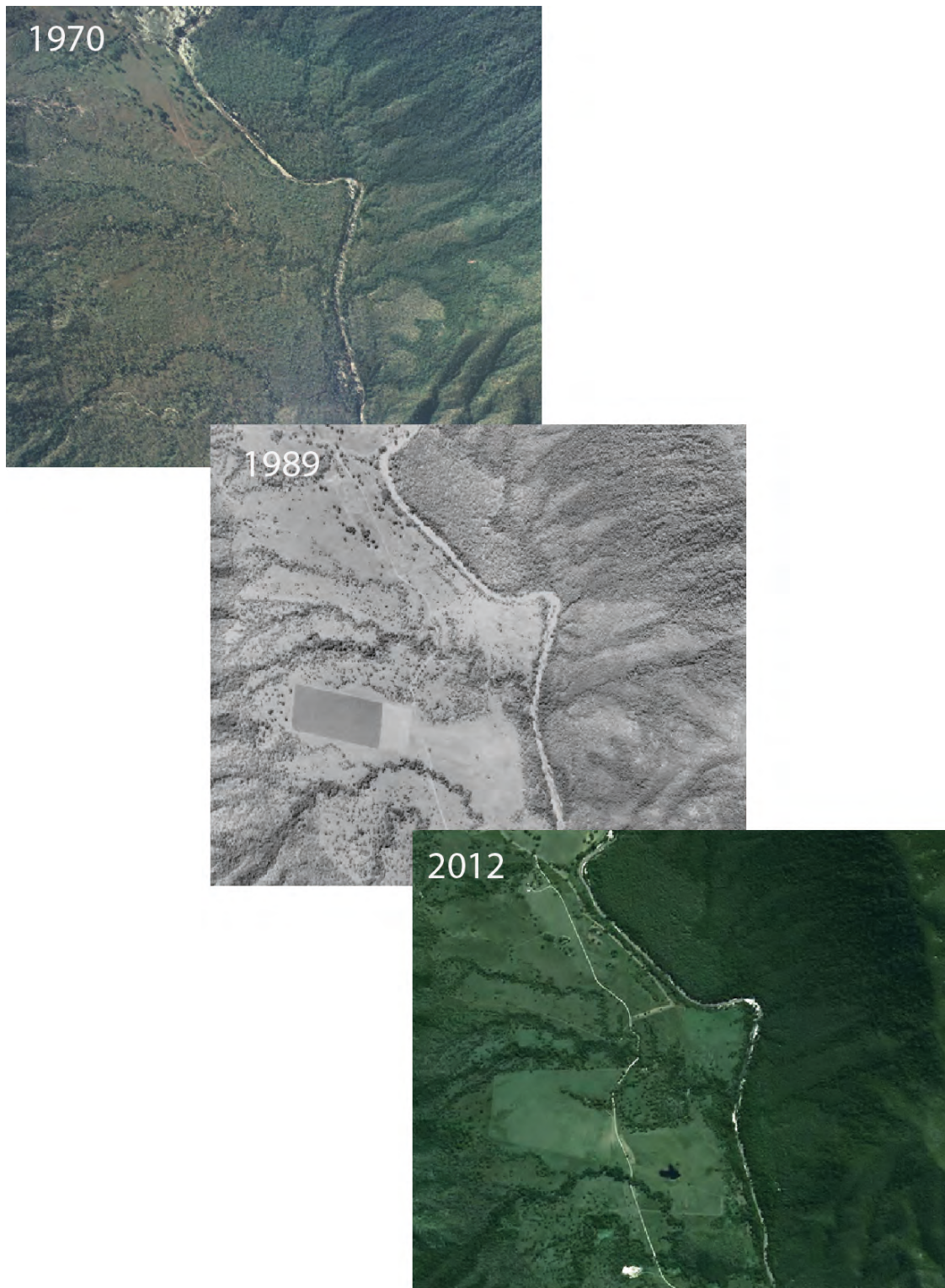


Figure 15: An example of a control site (~84% riparian vegetation) in the Mackay Whitsunday catchment (Control site 2).



Figure 16: An example of an impacted site (~47% riparian vegetation) in the Mackay Whitsunday catchment (Impact site 2).

