

A comparison of tools for monitoring and evaluating channel change

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ACRONYMS

DEM.....	Digital Elevation Model
DoD	DEM of Difference
DSITI	Department of Science, Information Technology and Innovation
GBR.....	Great Barrier Reef
M&E.....	Monitoring and Evaluation
NESP.....	National Environmental Science Programme
PEEP	Photo-Electronic Erosion Pin
RMSE	Root Mean Square Error
TLS	Terrestrial Laser Scanning
TWQ	Tropical Water Quality

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EXECUTIVE SUMMARY

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 and improve stream health. However, measuring the effectiveness of these investments is challenging due to the variability in stream size and erosion rates. A synthesis of measured bank erosion rates for the Great Barrier Reef catchments suggests erosion can vary from ~0.01 m to ~5 m per annum. Therefore the tools used to measure and evaluate changes in channel erosion need to be conducted at the appropriate scale to enable the detection of channel change.

This study provided a comparison of two terrestrial laser scanning instruments (RIEGL VZ400 and Zebedee). Change detection using these instruments was also compared to multi-temporal airborne LiDAR. The RIEGL and Zebedee instruments were trialled on one gully and one stream-bank site in the Weany Creek catchment, in the Burdekin. Repeat captures were taken on the same day and were used to estimate the error in characterising surface morphology and to detect 'real' change (erosion or deposition). Fortunately, a 64 mm rainfall event occurred following the initial sampling, therefore a repeat scan using both instruments allow DEM's of difference (DoD) to be derived, and estimates on erosion, deposition and total volumetric change were calculated at the gully site.

The main focus of this study was the testing and comparison of the RIEGL and Zebedee instruments. The study found that the threshold for detecting elevation change varied between the two instruments. The Zebedee threshold was $\sim \pm 0.12$ m, and its benefits relate to the speed and relatively low cost of data collection. It cannot cover large areas like airborne LiDAR, but would be useful for rapid on-ground assessment of stream channels or gullies before and after remediation. The RIEGL was more accurate with an erosion detection threshold of $\sim \pm 0.067$ m. This higher level accuracy comes at the expense of slower data collection times and the high cost of the instrument. However, this would be the preferred instrument where high precision is needed to detect and quantify channel change. The airborne LiDAR detection limit could not be determined using the present dataset but other studies show that this is likely to exceed ± 0.2 and could be as high as ± 1.0 m. The airborne LiDAR is influenced by factors such as sensor configuration and topographic complexity of the surveyed area. The benefit of airborne LiDAR is that it can cover larger areas rapidly (hundreds of kilometres), however, the capture and processing costs can be substantial (~\$1000 - \$2000 km²).

This project has provided new information on the suitability of the RIEGL VZ400 and Zebedee instruments to help benchmark and evaluate future investments in riverbank and gully remediation in the GBR catchments. Use of these instruments will provide the quantitative data needed to detect the improvements at the appropriate scale, and can be used to support scenario analysis in the catchment models. Monitoring and evaluation (M&E), using the right tools, is critical to justify the use of Government spending on remediation, but also as a marketing tool to encourage other farmers to undertake remediation. Rigorous M&E will provide increased confidence in targeting future investments and lead to improved water quality delivered from streams and gullies to the Great Barrier Reef.

1. PREFACE

1.1 Background and Context

Stream-bank and gully erosion are estimated to contribute ~30% and ~40% to end of catchment sediment yields in the Great Barrier Reef (GBR) catchments, respectively (Wilkinson et al., 2015). Collectively, these processes are known as channel erosion, and deliver ~70% of the fine sediment to the GBR. Channel erosion occurs as (i) channel network extension, (ii) as large irregular erosion features in alluvium that is connected or adjacent to the stream bank, and (iii) as channel expansion (width and depth) on minor streams. This latter type is not included in the stream network modelled by the Dynamic SedNet model within the Paddock to Reef Program, but is often regarded as stream-bank erosion by land holders.

However, our understanding of the degree of alteration of gully and stream-bank erosion from natural rates since the introduction of agriculture, and the success of methods for remediating erosion (using approaches such as revegetation and livestock exclusion fencing), 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.

One knowledge gap limiting understanding is the absence of data on erosion rates before and after management change. Such data are difficult to obtain because erosion rates over several years are similar to the accuracy of remote measurement techniques such as airborne photography and airborne LiDAR.

1.2 Objectives

The objectives of this project were (i) to provide new data sets to evaluate the current predicted rates of stream-bank erosion; and (ii) to provide more robust benchmarking of future stream-bank remediation interventions. Objective (i) was addressed in the accompanying report Bartley et al., (2016a). The techniques used to assess channel change vary depending on whether you are looking at large rivers (>30 m wide) compared to small headwater streams (5-30 m wide). Measuring and bench-marking channel change will require different techniques with varying levels of precision and accuracy. This report presents a comparison of two terrestrial laser instruments to characterise gully and stream-bank morphology and measure channel change. The results are also compared to multi-temporal airborne LiDAR at each site.

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 modeling 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

Erosion of the channel boundary, which includes bank and gully erosion, is considered to represent ~ 70% of the sediment flux reaching the coast from the catchments draining to the Great Barrier Reef (GBR) (Tims et al., 2010; Hancock et al., 2013; Olley et al., 2013; Wilkinson et al., 2013a). Expansion of minor stream channels can be termed either gully or stream-bank erosion. The area occupied by gullies is estimated to have increased ~ 10 fold since European settlement in parts of Northern Australia (Shellberg et al., 2010). It is difficult to quantify how much the contribution from stream-bank erosion has changed with agricultural expansion, however, we do know that channel erosion rates are generally lower on channels with in-tact riparian vegetation, compared to channels without riparian vegetation (Bartley et al., 2008). Using this knowledge, and the fact that riparian vegetation is important for stream health (Pusey and Arthington, 2003), Local, State and Federal organisations are keen to increase investment in riparian zone management in the GBR.

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 and improve stream health (Bernhardt et al., 2005; Kondolf et al., 2008; Kurth and Schirmer, 2014; Wohl et al., 2015). However, measuring the effectiveness of these investments is challenging due to the variability in erosion processes, variation in stream size and often long lag times between remediation and response (Bernhardt and Palmer, 2011; Kristensena et al., 2014).

