A comparison of methods for measuring water quality improvements from gully rehabilitation in Great Barrier Reef catchments.

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Key Points

- There is no one size fits all method for monitoring gully rehabilitation effectiveness. Methods need to be tailored to the scale of the site, the method cost as a function of the rehab investment, the type of treatment and the expected magnitude of response.
- Standard airborne LiDAR (ALS~ 6-12 pts m^{-2}) is not an appropriate rehab monitoring technique on its own, over timescales < 10 years. It is however, extremely useful for: broadscale gully mapping and characterisation; determination of baseline gully and streambank erosion rates at timescales > 2 yrs; gully drainage contribution assessment and site planning
- Terrestrial LiDAR (TLS) is best suited to monitoring simple gullies or fine resolution erosion processes in parts of larger gully complexes - not whole gully complexes. Vegetation effects are a problem for Terrestrial LiDAR, and there is a danger that results can be biased towards the more active unvegetated parts of gullies if this approach is used in isolation.
- High reslt'n airborne LiDAR (HRALS >100 pts m^{-2}) shows promise as a highly cost-effective tool for gully rehabilitation over large areas (>10 ha) – giving a much more even pts spread than TLS.
- It is highly advisable that water quality monitoring is paired with morphological monitoring using terrestrial or high resolution airborne LiDAR.
- A combination of WQ monitoring approaches is advised for redundancy, but where budgets don't allow use of high cost auto samplers, a combination of PASS and RS samplers is a minimum.

Abstract

Recent advances in our understanding of the causes of declining water quality in the catchments draining to the Great Barrier Reef World Heritage Area (GBRWHA) have highlighted gully erosion as a key sediment source. Both the Australian and Queensland Governments now have major programmes focused on gully rehabilitation. With this focus, however, there is an increasing need to be able to quantify the water quality improvements associated with gully rehabilitation efforts, particularly as it appears likely that resource allocation will shift towards a model that funds quantifiable water quality outcomes through a Reef Credits market-based approach. Under such an approach, water quality improvements must be measurable, and hence the monitoring methods employed must be both scientifically rigorous, but also cost-effective. At present there is no standardized approach employed in monitoring gully rehabilitation success, but the success of an outcome-based funding model depends on the development of rigorous approaches with known margins of error and signal to noise ratios. In this paper we outline and compare a range of gully monitoring methods and discuss the pros- and cons of the various techniques. We compare various LiDAR methods, including standard resolution airborne LiDAR (typically 4-6 pts m^{-2}), terrestrial LiDAR (up to 5000 pts m^{-2}) and high resolution airborne LiDAR (up to 300 pts m^{-2}). We also compare various water quality monitoring methods, including Sigma auto-samplers, low cost Rising Stage Samplers, and a new low cost integrated sampler know as a Pumped Active Suspended Sediment (PASS) sampler developed at Griffith University.

Keywords

Gully rehabilitation, monitoring methods, LiDAR, HR ALS; TLS, PASS Sampler; Rising Stage Sampler

Introduction

Gully erosion is now estimated to contribute around 40% of the accelerated erosion in Great Barrier Reef (GBR) catchments, varying between 30–60% for the major dry tropics catchments (Thorburn et al., 2013; Bartley et al., 2017). Hence the fine suspended sediment derived from gully erosion represents a major source of elevated sediment loads to the GBR lagoon. Preliminary research is also indicating that gully erosion is a significant source of bioavailable particulate nutrients (Garzon-Garcia et al., 2016), and as such the management of gully erosion has the potential to contribute towards significant improvements in both suspended sediment and nutrient pollution sources to the GBR lagoon. In response to the weight of scientific evidence regarding the significance of gully erosion as a major source of water pollution to the GBR (e.g. Brooks. ,et al., 2013; 2016, Shellberg and Brooks., 2013; Wilkinson et al., 2013, 2016) both the Australian and Queensland Governments have established major programmes focused on rehabilitating gully erosion, and consequently there is a need to monitor the effectiveness of the treatments so that the water quality improvements can be quantified. In the past water quality improvements associated with a variety of catchment management interventions have often been assumed, but increasingly there is an expectation that quantifiable water quality improvements must de demonstrated using robust monitoring approaches. As such there is a need to assess the range of approaches appropriate for monitoring and assessing the costs and benefits of different rehabilitation methods in different settings. In this paper we present examples of a range of monitoring techniques and discuss the pros and cons of the various methods trialed in two large experimental alluvial gully rehabilitation projects at Crocodile Station (-15.6699S;144.5944E) in the Normanby catchment and Strathalbyn Station in the Burdekin (-20.1897S;147.3261E).