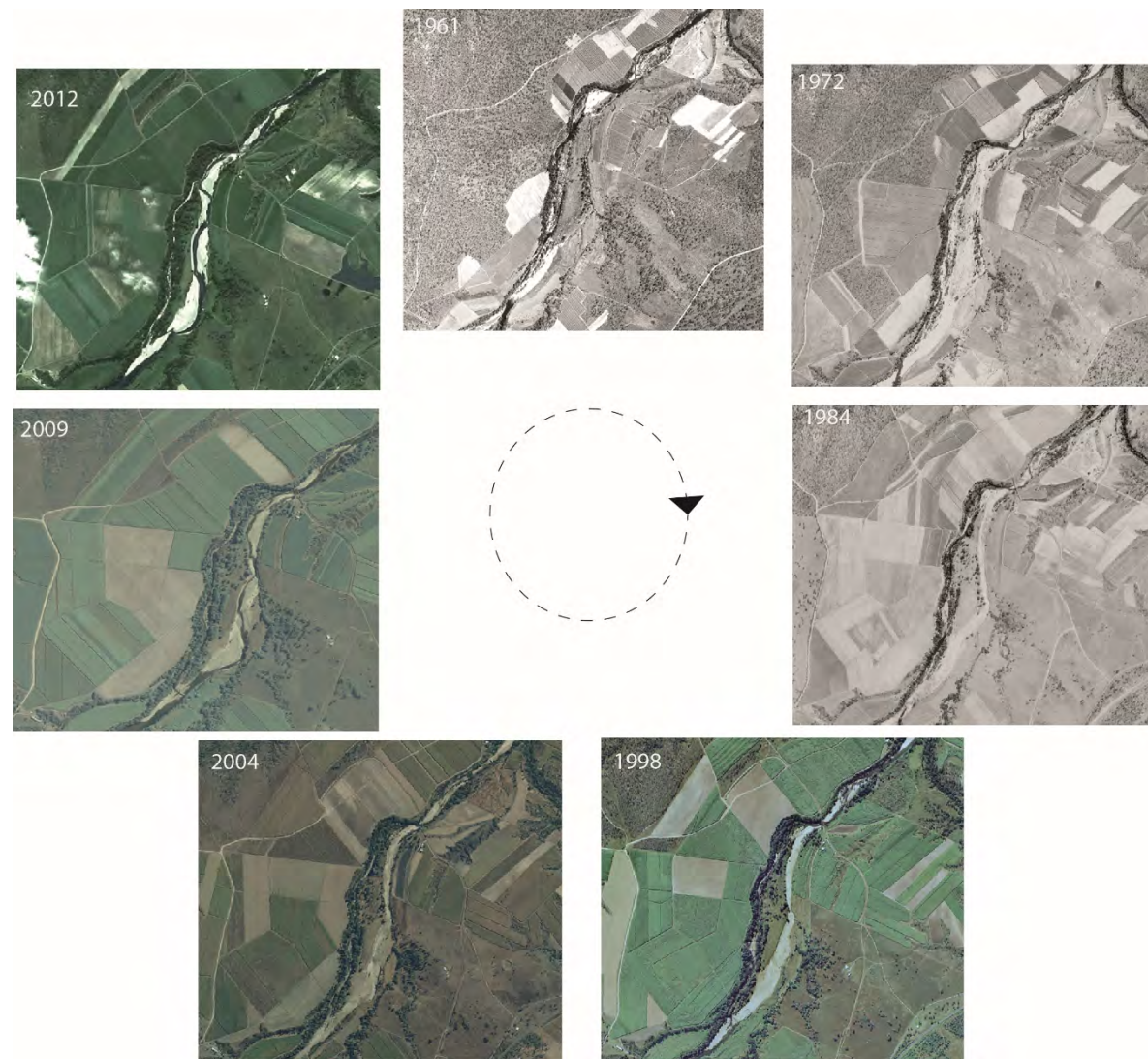


Figure 17: An example of the Upper Andromache channel confluence remediation site (~47% riparian vegetation) in the Mackay Whitsunday catchment (Remediation site 6). Note data from this site was not included in the overall statistical analysis as this site was only recently completed by Reef catchments, and was not provided with the original data set.