Riparian vegetation has different influences at different spatial scales (Curran and Hession, 2013), and it has different impacts on stream processes depending upon its position down a catchment (Abernethy and Rutherford, 1998). The presence of vegetation is useful for all types of erosion, but its specific influence may vary within the catchment. Before it is possible to quantify the effectiveness of remediation, it is important to know what the relative rates of stream-bank erosion are for different rivers in the GBR catchment. Studies of stream-bank erosion and channel change following catastrophic floods (>1 in 100 year recurrence interval), such as that on the Burnett River in 2011, demonstrate that erosion rates can be as high as ~5 m yr⁻¹ on the main river channel (Table 1). However, most studies of stream-bank erosion or channel change in the tropical rivers draining to the GBR have shown much lower rates of channel change in the order of < 1 m yr⁻¹, and commonly lower than 0.1 m yr⁻¹ in the drier catchments.

The catchments of the Great Barrier Reef (GBR) cover an area of ~420,000 km² and include ~290,000 km of stream lines (based on the 1:250 K topographic data). These streams and rivers range from small ephemeral streams less than 5 m wide, to channels in excess of 1 km in width. The methods used to estimate changes in erosion or channel form depend on the size of the channel, the magnitude of channel change, the frequency of measurements and the monitoring budget available. Traditionally, aerial photos, erosion pins and topographic surveying were used to estimate channel change (Lawler, 1993), and terrestrial photogrammetry (Barker et al., 1997) and automated PEEP sensors have also been employed (Lawler, 2005). More recently, repeat airborne LiDAR (Light Detection And Ranging system) is used to identify and quantify rates of channel change (Croke et al., 2013; Grove et al., 2013; Thompson and Croke, 2013; Brooks et al., 2014; Simon, 2014). The more traditional techniques such as erosion pins and surveying using total stations can have an accuracy of ± 1-2 mm, but can generally only cover small areas (reach or site) and are

relatively labour intensive. The more recent techniques such as airborne LiDAR can cover large areas (hundreds of kilometres), but can be relatively expensive to purchase and process, and can have errors in the order of ± 0.2 m to ± 1.0 m (Wheaton et al., 2010; Croke et al., 2013; Grove et al., 2013) which is generally greater than the annual erosion rate for most streams in the GBR (Table 1). Therefore, whilst airborne LiDAR is extremely useful for estimating changes on larger channels that accumulate over multiple years, or after major flood events, it is unlikely to pick up subtle changes in channel morphology over annual or intra-annual time frames. Likewise, there are several satellite and unmanned aerial vehicle products emerging that use photogrammetry approaches and could potentially be used for tracking two- and three-dimensional channel change over time, however, these products are currently still largely untested as to whether they have the appropriate spatial resolution and accuracy required for erosion detection (see Table 2).

More recently, instruments such as terrestrial laser scanners (TLS) which is a form of ground based LiDAR, and portable handheld laser scanners (such as the ZebedeeTM) have become available. These sensors follow the same principal as airborne LiDAR in that they create 3D point clouds of the terrain surface, but they generally have much greater point density and ranging accuracies than airborne LiDAR. Given that these sensors are relatively new to terrain analysis, there has been limited rigorous review and comparison of the different instruments available (e.g. Castillo et al., 2012; Kaiser et al., 2014).

The aims of this study were threefold. Firstly, to compare the application of airborne LiDAR, TLS and Zebedee at a single site to provide a general assessment of how well each approach represented the channel terrain. Secondly, to estimate and compare the relative error associated with the TLS and the Zebedee and to see how the errors compare with known limits of airborne LiDAR. Understanding these measurement errors is critical for accurate estimation of channel erosion rates to evaluate the effectiveness of the remediation against erosion rates prior to remediation, or in similar channels which have not been remediated. Thirdly, to estimate the cost of running each approach in terms of data collection and handling time, processing time and error estimation.

Table 1: Summary of stream-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 (2015)
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 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)	Bartley et al., (2016)a
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)	Bartley et al., (2016)a
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)

Table 2: Summary of satellite sensors currently available (Source: Neil Simms, CSIRO, Melbourne)

Sensor	Spatial resolution (m)	Temporal frequency (Collection Interval, days) <i>although many need to be commissioned for capture</i>	Year of launch
Landsat TM	15 to 30	16	(1972) 2013
NOAA AVHRR	1100	1	1986
SPOT	10	5	1986
Ikonos	1 to 4	3	1999
MODIS	250 to 1000	1	2000
Quickbird	0.6 to 2.4	3	2001
Worldview 3	0.31 to 3.7	1	2014
ALOS PALSAR2	1 to 100	<14	May 2014
Sentinel 1	1.5 to 80	2-3	Apr 2014
Sentinel 2	10 to 60	10	Jun 2015
Himawari 8	500 to 2000	10 mins	Oct 2014

3. STUDY SITE

The study site chosen to trial a comparison of the airborne LiDAR, Zebedee and RIEGL was Weany Creek on Virginia Park cattle station in the Burdekin catchment (Figure 1). This site has a long history of research (Bartley et al., 2014) including previously measured annual rates of gully and stream-bank erosion at the site (Bartley et al., 2007; Wilkinson et al., 2013b). It also had repeat airborne LiDAR capture in 2010 and 2013.

In brief, the Weany Creek catchment is $\sim 14 \text{ km}^2$ headwater catchment located within Virginia Park, a commercial grazing station $\sim 100 \text{ km}$ west of Townsville in the Burdekin catchment (Figure 1). The channel has a mean bed slope of $\sim 0.5\%$, and gently sloping valley sides averaging $\sim 4\%$. Weany Creek is part of the Dalrymple land system and representative of the highly dissected granodiorite 'Gold-fields' land type (Rogers et al., 1999). The current vegetation on Weany Creek is Eucalypt savanna woodland overlaying a layer of tussock and stoloniferous grasses (e.g. Indian Couch). Weany Creek is ephemeral and generally only flows sporadically between December and April each year. The 10-year (2002-2011) mean annual rainfall for the site is $\sim 658 \text{ mm}$ (S.D. of mean, 317 mm) (Bartley et al., 2014).

We chose one gully and one stream-bank site to compare the techniques. The morphology of these features is relatively simple, and was therefore suitable for comparing techniques. The selected gully is a classic linear hillslope gully that is $\sim 100 \text{ m}$ long and 5 m wide (Figure 2). The stream-bank site is a simple outside bend on an ephemeral stream system that has walls that are approximately 1.5 m high and a channel width of $\sim 20 \text{ m}$ (Figure 3).