LiDAR

Light detection and Ranging (LiDAR) is now widely used for a range of topographic mapping applications at a range of resolutions. Repeat LiDAR surveys enable volumetric changes to be determined between consecutive surveys, and as such are extremely valuable for measuring baseline erosion rates from gullies and stream banks where there is sufficient time between samples to detect changes greater than the minimum limit of detection (LoD). In the following section we compare three different LiDAR survey techniques, and summarise the appropriate applications of each approach.

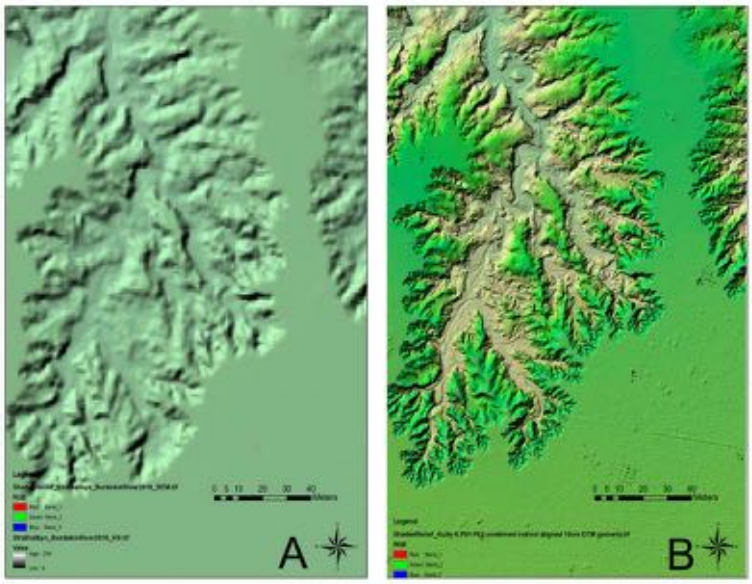

Figure 1 (A) 1m resolution hillshade DEM derived from Standard ~6 pts m^{-2} airborne LiDAR compared with (B) 0.1m resolution hillshade DEM derived from ARA's high resolution airborne LiDAR >100 pts m^{-2}

Standard Airborne LiDAR (ALS)

Standard airborne LiDAR typically collects data at a resolution of around 6-12 return points per m^{-2}, usually with 3-4 pts m^{-2} as ground returns. Standard LiDAR at this resolution (Figure 1A; Figure 3A) is highly cost-effective at around \$1.00 – \$1.50/ha (Table 1), and is best suited to broad scale mapping (1000km^2 +) enabling characterisation of different gullies or channels, and for identification of the rapidly expanding portions of gullies or streambanks. It is also critical data for identification of the contributing catchment area to each gully (Figure 2).

High Resolution Airborne LiDAR (HRALS)
High resolution airborne LiDAR is typically flown from ultralight aircraft, which are collectively known as Small Environmental Research Aircraft (SERA). These aircraft can fly lower and slower than the light aircraft platforms used in the acquisition of standard airborne LiDAR, and can therefore capture many more points per unit area with a smaller beam footprint than standard LiDAR. They are also highly maneuverable, and can cost effectively fly multiple passes in both directions to increase the points coverage and ensure that ground is covered from multiple angles, maximizing the potential for achieving a high penetration to ground level, even with relatively dense vegetation. This method is most appropriate for collecting data across sites encompassing 10s to 100s of hectares, and is well suited to quantifying the effectiveness of gully and stream bank rehabilitation efforts, given that it can resolve changes down to a few cm in both the vertical and horizontal dimensions (Figure 1B, Figure 4). As outlined below, it has significant advantages over Terrestrial LiDAR for larger, more complex, gully systems.