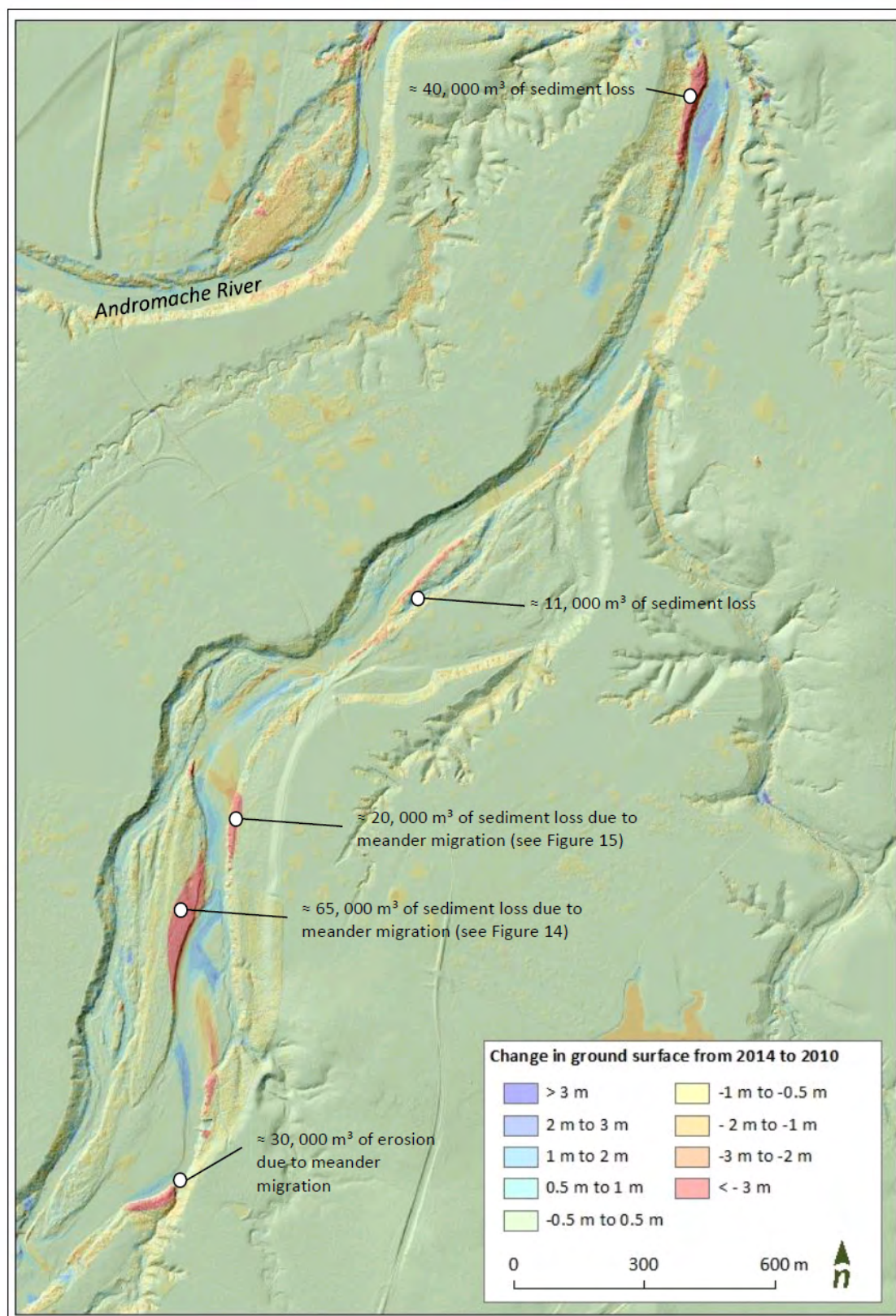


Figure 18: Changes in elevation between 2010 and 2014 using a DEM of Difference (DoD) based on repeat LiDAR (Source: Alluvium, 2014).



Figure 19: Recent remediation using log groins work at remediation site 6 (Source: Chris Dench, Reef Catchments).