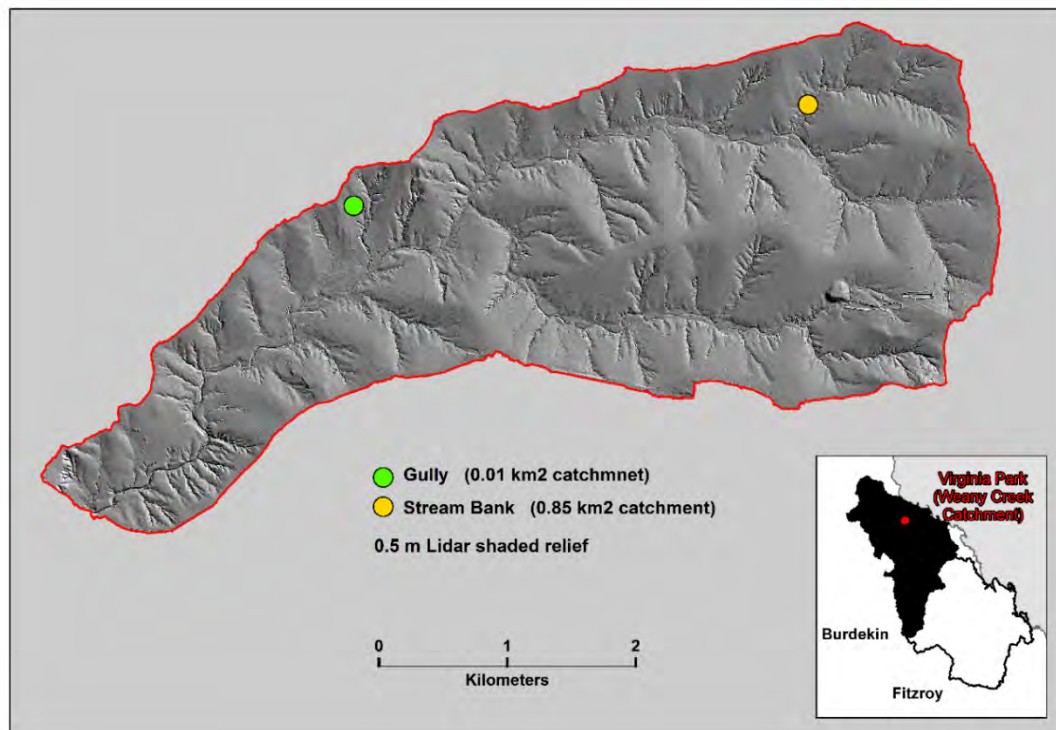


Figure 1: Location of test gully and stream-bank site within the Weany Creek catchment



Figure 2: The gully site showing (left) the main gully channel and (right) the eroding side walls



Figure 3: The stream-bank site in 2003 (left) and in 2016 (right)

4. METHODS

Terrain data were collected using three different techniques in the Weany Creek catchment: airborne LiDAR, the Zebedee scanner and RIEGL terrestrial laser scanner (TLS). The LiDAR data were not collected as part of this project, but are provided here for comparison with the other sensor products (Tindall et al., 2014). The main focus of this study was the testing and comparison of the RIEGL and Zebedee instruments. The approach was conducted in two steps:

- (1) To estimate the error for each instrument. This included quantifying the (internal) registration errors of each sensor, and the repeatability of each approach when surveys are taken on the same day. The repeated scans taken on the same day helped derive a U_{crit} value, which is essentially the threshold for error estimation or threshold for detecting change (erosion or deposition).
- (2) The gully and bank sites were surveyed immediately before and after a 64 mm rainfall event in Nov 2015 using both instruments. Using these before and after surveys, it was possible to derive DEM's of difference (DoD) which allowed a comparison of a sediment budget (erosion, deposition and loss) for the gully site. A volumetric change was then calculated at the gully site using both instruments.

4.1 Data collection

4.1.1 Airborne LiDAR

A multi-date airborne LiDAR dataset was captured for the Weany Creek catchment as part of a larger airborne LiDAR data capture outlined in Tindall et al., (2014). In brief, the Burdekin sites were captured on two dates in 2010 and 2013 using a similar capture configuration between dates. To ensure the supplied data matched required specifications and to provide confidence that detected change corresponded to real events, a series of data pre-processing checks were undertaken to assess the data quality. This included checking the spatial extents, pulse densities, horizontal and vertical accuracies, and overlap of flight-runs. For the 2010 and 2013 captures, the sensors were configured to sample the gully environment with an average pulse density of 4.2 m^2 (each pulse was able to record up to 5 returns) and an overlap of 50% between flight runs to minimise the impact of occlusion from variable terrain and vegetation; this results in an average of 8 pulses/ m^2 . Digital orthophotos (15 cm resolution) were acquired coincident with the LiDAR data in 2010 and 2013. DEM surfaces were interpolated for each of the sites using the natural neighbour algorithm (Sibson, 1981) at a spatial resolution of 50cm using the LiDAR returns classified as ground. More detail on LiDAR capture specifications and quality assurance checks are given in Tindall et al., (2014).

4.1.2 The RIEGL Terrestrial Laser Scanner

The TLS instrument used in this study was the RIEGL VZ400 (Figure 4). The RIEGL is a high cost, survey grade, precision instrument. The approximate cost of the RIEGL VZ400, including all associated parts and equipment is \$200,000. The RIEGL Instruments are available for hire through a single commercial provider in Australia. Previous quotations for use were in the order of several thousand dollars per day.

The time to undertake repeat scans of the gully site was approximately 4 hours. The time taken for the stream-bank site was similar. Ideally, the field effort required for the RIEGL requires two staff due to the amount of additional equipment required (e.g. reflectors, bipods, batteries etc). Post-processing and analysis of the RIEGL data took approximately 1 day for both sites. This processing was already largely automated and undertaken using high performance computing systems by Queensland State Government.

The TLS was registered using five ground control points at each site. The control points consisted of a star picket driven 50 cm into the ground with a concrete collar. Survey bipods with reflectors were then placed over these marks to establish consistent xyz locations between scanners and for repeat surveys. To link RIEGL scans collected on the same day, additional 'mobile' reflectors were placed strategically around the sites. Registration was then performed by matching distances between reflector pairs (see Goodwin et al., 2016 for details). The RIEGL has an inbuilt fine-scan option to accurately locate reflector locations, which were projected into the same coordinate system with a crude offset to approximate the location of the field sites. To develop the DEMs using the RIEGL, data from two sets of 24 scans were linked for the gully site, and 17 scans were linked for the stream-bank site.



Figure 4: (left) a survey bipod with cylindrical reflector and (right) the RIEGL TLS at the gully site

4.1.3 Zebedee

The Zebedee, a portable, handheld laser scanner (<http://www.csiro.au/en/Research/D61/Areas/Robotics-and-autonomous-systems/Sensing-and-mapping-our-environment/Zebedee>), consists of a rotating 2D laser scanner and an inertial measurement unit (IMU) mounted on a spring that causes the scanner head to sway

in response to the movement of the operator as they walk (Figure 5). This movement creates a 3D point cloud with a range extending up to 35 m and a precision of 1–3 cm.