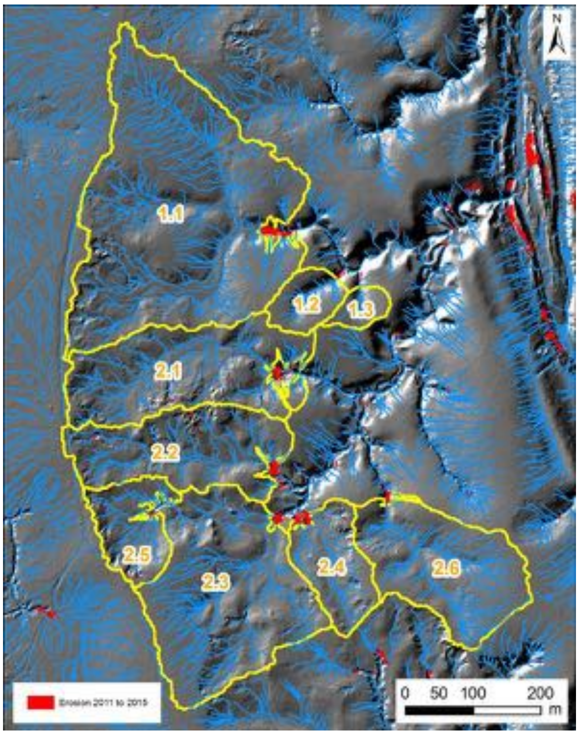

Figure 2. Standard resolution LiDAR showing drainage network analysis used to derive gully catchment areas and the location of highly active erosion (in red) from repeat LiDAR DoD.