6. DISCUSSION AND CONCLUSION

In both the Fitzroy and Mackay Whitsunday catchments, the null hypothesis was rejected as it was not possible to conclude that riparian vegetation influenced changes in channel width (over the last 50 years) in either catchment. There are a number of possible reasons why we obtained this result contrary to the popular belief that riparian vegetation is an important factor in maintaining and stabilising channels (measured here as channel width). Some of the reasons include:

- That the technique employed (historical aerial photo analysis), is not suitable for capturing the subtle changes that riparian vegetation plays in reducing bank erosion (e.g. see Bartley et al., 2008). Within the time and financial constraints of this short (<9 month) project, there were not really any other options available to evaluate channel change over such a large spatial scale;
- That the definition of riparian vegetation estimated for the aerial photo, may be different to the % riparian vegetation estimated for the representative stream link in the catchment models using remote sensing (Figure 5). With more time and resources, riparian vegetation would have been assessed on the ground and then calibrated back to the remotely sensed and air photo estimates of riparian vegetation extent. Time and budget constraints meant it was not possible to undertake rigorous field work in this desk-top assessment;
- Changes may have occurred in the bed of the channel (aggradation or incision) as a result of changes in the amount and extent of riparian vegetation, however, such changes are difficult to detect using changes in channel width alone;
- The study assumed that the selected study reaches were from the same sample population when in reality, the rivers and streams in basins the size of the Fitzroy and Mackay Whitsundays are extremely diverse and include anastomosing and single channels (Amos et al., 2008). Riparian vegetation may play different roles depending on the type of channel being assessed;
- It is possible that the impacted sites had already undergone a period of channel expansion when many of the sites were cleared in the late 1800's and early 1900's, and what we have observed in this study is post-disturbance channel contraction (e.g. Schumm et al., 1984; Schumm et al., 1987; Simon, 1995);
- It is likely that large infrequent runoff events are a dominant driver of major channel change in these systems, as demonstrated in the Burnett (Simon et al., 2014) and Lockyer Valley systems (Croke et al., 2013; Grove et al., 2013; Thompson and Croke, 2013). Therefore it may have been more useful to assess channel change following extreme events rather than averaging channel change across decades;
- There are a large number of weirs and dams in the Fitzroy catchment that may have influenced the results by buffering the effect of riparian vegetation on channel change.

Despite these limitations, this study did provide a number of useful insights. These insights and associated recommendations are outlined below:

- (1) It was insightful to discover that many of the 'remediation' approaches implemented by the Regional bodies were not directly influencing the amount and extent of riparian vegetation. That is, many of the remediation projects were indirectly influencing riparian zones by removing stock, using fencing or installing off-site stock watering points. Given the long lag times between fencing and the establishment of riparian vegetation from natural seeding, it is likely to be several years to decades before there is a measurable response from such activities. Given the control and impact sites did not show a statistically significant difference in this study, it was difficult to estimate the lag effect time frame in this study, but other studies have suggested that improving vegetation will take >10 years (Bartley et al., 2014b). Based on a review of the International literature of riparian zone effectiveness, Bartley et al., (2015) found that water quality took between 2-18 years to improve following riparian restoration. This has major implications for the Source Catchments modelling as they assign the water quality benefit from a management practice change to the year that the investments occurs (Waters et al., 2013).

Recommendation 1: That a 'lag effect' estimate is added to the Source Catchments modelling framework. These models are increasingly being used to estimate the cost-effectiveness of remediation activities (Behr et al., 2016; Kroon et al., 2016), however, unless a lag term is associated with the 'effectiveness' term, then the costs will not be discounted appropriately, and the cost-benefit estimates may be mis-calculated. It is also assumed that the 'contributor' function, that calculates the probability of sediment from a given link actually reaching the coast, is being used within the modelling framework (McKergow et al., 2005). If not, a combination of distance to the coast, and a lag term, are needed to help prioritise sites for remediation.

- (2) The total (amount and condition) of upstream vegetation is important for reducing runoff, and by consequence, reducing stream powers and improving water quality downstream. So promoting the establishment of riparian management on its own is unlikely to have the water quality improvements anticipated. The riparian zone should not be evaluated independently of the land use type and condition upstream. That is, if the land upstream of a given reach is in poor condition with low cover, severe gullyng and scalded areas, then having an in-tact 100 m riparian zone is unlikely to compensate for the changed hydrology and sediment delivery from the degraded areas above (for example, see Figure 20).

Recommendation 2: That the influence of vegetation on channel stability and erosion potential (or risk) consider both the local (reach) and upstream (catchment) condition of the vegetation. Riparian vegetation on its own will, at best, provide a local buffer to erosion. There are likely to be additional influences on the runoff delivered to a given reach that are related to the amount of vegetation upstream. Consider integrating multiple estimates of vegetation within the modelling framework.