Repeat scans of the gully system (~100 m), and the stream-bank site (~50 m) were conducted by walking up and down the sites and around each reflector to create a closed loop survey for DEM generation. For the gully site, a single survey consisted of two transects - one upstream and one downstream. For the gully site, a single survey consisted of one closed loop transect. The rate of capture using Zebedee is typically around 30 minutes for a 1km long gully.

The raw data files were uploaded from the recording device to a processing server and automatically transformed into a 3D point cloud using the proprietary simultaneous localization and mapping (SLAM) algorithm (Bosse et al., 2012). All point clouds collected on the same day under the same project were then aligned to one another using a Merge routine on the processing server which combines a place recognition routine (Bosse and Zlot, 2009) with fine-tuning by SLAM. The resultant point clouds should then be coincident with one another. The merge routine does not explicitly use the reflector locations to aide in the alignment, but the reflectors were subsequently identified in the point clouds and then used to register all data to the reflector coordinates.



Figure 5: (left) handheld Zebedee in action and (right) the Zebedee at the gully site

4.2 Change detection, error analysis and repeatability

Five centimetre resolution gridded digital elevation models (DEMs) for all surveys from the Zebedee and RIEGL scanners were produced by selecting the minimum (ground) elevation from all the points in a 5cm x 5cm XY interval. A 3 x 3 median filter was applied to the resulting grid to remove spurious values. Common extents were required for comparison of the DEM's. For the gully, a modified region grow approach was applied to an unclipped RIEGL DEM. This approach utilises a difference from mean elevation (DFME) (Evans and Lindsay, 2010) and a slope layer to detect the gully edges. A ten pixel (50 cm) buffer was then applied to ensure full capture of the gully edges. The bank site extents were defined

manually to maximise the common area of overlap between the two sensors within the river bank/channel.

To statistically separate ‘true’ from ‘false’ geomorphic change, repeat surveys collected on the same day, using the same instrument, were used to create the two DEMs and quantify error. Any residuals between the DEMs were assumed to be false. Error is then quantified as the 95th confidence interval using the equation below (after Brasington et al., 2003; Heritage et al., 2009; Wheaton et al., 2010):

$$U_{crit} = t \cdot \sqrt{(\sigma_{e1})^2 + (\sigma_{e2})^2}$$

where:

U_{crit} is the propagated error term, σ_{e1} and σ_{e2} are the uncertainties or standard deviation (SD) of residuals for time 1 and 2 (which are represented by the same value in this study), and t is the confidence interval which we set at 1.96 for a 95% confidence interval.

4.3 Cost of data collection (acquisition) and processing

To provide an estimate of the costs and benefits of each approach, and allow commentary on the appropriate application scenarios for each technique, estimates of the cost (instrument purchase or data acquisition), data collection time, processing time, error or precision were collated. It is important to note that a robust (like for like) comparison of these instruments in an operational context could not be derived from these initial instrument comparisons, but the indicative times and costs do provide some idea of the initial outlay required for these instruments, and the staff and computing resources required to capture and process the data.

5. RESULTS

5.1 Digital elevation models

A comparison of the 50 cm LiDAR derived digital elevation model, with the 5 cm resolution elevation models created from the Zebedee and RIEGL data for the gully and stream-bank sites, are shown in Figure 6 and Figure 7, respectively. The two terrestrial scanners show significantly more detail than the airborne LiDAR, and appear to be detecting similar levels of detail to one another. Some (small) gaps or holes are visible in the DEM's (Figure 6 and Figure 7). These gaps/holes occur when there were no returns from the scanner in the 5 cm area that was sampled. This could be due to obstructions such as vegetation. The surveys were designed to minimize these gaps/holes.

The original survey extents shown Figure 6 and Figure 7 were clipped to smaller areas for error analysis and change detection. For the gully, the storm on early November resulted in an aborted RIEGL survey, so all analysis was restricted to these extents. For the stream-bank, a polygonal extent was used based on the area of maximum overlap of the surveys.

