COMMENTS FROM REFEREE 1:

GENERAL COMMENTS FROM REFEREE 1:

The manuscript hess-2020-268 titled "Landscape scale remediation reduces concentrations of suspended sediment and associated nutrients in alluvial gullies of a Great Barrier Reef catchment: evidence from a novel intensive monitoring approach" has been reviewed. The manuscript is really interesting and fits in the broad scope of the journal. The authors present a detailed comparison analysis of two gullied areas in Australia: One remediated area and one control area. I consider that moderate/major revisions should be carried out before a final decision. Some important questions should be answered and small issues should be improved.

> *RESPONSE:* ***Acknowledge***. The authors acknowledge this positive comment and have undertaken specific reconsideration to address the other key points raised by the reviewer (see below).

SPECIFIC COMMENTS FROM REVIEWER 1:

Specific Comment 1. "One of my main concerns is the limited study period: only two years, and some limitation in sediment samples that were only recorded during three events. The authors stated this problem in the text, but I think that the limitations should be highlighted in the results and discussion section and also in the conclusion section. - I consider that the landscape scale remediation that has been carried out in this area, is really significant to understand all the process, and it should be noted. In that sense, I consider that: - Some photos should be included with situations before and after the reclamation activity (it is included the video, but I consider interesting to include some photos). - In the abstract, you should already inform about the remediate measures. - You should also discuss about the feasibility of this remediation work. Would it be possible to carry out this work in other study areas? Which was the cost of this remediation technique? – I don't really understand the information that you provided in the lines 95-115. Is it about previous remediation activity? I'm not totally sure if this information should be included in this section or it should be moved to the introduction or event results section.

RESPONSE: ***Accept/Clarify.*** The authors accept the suggestions by the referee and wish to clarify the following points:

Two-year study period: Accept. New text has been added to the Results and Discussion and Conclusion sections regarding this:

Line 319-321**: "**However, because this study only includes two wet seasons of data it should be considered preliminary until it is further validated by continued monitoring of the remediated gully for several additional wet seasons."

Line 506-509**:** "Further monitoring at the site should be conducted over longer timescales (i.e., decades) to evaluate the longevity of the erosion mitigation controls used as part of the gully remediation works."

Sediment samples collection: Accept. The text has been revised:

Line 434-438**:** "A total of 40 samples were collected from the remediated (n=14) and control (n=26) gullies for nutrient analysis. The hydrographs and SSC trends of these sampling events indicate they were representative of the other flow events observed in the two gullies (SI-3) and provide enough data for a preliminary assessment of nutrient transport trends within the gullies."

Before and after photos: Please refer to Figure 2

More detail on remediation in Abstract: Accept:

Line 20-24**:** "The gully remediation method was a first attempt, in the region, to invest a high level of financial (total cost of remediation ~$90,000 AUD) and logistical effort (e.g., intensive earthworks including the establishment of an on-site quarry) to develop long lasting erosion mitigation measures (i.e., regraded, compacted and battered gully walls, rock armouring of banks and channel, and installation of rock check dams)."

Mention cost of remediation in Abstract: Accept. Please refer to the comment above.

Unclear description of gullies in Methods (Lines 95-115): Accept. The text now states:

Line 118-132**:** "Two gullies were used to evaluate the effectiveness of the remediation works. The remediated gully is the larger of the two which encompasses several gully lobes that drain into a central channel. The gully treatment area is ~0.6 ha, with a catchment area of 13.7 ha. The catchment of the remediated gully is a conglomerate of three sub-catchments (Sub-catchments 1-3) (Figure 1). The active secondary incision of the control gully is ~0.2 ha while the gully catchment, which drains directly into the headscarp, has an area of 3.3 ha. Both gullies are situated in highly-dispersible and slaking sodic alluvium. Prior to remediation, both gully catchments would have undergone similar erosion processes (i.e., scalding, sheet erosion, rilling in the gully catchment and tunnel erosion, head scarp mass-failure, and gully sidewall erosion within the incised part of the gully). Erosion rates derived from repeated airborne LiDAR collected before remediation was conducted (2009 to 2015), indicate the control gully produced slightly more sediment (61 t/ha/yr) compared to the remediated gully (50 t/ha/yr), based on gully catchment area (Brooks et al., 2016). Comparison of particle size distribution (PSD) (Section 3.2.3) from readily erodible soil collected from the two gullies, prior to remediation activities, showed there was no significant difference between the two gullies. It is likely that these soils would have eroded into suspended sediment in a similar manner, thus, it is assumed that the suspended sediment concentration (SSC) and PSD from the two gullies would have been similar, pending any significant differences in water velocity."

Specific Comment 2. "One really important issue is about literature review and other reclamation examples. In your case, your literature is mainly focused in studies carried out related to the GBR. However, there are other worldwide examples that could be included in the introduction and discussion section to discuss about remediation works. Some examples of remediation can be found in other areas as the Draix catchments (Rey et al. Burylo et al., 2014; Breton et al., 2016) or in Spain (Ballesteros et al. 2017; Oleagordia Montaña et al. 2016). I think that this information could be included and discussed about the feasibility of remediation works in gully and badland areas."

RESPONSE: ***Acknowledge***. The authors acknowledge that the literature review may focus too much on studies completed in catchments of the Great Barrier Reef and will include discussion on relevant remediation works completed elsewhere to provide a more global context to the study. The authors thank the referee for the suggested examples and will consider them when revising the literature review.