- (3) This study highlighted how relatively simple geomorphological techniques, such as the use of historical aerial photos, can provide important insights into how channels have changed over the recent (~50 year) past. This was best demonstrated on the O'Connell River where the channel has expanded an average of $\sim 1.45 \text{ m yr}^{-1}$ over the last 50 years, which is ~ 24 times higher than the median rate for the control sites in the region. This assessment helps justify the need for remediation at this site, however, there is an urgent need to evaluate the cost-effectiveness of these engineered remediation projects versus cheaper fencing and revegetation options. Given the relatively large investment in on-ground remediation works across the entire GBR region over the last decade, very little funding has gone into formally evaluating the cost-effectiveness of the investments on improved water quality. A review of stream restoration projects in the US found that less than 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). Without this knowledge, we will not know the most cost-effective approach to use to reduce erosion and improve water quality in the GBR catchments.

Recommendation 3: A specific budget ($\sim 10\%$) should be given to formally evaluating the effectiveness of on-ground remediation works on water quality. This should be done at the investment scale (e.g. reach, paddock scale), using measurements. Evaluation should not rely on modelling alone. Monitoring should also be assessed against reference sites rather than simply tracking change over time at the site restored (Gonzalez et al., 2015) and should be embedded with a robust conceptual and methodological framework (Gilvear et al., 2013).



Figure 20: Example of land clearing along an impacted reach in the Fitzroy catchment. This reach is estimated to have ~46% riparian vegetation, however, the surrounding and upstream landscape has very low ground cover. The thin thread of riparian vegetation is not going to compensate for the altered landscape condition.

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APPENDIX A

Table 8: Fitzroy Catchment control reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

Control 1	x-section	1966	1978	1985	1995	2006	2012
	1	51.39	50.42	48.5	58.87	47.37	60.54
	2	44.82	50.83	44.14	62.32	59.43	65.24
	3	50.96	60.25	57.36	59.4	65.94	84.72
	4	49.12	59.25	53.86	48.29	47.17	68.89
	5	98.78	110.48	108.18	82.49	65.03	126.63
Control 2	x-section	1953	1975	1983	1995	2006	2012
	1	39.97	51.89	50.19	43	35.13	36.34
	2	35.49	67.89	48.11	39.95	36.72	45.8
	3	73.28	75.42	65.88	44.78	45.29	64.99
	4	44.34	43.33	51.97	36.38	34.93	52.7
	5	58.27	51.99	63.17	51.99	40.47	50.42
Control 3	x-section	1966	1973	1981	1989	1999	2012
	1	64.28	71.08	72.49	61.93	64.08	68.29
	2	60.86	58.58	73.34	68.9	63.72	79.94
	3	65.91	65.02	77.8	59.51	61.5	75.58
	4	66.2	63.11	72.65	72.73	59.72	70.36
	5	70.83	69.65	79.62	68.54	64.61	78.79
Control 4	x-section		1971	1981	1987	1996	2012
	1		46.58	60.3	62.78	72.51	65.54
	2		74.41	74.56	60.94	90	89.143
	3		60.76	64.45	62.24	65.96	57.39
	4		130.21	146.3	129.07	150.63	141
	5		30.96	35.74	39.06	86.19	64.02
Control 5	x-section	1966	1974	1986	1995	2004	2012
	1	85.09	47.72	59.15	55.73	52.15	58.63
	2	58.75	62.35	61.65	63.13	64.12	67.1
	3	70.36	73.13	70.15	71.58	75.2	72.79
	4	56.42	66.32	66.71	73.48	64.95	78.09
	5	57.37	55.1	59.64	57.99	52.68	50.92

Table 9: Fitzroy Catchment impact reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