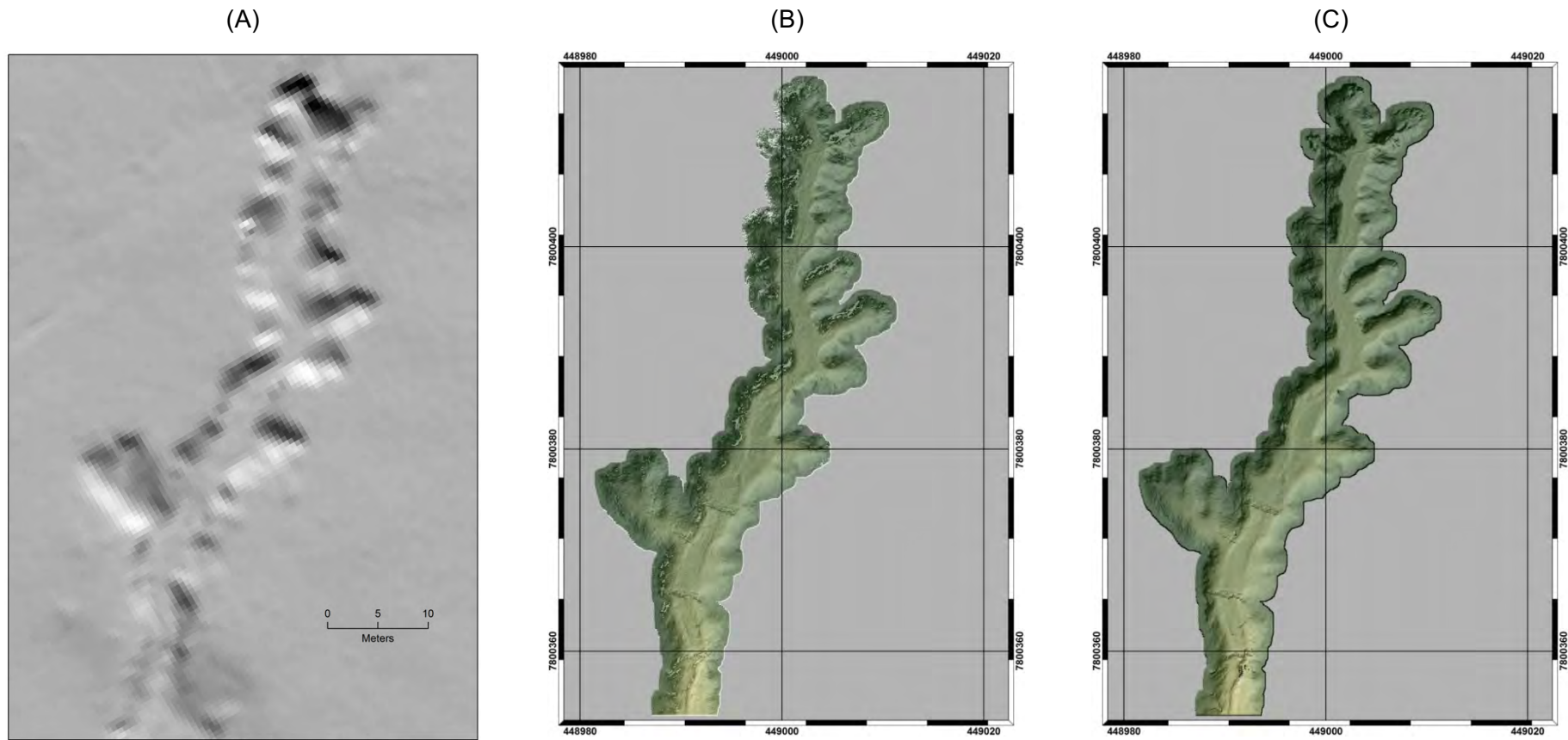


Figure 6: Hill-shaded DEMs derived for the gully site using (A) airborne LiDAR, (B) Zebedee and (C) RIEGL.

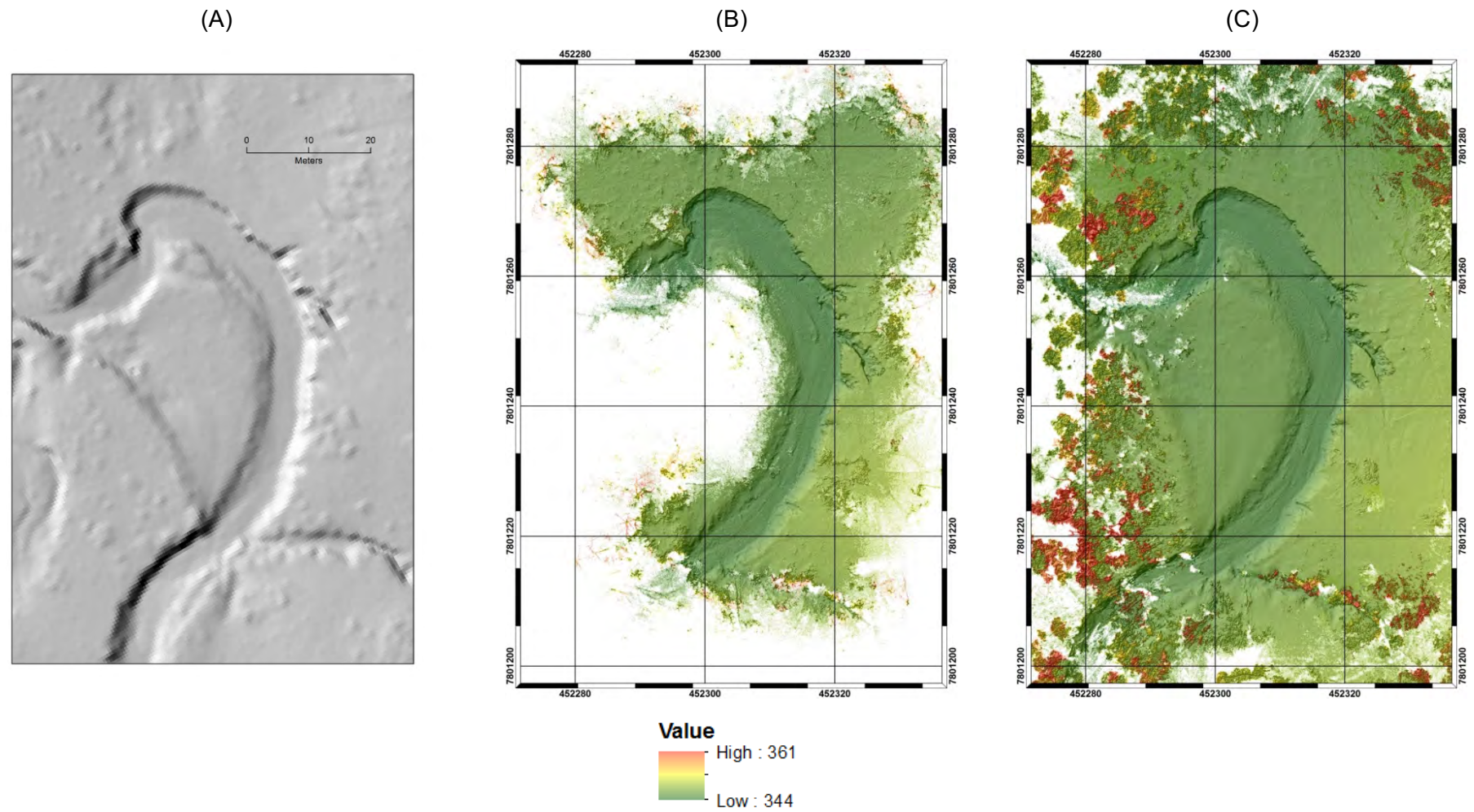


Figure 7: Hill-shaded DEMs derived for the bank site using (A) airborne LiDAR, (B) Zebedee and (C) RIEGL.

5.2 Error analysis

There are two steps in estimating the error for each instrument. The steps relate to (i) the registration performance of the sensors with the reflector markers; and (ii) the repeatability of each approach when surveys are taken on the same day.

5.2.1 Registration performance

The gully datasets, for both instruments, registered to the reflector control points with average RMSE values <2.1 cm (Table 3). The stream-bank registration accuracy of Zebedee data was considerably lower than for the gully site (Table 4). It is expected that additional scanning of the reflectors would have improved these results. The registration was better for the RIEGL data, as this instrument has been designed as a survey grade instrument and is therefore has specific functionality for this task.

Table 3: Gully registration results using the Zebedee and the RIEGL.

Attribute	Zebedee		RIEGL	
Scan number	1	2	1	2
Control points found	4	5	5	5
Control point transform RMSE (m)	0.0207	0.0126	0.0117	0.0087

Table 4: River bank registration results using the Zebedee and the RIEGL.

Attribute	Zebedee	RIEGL
Control points found	5	5
Control point transform RMSE (m)	0.0600	0.0064

5.2.2 DEM repeatability

The repeatability errors for the DEM profiles collected on the same day for both the RIEGL and Zebedee are presented in Table 5 and Figure 8. The RIEGL data is well registered with comparatively low SD of residuals of 0.0189 m for the gully site and 0.0242 m for the stream-bank site. The Zebedee data recorded higher registration errors and SD of residuals for the gully (0.0336 m) and stream-bank sites (0.0449 m). Results were consistent at both the gully and stream-bank site with Zebedee recording >56% higher SD of residuals. In general terms, the higher the SD of residuals, the lower the ability to detect subtle change.