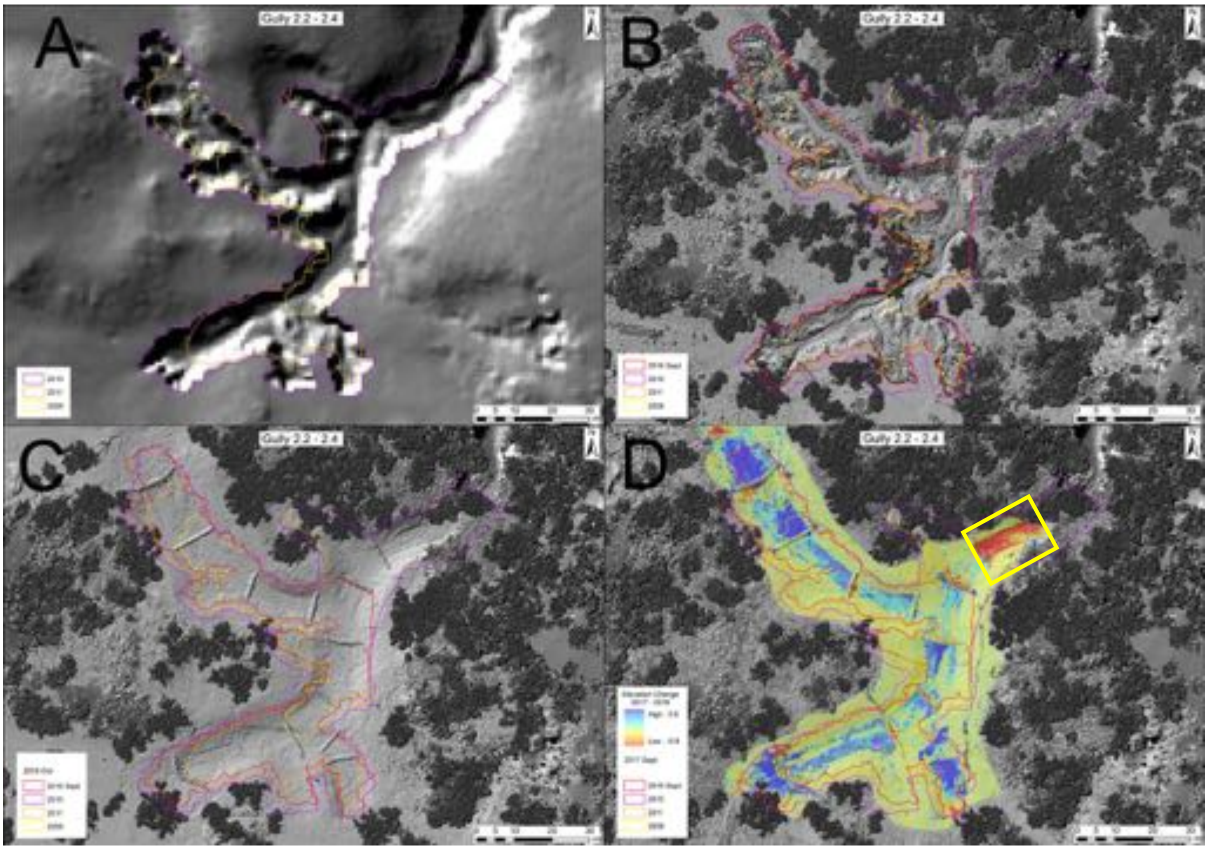

Figure 3 Examples of two different types of LiDAR data from the Crocodile Station gully rehab site. Repeat surveys of standard airborne LiDAR shown in (A) were used to determine baseline erosion rates. Repeat surveys from 2009, 2011 & 2015 (yellow, orange & purple lines respectively) show gully growth rates over this 6 year period. Terrestrial LiDAR surveys from Sept 2016 (B); Oct 2016 (C) and Oct 2017 (D) show the gully before (B) and after rehab (C) and then DoD changes after 1 wet season post rehabilitation (D).

Terrestrial LiDAR (TLS)

Terrestrial laser scanning (TLS) can provide very high resolution topographic data (down to several mm), and as such can be extremely valuable for resolving erosion processes that are unable to be detected by the coarser resolution LiDAR (ALS). This is particularly important where subtle changes need to be detected over short time frames, when it is not practical to wait 5 – 10 years before such changes can be detected using the coarser lower cost methods. The example shown in Figure 3 shows the comparison between standard ALS (A) and TLS of the Crocodile treatment gullies 2.2-2.4 (see Figure 2) before (B), and then a scan immediately after treatment (C) down sampled to around 100 pts m^{-2}. Note that this DSM currently includes the non-ground vegetation cover as well. A DEM of Difference (DoD) of the non-vegetated section of the gully shown in (D), indicates how the site responded over the first wet season post-rehabilitation. Summarised in Table 1 are the minimum sediment yields derived from ALS DoD analysis between 2009-15, extended to 2016 with TLS. Change detection is then conducted with TLS after the first wet-season, picking up changes that would be undetectable using ALS. Note that the gully erosion has been effectively stopped by this treatment.

Table 1 Crocodile Rehab gully min. sediment yield from ALS DoD analysis (09-16) & TLS DoD analysis (16-17)

	gully 2.1 (cntrl)	gully 2.2	gully 2.3	gully 2.4	Total rehab gully
catchment area (ha)	*4.18*	3.31	8.60	1.60	13.5
sediment yield 2009-11 (t/yr)	*175.5*	221.4	331.2	91.8	**-644**
sediment yield 2009-16 (t)	*741*	886	914	281	**-2081**
sediment yield 2009-16 (t/yr)	*93*	111	114	35	**-260**
Vol change post rehab (m^3)(16-17)	*Not available*				**-2.1**
(excluding area at gully exit in box)					**+12.4**

Table 2. Summary Comparison of ALS, HRALS and TLS

LiDAR method	Typical pt density (pts m^{-2})	Typical DEM resolution (m)	Cost per Ha (capture & processing)*	Typical application	limitations
Standard aerial LiDAR	6-12	0.5 – 1.0	\$1.00-\$1.50	Broad scale gully mapping; ID of highly active erosion sources across large areas (via repeat surveys) at scales $10^2 – 10^3$ km^2	Limit of detection (LOD) = ~ 0.5m - hence can only detect very active gully head or streambank at rates typically > 1m lateral change/year
High Resolution aerial LiDAR	100-300	0.05-0.1+	\$100-\$150	Monitoring of large complex rehab sites, particularly with significant vegetation cover at scales 10^1-10^2 ha	LOD = ~ 5cm Does not capture side wall undercuts
Terrestrial LiDAR	100 - 5000	0.01-0.05+	\$2000-\$5000'	Simple gullies, with little vegetation cover, or portions of large gully complexes to determine erosion rates from slope processes: e.g. fine resolution slope ablation or undercutting of side walls, etc.	LOD = ~ 0.5 – 1cm - Highly susceptible to noise associated with grass and herbaceous ground cover. More difficult to remove non-ground vegetation points than from aerial survey - Very time-consuming to undertake whole gully surveys in large gully complexes, and almost impossible to practically achieve even coverage that results in no data voids due to shadowing effects.