Impact	x-section	Year					
		1965	1977	1984	1990	2000	2012
Impact 1	1	27.56	17.72	17.66	18.62	17.11	17.07
	2	19.44	19.46	20.71	20.04	20.91	20.71
	3	25.45	24.87	23.61	23.7	21.74	25.52
	4	32.27	31.13	27.6	27.22	26.36	28.36
	5	32.86	32.18	25.36	30.31	31.02	30.61
Impact 2	1	30.91	24.55	25.81	29.06	23.47	26.18
	2	32.9	28.78	28.59	36.54	29.21	32.58
	3	40.3	33.66	31.86	38.76	32.35	36.38
	4	43.86	41.31	41.27	43.85	42.13	50.59
	5	44.3	41.58	32.55	35.95	34.47	44.06
Impact 3	1	99.8	56.17	65.82	47.99	45.93	90.71
	2	67.92	32.79	39.65	30.26	43.22	34.44
	3	78.13	75.17	148.82	98.04	34.24	38.47
	4	77.88	58.2	80.39	43.85	44.91	39.15
	5	77.04	64.1	111.71	93.78	33.72	41.41
Impact 4	1		32.23	29.49	29.26	28.66	29.9
	2		28.69	27.99	26.37	29.88	22.95
	3		22.17	29.73	30.71	25.24	34.73
	4		23.57	28.65	29.05	28.35	27.15
	5		28.36	26.94	31.52	35.22	34.23
Impact 5	1	160.52	165.82	166.1	167.04		190.14
	2	168.87	170.15	170.94	177.64		185.38
	3	184.76	188.76	182.01	194.26		204.69
	4	187.94	192.15	197.9	191.7		210.81
	5	205.59	202.45	202.12	204.31		217.24

Table 10: Fitzroy Catchment remediated reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

Remediation 1	x-section	Year						
		1956	1966	1978	1987	1994	2006	2012
	1	34.9	33.8	32.83	30.75	32.35	32.61	32.81
	2	40.31	33.14	32.1	32.22	31.17	31.3	32.47
	3	28.56	26.64	27.08	29.56	29.34	27.11	33.81
	4	34.99	33.89	37.69	41.14	35.67	41.71	35.15
	5	28.66	26.18	23.33	26.66	27.22	24.82	36.02
Remediation 2	x-section	1950	1960	1973		1994	2007	2012
	1	39.21	34.05	32.25		35.3	41.18	37.64
	2	37.13	39.08	35.31		42.32	42.27	48.63
	3	29.55	38.45	45.03		37.98	36.71	47.15
	4	43.11	37.87	43.91		33.56	34.98	45.89
	5	44.04	32.55	40.7		39.05	41.26	43.35
Remediation 3	x-section		1969	1971	1987	1999		2012
	1		30.09	28.59	33.36	25.35		44.96
	2		31.23	32.31	32.93	32.59		31.94
	3		27.18	19.94	22.58	20.31		27.96
	4		24.65	28.13	31.59	31.84		33.82
	5		44.01	40.46	45.1	36.29		43.71
Remediation 4	x-section	1953	1966	1973	1984	1999		2012
	1	52.04	48.07	46.29	53.84	46.32		54.31
	2	32.69	46.72	57.79	119.47	114.63		108.93
	3	86.62	100.98	104.08	108.07	112.94		123.12
	4	109.33	112.45	110.73	144.61	133.61		161.36
	5	134.46	129.61	148.57	154.82	164.48		181.12
Remediation 5	x-section	1957	1966		1987	1998	2000	2012
	1	34.76	36.17		32.22	32.61	32.28	34.54
	2	39.37	38.4		31.25	33.76	31.83	37.63
	3	34.03	37.74		34.03	43.11	34.69	42.14
	4	30.57	32.61		28.3	30.48	29.38	33.76
	5	33.62	34.78		32.5	32.33	32.51	38.19

Table 11: Mackay Whitsunday Catchment control reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

			Year					
Control 1	x-section		1961	1972	1985	1993	2004	2012
	1		27.28	31.22	36.31	39.42	38.19	35.73
	2		24.21	23.46	24.25	27.11	25.41	29.77
	3		29.58	30.59	25.82	27.74	26.19	35.27
	4		28.59	28.03	31.64	29.62	34.56	47.9
	5		31.8	36.44	30.53	33.62	37.7	38.23
Control 2	x-section			1970	1984	1989	2006	2012
	1			51.45	40.34	54.9	39.32	44.18
	2			48.22	49.52	52.55	33	39.6
	3			54.49	47.11	55.91	36.59	39.49
	4			51.58	42.43	56.44	40.98	39.36
	5			82.25	50.16	64.51	28.57	33.89
Control 3	x-section	1953	1962	1976	1982	1991	2009	2012
	1	86.51	97.84	96.49	101.2	98.82	89.89	97.27
	2	120.2	107.44	113.04	112.21	108.22	106.42	109.33
	3	94.93	90.27	96.4	78.21	94.68	95.64	93.07
	4	84.47	85.31	90.66	86.41	102.23	96.75	89.41
	5	75.53	87.99	83.22	72.46	99.69	85.8	83.15