The U_{crit} values, which are an estimate of overall error, are lower for the RIEGL being 0.0524 for the gully and 0.0672 for the stream-bank survey. The U_{crit} values are higher for the Zebedee, at 0.0933 and 0.1244 for the gully and stream-bank sites, respectively (Table 5). This suggests that the Zebedee is less precise and may not necessarily pick up subtle changes in erosion and deposition typical of individual events (e.g. 64 mm rainfall event).

Table 5: Repeatability of RIEGL and Zebedee derived minimum height DEMs. The SD of residuals for σ_{e1} and σ_{e2} were the same value.

Erosion feature	DEM1	DEM2	Mean residual	SD of Residuals	U_{crit}
Gully	RIEGL (run 1)	RIEGL (run 2)	0.0009	0.0189	0.0524
Bank	RIEGL (run 1)	RIEGL (run 2)	0.0002	0.0242	0.0672
Gully	Zebedee (run 1)	Zebedee (run 2)	-0.0037	0.0336	0.0933
Bank	Zebedee (run 1)	Zebedee (run 2)	<0.0001	0.0449	0.1244

(A)

(B)

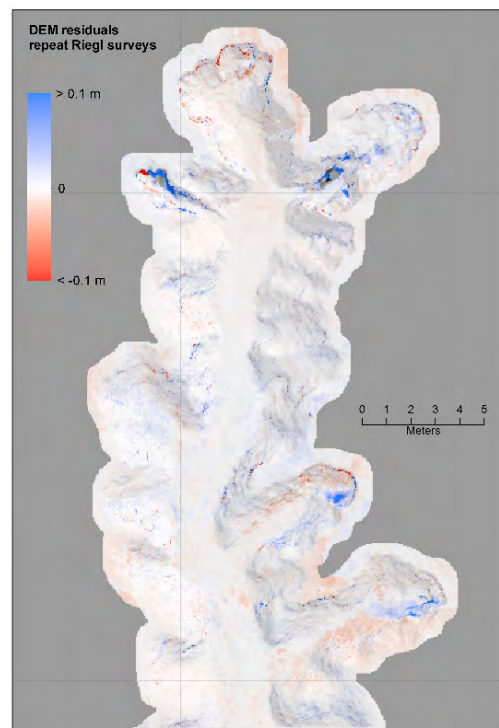
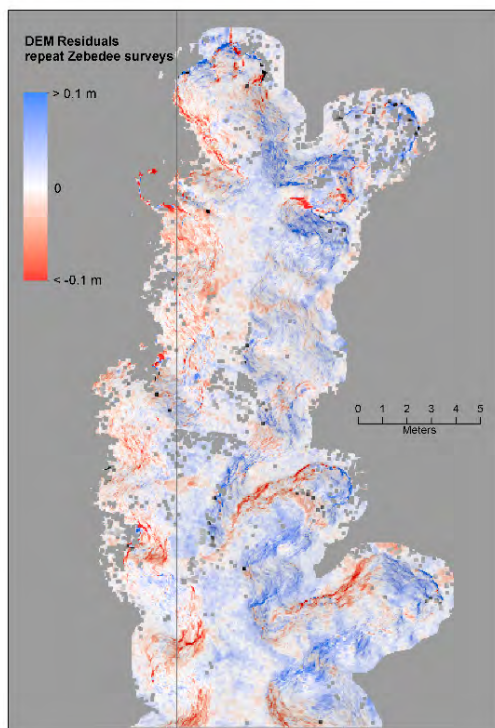


Figure 8: DEM residuals for the repeat surveys taken on the same day for (A) Zebedee (B) RIEGL. The 0.1 threshold was an arbitrary value used for display purposes only.

5.3 DEM's of Difference (DoD) – estimates of erosion

Estimates of erosion, deposition and sediment loss (or volumetric change) were calculated from the DoD the for the gully site only (Table 6). Images of the gully before and after the rainfall event are presented in Figure 9. Due to the differences in erosion and deposition detected during the storm event, the net change or loss estimates also varied between the instruments. The RIEGL estimated a net erosion loss of 0.45 m^3 , and the Zebedee estimated

a net deposition of 0.38 m^3 during the event. This highlights the importance of understanding the error calculations involved in using each instrument as these results can have significantly different consequences when evaluating remediation effectiveness. Examples of the DoD for the gully and stream-bank site are shown in Figure 9 and Figure 10, respectively. Both of these images compare the Zebedee and RIEGL data to the LiDAR DoD, however, it is important to note the airborne LiDAR DoD was based on a three year period and the Zebedee and RIEGL DoD was based on a single rainfall event in November 2015.

Table 6: Gully volumetric change results using the RIEGL and Zebedee. The negative values mean net deposition and positive values mean net erosion.

DEM1	DEM2	U_{crit}	Erosion (m^3)	Deposition (m^3)	Net change (m^3)
RIEGL	RIEGL	0.0524	0.4978	0.0472	0.4506
Zebedee	Zebedee	0.0933	0.2148	0.5921	-0.3773