* Includes all mobilisation costs - assuming fairly remote location

' TLS incl. ground control setup with a crew of 2 fully costed people in the field with all associated field costs,, surveying 0.2-0.5 ha/day +

Pros and Cons of the Three LiDAR types

From the brief overview provided above, and from the summary provide in Table 2, it is clear that each of these LiDAR methods has their strengths and weaknesses depending on the objectives to which they are being applied, and the scale of the survey task at hand, both spatially and temporally. What is clear is that no one method can suite all applications. ALS is now a very mature technology and the data processing workflows are fairly efficient at removing non-ground vegetation cover and infrastructure to provide a relatively high quality bare ground DEM that can be used for broad-scale mapping of landforms such has gullies, and detecting the rapidly eroding parts of these gullies, when repeat surveys are conducted over several years. Standard ALS workflows, however, are insufficient for undertaking DoD analysis in complex terrain to determine erosion rates from gullies or streambanks, hence, specialist knowledge is required to undertake such analyses to ensure that spurious data and noise is appropriately excluded from the dataset. From the example shown in Figure4, it is apparent that the HRALS methods that are being pioneered by Airborne Research Australia, have huge potential as a very efficient and cost-effective monitoring method for large scale gully rehabilitation. As shown in this example, TLS can provide very high resolution data at a localized scale, but the logistics and practicalities of doing sufficient scans at a site this complex makes in completely impractical to use this technique at the whole of gully scale.

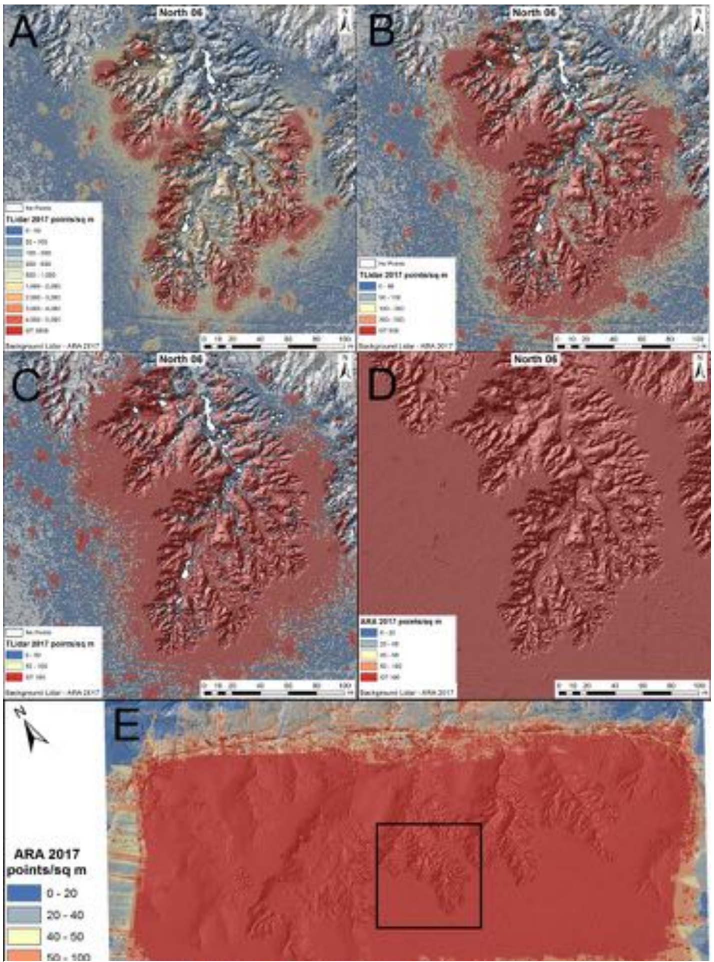

Figure 4 Comparison of TLS survey points coverage in a large alluvial gully complex on Strathalbyn Station, compared with HRALS captured by Airborne Research Australia in Sept 2017. Note that while the TLS can produce extremely high pt densities for small areas (A), it is very difficult to produce a gap free dataset even at lower pt densities. HRALS by comparison can produce a very even coverage >100 pts m^{-2} across an area of around 90 ha. This coverage was acquired in < 1 hr; whereas the TLS acquisition took ~1 week. Note the box is the area represented in higher resolution in A-D.