Table 12: Mackay Whitsunday Catchment impact reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

			Year						
Impact 1	x-section		1961	1975	1983	1996	2007	2012	
	1		49.7	57.41	75.97	52.87	60.93	57.14	
	2		58.61	70.35	69.28	46.31	42.65	45.28	
	3		39.41	84.91	71.46	66.26	53.93	50.03	
	4		59.03	73.52	72.93	50.89	55.26	41.45	
	5		62.31	66.6	62.31	53.39	56.05	44.47	
Impact 2	x-section		1961	1972	1984	1993	2004	2012	
	1		129.73	123.36	126.13	152.37	123.3	121.67	
	2		168.15	167.19	161.94	167.79	156.22	159.26	
	3		155.89	162.63	157.2	161.6	145.84	145.34	
	4		115.13	135.23	131.17	127.52	127.25	130.42	
	5		140.6	141.28	141.13	136.49	131.65	125.86	
Impact 3	x-section		1953	1962	1972	1982	1993	2004	2012
	1	132.05	135.89	138.54	140.49	140.35	139.79	137.23	
	2	170.48	168.12	178.74	180.07	189.66	183.91	176.25	
	3	208.68	203.05	210.46	206.7	217.6	207.15	207.04	
	4	243.18	230.83	219.33	196.85	228.35	215.69	207.18	
	5	265.22	258.83	258.15	271.61	249.84	241.51	235.75	

Table 13: Mackay Whitsunday Catchment remediated reach channel widths (measured in metres) in a given photo year. Five cross-sections were measured in each reach.

			Year					
Remediation								
1	x-section		1962	1972	1984	1991	2004	2012
	1		25.73	27.72	32.68	41.59	25.73	26.73
	2		60.46	53.68	36.74	69.41	45.7	59.47
	3		42.01	40.88	49.58	72.81	61.04	65.81
	4		31.46	27.18	30.06	37.47	32.73	35.08
	5		24.82		23.94	26.8	20.81	19.82
Remediation								
2	x-section	1957		1970	1985	1999	2009	2012
	1	17.95		16.34	18.4	18.08	19.64	20.38
	2	13.9		20.12	20.12	19.4	19.82	20.13
	3	20.48		17.79	17.56	19.49	18.34	18.48
	4	14.9		13.92	18.08	22.34	19.7	25.38
	5	21.44		20.42	21.57	20.85	20.74	23.85
Remediation								
3	x-section	1959	1962	1972	1984	1993	2004	2012
	1	77.88	65.53	72.5	48.76	74.41	50.62	72.81
	2	59.12	83.26	48.82	72.53	99.92	65.92	82.44
	3	50.46	52.1	50.86	52.21	79.15	56.28	67.19
	4	53.06	53.1	61.13	95.3	131.7	60.279	73.19
	5	52.14	53.07	56.2	60.24	80.32	46.09	57.14
Remediation								
4	x-section		1961	1972	1984	1991	2004	2012
	1		28.67	30.18	25.72	80.76	52.79	47.48
	2		58.23	54.59	50.1	65.63	64	64.58
	3		138.29	118.1	119.13	163.9	121.55	97.11
	4		34.9	39.1	39.76	51.6	57.98	75.9
	5		42.74	42.68	59.55	63.62	65.63	59.57
Remediation								
5	x-section		1961	1972	1984	1991	2004	2012
	1		113.07	107.97	110.45	110.98	103.34	104.23
	2		149.22	151.42	145.47	141.68	101.83	94.3
	3		67.08	69.39	85.27	87.42	87.42	79.12
	4		88.24	97.22	104.32	109.14	98.03	84.48
	5		109.36	133.24	92.45	80.9	68.28	96.21
Remediation								
6	x-section		1961	1972	1984	1998	2004	2012
	1		66.68	92.85	95.04	93.57	84.56	88.2
	2		24.93	17.31	78.03	112.89	119.31	146.12
	3		20.46	27.34	39.58	37.88	40.58	127.46
	4		36.41	65.41	72.79	75.39	97.15	118.47
	5		61.67	71.71	73.05	79.08	76.27	76.51