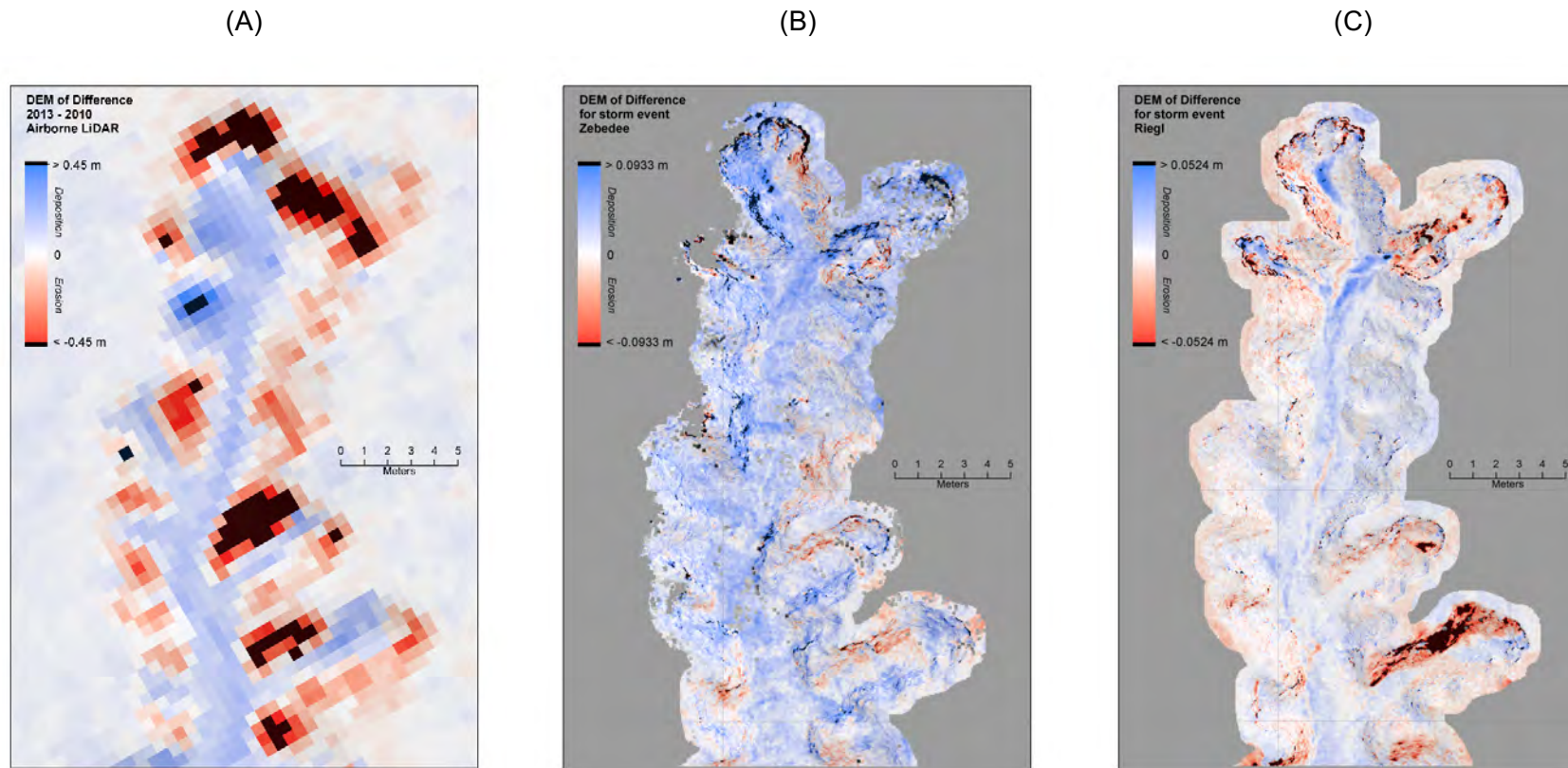


Figure 9: DEMs of Difference (DoDs) for the gully site. (A) airborne LiDAR (B) Zebedee (C) RIEGL. Red represents a decrease in elevation between the earlier and later DEMs, and blue indicates an increase in elevation. Black represent areas of change in exceedance of the detection threshold and are interpreted as erosion and deposition respectively, with volumes for Zebedee and RIEGL reported in Table 6. Detection thresholds for the airborne LiDAR were based on Tindall et al., (2014) and for the Zebedee and RIEGL the values were derived from the U_{crit} values in Table 5. Note the airborne LiDAR DoD represents a three year period and the Zebedee and RIEGL are based on a single rainfall event in 2015, so they are not directly comparable but do provide an indication of the key areas of erosion and deposition with this particularly gully system.