Water Quality Monitoring Methods

From the discussion above, it is apparent that repeat LiDAR surveys can provide detailed data on net changes in gullies, and hence net sediment yields, at annual timescales, with a high degree of precision. However, these data only provide part of the story, given that they can't differentiate sediment entering from upslope of the gully, nor can they shown how the sediment yield varies with individual events. For this reason we have also undertaken water quality monitoring at the gully outlets at the Crocodile site (Figure 2). Four water quality monitoring methods (automatic sampler (Sigma® 900), pumped active suspended sediment (PASS) sampler, rising stage sampler, and turbidity logger (Observator NEP495) were used to measure the concentration of suspended sediment travelling through ephemeral gullies. The samplers and logger were all placed in the floor of gullies 1.1, 2.1 approximately 30-50 m downstream of the gully head scarp and at the gully outlet for the amalgamated gullies 2.2, 2.3 & 2.4. Sampler intakes and logger measurement points were set at the same height above the channel bed (approximately 20 cm). Additional rising stage samplers were set at increasing height intervals of 5 cm between 20 and 45 cm above the channel bed. The automatic and PASS samplers were activated/deactivated by float switches set at their respective intakes. The automatic sampler and turbidity logger were programed to collect a sample or measure turbidity every ten minutes. The automatic sampler would only collect samples when water was present. The PASS sampler continuously sampled when activated by the presence of water. A stage recorder, programed to measure water level every 2 minutes, was placed at the base of the rising stage sampler support.

Evaluation and Comparison of Water Quality Monitoring Methods

All of the water quality monitoring equipment were maintained over the 2017/2018 wet season (approximately six months). Over 200 samples were collected and are currently being processed. During the monitoring period several maintenance and sample collection visits were required to ensure the equipment operated correctly. The automatic sampler had proved to be the most unreliable with false activations, system malfunctions, and insect infestations of the sampler resulting in reduced monitoring effectiveness (e.g., flow events being missed). The other monitoring equipment were found to be reliable for the duration of the monitoring period. A limitation of all of the monitoring equipment used is that they rely on a single point of sample collection or measurement within the channel cross section. This adds a degree of error or variability because the samples are not representative the whole gully cross section. However, it should be noted that the gully cross sections monitored were short and suspended sediment concentration variability over the cross section should be minimal. Another problem with a single sampling/measurement point is that it does not account for the dynamic nature of the channel bed. The floor of the monitored gullies tended to aggrade or incise, as coarse sediment moved through under different flow conditions. This resulted in sample intakes being located in undesirable monitoring locations depending on the channel bed rising or falling away.

An evaluation of the monitoring equipment capabilities to collect representative water quality data found the automatic sampler and turbidity logger provided the best sample data resolution. However, the automatic sampler either missed or could not sample entire storm events and the turbidity logger required additional samples to be collected by another method for calibration purposes. The PASS and rising stage samplers were the most robust methods. They required little maintenance and collected samples that were highly representative of site conditions and were found to be ideal for comparing water quality conditions of the different gullies monitored (Table 3). Initial data fortuitously captured by the auto-samplers during a storm that occurred while we were on site, immediately after servicing and resetting the equipment, provides an example of the quality of data that can be collected when everything is performing as it should. These results demonstrate the relative effectiveness of gully remediation works at reducing suspended sediment yields within the first and second wet season respectively after rehabilitation.