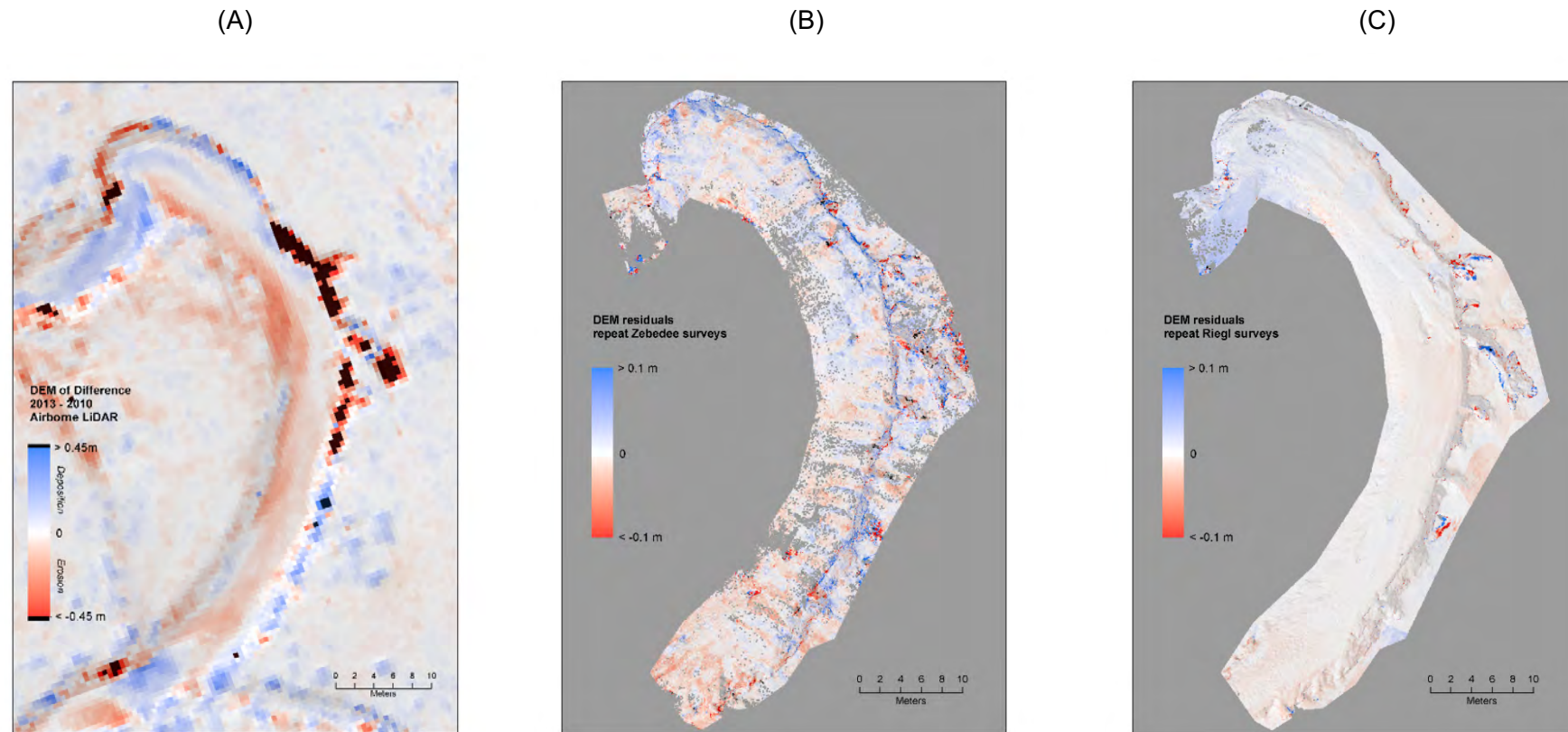


Figure 10: DEMs of Difference (DoDs) for the bank site. (A) LiDAR (B) Zebedee (C) RIEGL. Red represents a decrease in elevation between the earlier and later DEMs and blue indicates as increase in elevation. Detection thresholds for the LiDAR were based on Tindall et al., (2014) and for the Zebedee and RIEGL the values were derived from the U_{crit} values in Table 5. Note the LiDAR DoD represents a three year period and the Zebedee and RIEGL are based on a single rainfall event in 2015, so they are not directly comparable but do provide an indication of the key areas of erosion and deposition with this particularly stream-bank system.

5.4 Sampling and processing costs and time

Estimates of the cost of data acquisition and processing for each technique is given in Table 7. Airborne LiDAR is suitable for capturing data across large areas and whole sub-catchments or catchments. The TLS and Zebedee is suitable for smaller scales and individual erosion units. It would be possible and appropriate to calibrate the airborne LiDAR data against the higher precision terrestrial laser scanners for the purpose of scaling up results from small individual gullies or banks to whole sub-catchments.

Table 7: Comparison of costs for acquiring and processing the different data sets. All information are approximate estimates only and may vary with time and area.

Approach	Threshold of erosion detection (m)	Source of information	Capital cost of equipment or data capture (\$)	Time to collect data	Processing time and considerations	General comments
RIEGL	± 0.05 - 0.067 m	This study	\$200,000 to purchase a RIEGL scanner + software licences	>4 hours per 100 linear metres	~7 hours that includes processing time and post-processing checks. Processing can be done in-house by trained staff using specialised software	Gold standard and best used when high precision is needed
Zebedee	± 0.09 - 0.12 m	This study	\$25,000 for commercial unit (Zeb1) + processing cost (\$0.25 per metre)	<1 hour per 100 linear metres	~3 hours per survey which includes ~1 hr for Zebedee server uploads and processing plus 1 hr for marker identification and alignment plus one hour for DoD from in-house software/scripts. (efficiencies could be made with high volume and improved workflow)	The main benefits of the Zebedee are the speed of data capture. It is therefore useful when numerous sites (e.g. gullies) are in close proximity
LiDAR	± 0.20 – 0.1 m	(Wheaton et al., 2010; Croke et al., 2013; Grove et al., 2013; Tindall et al., 2014)	\$1000 to \$2000/km ² (depending on provider, location and resolution)	Weeks to months depending on time of data capture and speed/experience of supplier	Processing such as ground classification are included in supply costs for LiDAR, but this can be of variable quality	Best for large areas (> 10km ²) with higher rates of erosion

6. DISCUSSION AND CONCLUSION

A review of bank erosion rates presented in this report determined that annual rates of change can vary from ~0.01 m to ~5 m per annum in the GBR catchments. Given the enormous diversity of the rivers draining to the GBR, there is a need for multiple techniques to evaluate change. This study provided a detailed comparison of three approaches to measuring erosion of channels (stream-banks and gullies). These included airborne LiDAR, the Zebedee hand-held laser scanner, and the RIEGL terrestrial laser scanner.

The airborne LiDAR data presented in this report is not strictly comparable to the other two sensors, as the time period of data collection was different. Overall, the LiDAR approach has a threshold of between 0.2 to 1.0 m, which means that any erosion and deposition below this threshold would be difficult to distinguish from other artefacts in the data (e.g. survey and sensor effects). Therefore, it is expected that airborne LiDAR will be useful for evaluating erosion and channel change on large river systems where it is more likely that erosion will exceed 0.5 m and potentially on smaller channels when the erosion rates are high (such as after extreme events).

The Zebedee scanner achieved a higher level of precision than the airborne LiDAR for the gully and bank sites evaluated in this study. The threshold of erosion detection is ~ 0.12 m, although this assessment was based on a relatively low complexity environment, and further testing of the Zebedee in more complex terrain would be needed to determine if a similar threshold applies in all situations. This study suggests that the Zebedee is best suited to measuring gully change in larger gully systems, where erosion rates are typically greater than 10 - 15 cm. It may also be useful for measuring cumulative, annual scale changes in smaller gullies. The major benefits of the Zebedee are the speed of data capture as well as the price of the instrument. The Zebedee data could be collected in about a quarter of the time of the RIEGL, however, there are currently higher post-processing overheads and a dependence on a third-party processing software.

The RIEGL scanner had the greatest level of precision and the residual errors suggest that its accuracy for change detection was very high. It had an erosion threshold of ~ 0.067 m. It is therefore the instrument of choice when detailed erosion estimates are required. For example, when it is necessary to have very precise estimates of erosion and deposition for a specific remediation site, the RIEGL, or a similar survey grade terrestrial laser scanner would be the recommended instrument to use. If there are a lot of sites in close proximity (banks or gullies) it may be more cost-effective to survey all them with the Zebedee, and only a select few with the RIEGL, using the RIEGL data to help quantify any uncertainty in change estimates derived from the Zebedee.

As with all instrumentation, they are constantly evolving and improving. Additional algorithm development is needed to address ground/non-ground point classification for all instruments. This would greatly help with automated gully extent classification. It is also possible that the RIEGL and Zebedee instrumentation could be used to derive greater precision from the airborne LiDAR data by helping to identify and resolve errors. Airborne LiDAR has the benefit that it may be captured over much larger areas, however, it is difficult to identify the erosion thresholds for all areas. These higher resolution terrestrial laser scanning instruments may help identify appropriate thresholds for use across a broad range of erosion and landscape features. Assessment of these approaches in more complex terrain and on larger stream and gully systems is warranted prior to broad scale application. It would also be useful to

compare these approaches to techniques such as image based modelling (e.g. Frankl et al., 2015).

This project has provided a comparison of instruments that will be used to help benchmark and evaluate future investments in stream-bank and gully remediation in the GBR catchments. Use of these instruments will provide the quantitative data needed to detect the improvements at the appropriate scale. This will also provide valuable information about the rates of change under various land use management scenarios that can be used by the SourceCatchments modellers. Evaluation is critical to justify the use of Government spending on remediation, but also as a marketing tool to encourage other farmers to undertake remediation. This will provide increased confidence in targeting future investments and lead to improved water quality from catchments to the GBR.

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