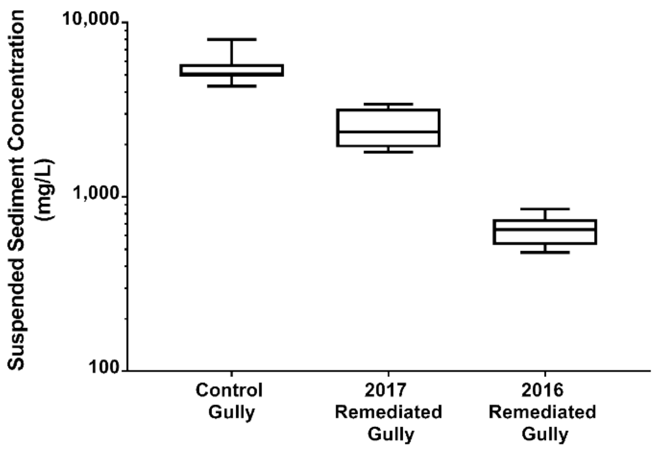

Figure 5 Box and whisker plots of suspended sediment concentration for the control and remediated gullies at Crocodile Station, QLD. The box and whisker plots present the minimum, 25th percentile, median, 75th percentile, and maximum of each gully dataset from rain storm samples collected with the auto-samplers on January 24, 2018.

Table 3 Assessment of monitoring equipment capabilities

Sampler Type	Cost	Installation and operation	Principal of operation	Sampling capacity	Analysis	Integrity of Data
 Automatic Sampler	$10,000-$30,000	Requires professional installation and regular maintenance for continued operation. Not overly reliable	Collects discrete samples triggered by a parameter (e.g., presence/absence of water in stream)	1-24 samples	High to low analysis effort depending on if samples are analysed as a composite or individually. Samples can be used for a limited number of multiple analysis.	Provides quality data for short flow events, with a high sampling frequency. Non-continuous, as well as potential incomplete sampling of an entire flow event can cause bias.
Turbidity Logger 	$4,000-$8,000	Non-technical installation. Requires little maintenance. Reliable	Collects measurements on a defined interval (e.g., every 5 minutes for several weeks)	>10,000 measurements over weeks or months	No analysis required. No other analysis can be conducted because a sample is not collected.	Provides quality data for, high frequency measurements, short and long term deployments. Data requires additional sampling and calibration to be converted to SSC.
 Rising Stage Sampler	$300-$600*	Requires professional installation and highly regular maintenance for continued operation. Reliable	Collects discrete samples of a single event as the water stage rises	3-12 samples depending on sample site.	High to low analysis effort depending on if samples are analysed as a composite or individually. Samples can be used for a limited number of multiple analysis.	Provides quality data for rising stage of hydrograph. Non-continuous sampling and lack of sustained or falling stage samples can cause bias toward initial flow concentrations.
 PASS Sampler	$400-$1200	Non-technical installation. Requires little maintenance. Reliable	Continuously collects water, when activated by a float switch,	1-3 samples depending on sample site	Low analysis effort. . Samples can be used for a high number of multiple analysis.	Provides high quality continuous data. Lacks short term resolution. (e.g., provides an average concentration compared to multiple concentrations along a hydrograph).

* = Price for six samplers, SSC = Suspended Sediment Concentration.

The data from a single storm on January 24th 2018 (20-30 mm of rain in under 6 hours) show that sediment yields from the works completed in December 2017 had reduced yield by around 50%, whilst those from the gully rehabilitated in October 2016 (Figure 3), which was into the second wet season post-rehabilitation, had a median suspended sediment concentrations 85% lower, than the un-remediated control gully 2.1 (Figure 5).

Conclusions

Based on our experience to date applying multiple methods to measure the effectiveness of gully rehabilitation, it is clear that no single technique can provide all the necessary information to fully quantify the effectiveness of the treatment, nor the water quality benefit. Inevitably the extent of monitoring will be a function of budget, and so it is not always going to be possible, or necessary, to use the complete array of monitoring methods outlined here. Nevertheless, we would recommend that some water quality monitoring should always be undertaken in conjunction with the LiDAR survey methods, designed to measure gross annual changes in gully volume. Gullies, are however, very challenging environments in which to undertake water quality monitoring, due to the very flashy hydrology, the very high sediment loads (prior to treatment), and the fact that the bed tends to aggrade and/or incise significantly through the monitoring period, with different events, and in response to the rehabilitation. Hence, fixed intake levels are problematic, and we would recommend multiple intakes, ideally with different units. The new PASS sampler looks to be a very cost-effective way to collect time-integrated samples across events, and due to their low cost, the potential is there to have multiple samplers set at different intake levels to account for bed movement.

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