Specific Comment 3. "Other important issue is about the methodology to check the effectiveness of remediation works. You have been mainly focused in this work in turbidity measures, water samples: but what about UAVs information? Maybe it could be also interesting to use other kind of instrumentation that can provide different data to complete the dataset. Which are the topographic changes that have been observed in the area?"

RESPONSE: ***Acknowledge***. The authors acknowledge that remote sensing methods used to estimate erosion (i.e., airborne Lidar) could provide a useful complimentary line of evidence for the study. The authors provide discussion points and relevant data derived from terrestrial and airborne Lidar measurements throughout the manuscript. However, the authors did not extensively compare the results of the two methods in more detail as this would make the manuscript less concise and is not related to the overall aim of the study (i.e. water quality aspects of gully remediation).

Specific Comment 4. "I consider that an initial research hypothesis should be included together with the objectives and research questions at the end of the introduction section. - You should specify all the abbreviations and that you have used in the text, in figure and table captions (for example table 1) - In my opinion the tittle is too long."

RESPONSE: ***Acknowledge***. The aim of the study is described in the final paragraph of the Introduction (Lines 76-78). The authors will revise this text to make the research questions and objectives clearer.

The objectives now state:

Line 99-104: "Here we aim to assess the effectiveness of landscape-scale remediation in improving the water quality of an alluvial gully situated in the tropics of Queensland, Australia, which flows to the Great Barrier Reef. We apply a recently developed gully water quality monitoring approach that facilitates accurate measurements while meeting the financial and operational requirements of monitoring in remote locations. This work, although done on a limited spatial and temporal scale, provides a critical foundation for developing and evaluating landscape-scale remediation of alluvial gullies in the Great Barrier Reef region."

The title of the manuscript has been revised, it now states: "Intensive landscape-scale remediation improves water quality of an alluvial gully located in a Great Barrier Reef catchment".

COMMENTS FROM REFEREE 2:

GENERAL COMMENTS FROM REFEREE 2:

General Comments 1. Overall, I considered this paper to be a suitable study for HESS and a useful contribution to our knowledge of alluvial gully remediation strategies. In my opinion this is suitable for publication with minor/moderate revisions.

> *RESPONSE:* ***Acknowledge****.* The authors acknowledge this positive comment and have undertaken specific reconsideration to address the other key points raised by the reviewer (see below).

SPECIFIC COMMENTS FROM REFEREE 2:

Specific Comment 1. "What was the cost of remediation? I think for a global audience this is important."

> *RESPONSE:* ***Accept.*** Text has been revised in abstract:
>
> ***Line 20-24*****:** "The gully remediation method was a first attempt, in the region, to invest a high level of financial (total cost of remediation ~$90,000 AUD) and logistical effort (e.g., intensive earthworks including the establishment of an on-site quarry) to develop long lasting erosion mitigation measures (i.e., regraded, compacted and battered gully walls, rock armouring of banks and channel, and installation of rock check dams)."

Specific Comment 2. "Placement of devices in the gully catchments: catchment 3 PASS is not on a drainage line but catchment 1 and 2 are (assuming blue lines in Figure 1 are drainage lines found using some routing method?). This seems to have an impact on measured sediment concentrations (for catchment 3 the upper SSC is 3556 while catchment 1 and 2 are 563 and 1517, respectively). Given the focus of the paper is on measurement methods I think a little more discussion about the placement of sensors would be good. I think some more discussion of this is important because it seems to have important implications for your conclusions. Taking the lower end estimate of TWA SSC from the control gully gives 4453 and the upper estimate from the hillslope in catchment 3 is 3556 which is ~80% of what is seen in the control gully. Without a larger sample it's hard to know whether this is representative or not but for me it suggests the possibility that hillslope erosion, in this environment, is a considerable source of fine sediment (potentially almost equal to gully erosion?). Given that, I think it warrants a little more discussion around possible ways to address the influence of sensor locations with respect to process interpretation."

RESPONSE: ***Acknowledge/clarify.*** The Referee makes a good point regarding the need for more detailed description of overland flow sampling methodology. Please note that the blue draining lines show in Figure 1 are only indicative of the actual overland flow characteristics observed at the site. Other factors (e.g., vegetation, natural debris, and termite mounds) influence water flows in ways that are not perceived by airborne Lidar-derived flow lines. The overland flow sampling locations were chosen based on observing locations that had consistent flows and were as close as possible to the transition of catchment to gully. The sampler located at catchment three was placed in a different location to the drainage line indicated in Figure 1 because of the presence of termite mounds and vegetation. The authors thank the Referee for making this observation and will provide commentary in the caption of Figure 1 to provide context for the blue flow drainage lines. The authors will also revise the text in the methods (Lines 181-185) to include more detail and photographs of overland flow at the sampling locations (these will be provided as supplementary information).

The referee makes a good point by comparing the suspended sediment dynamics of the catchments and gullies, specifically for catchment vs. gully sediment sources in the control gully. The authors caution the Referee against comparing catchment/gully suspended sediment sample concentrations collected from different locations (i.e., comparing the remediated gully catchment to the control gully outlet). This is not appropriate given there is suspended sediment sample data collected from a location that represents the majority of the catchment water draining into the Control gully. Furthermore, Section 3.2.2 Relationship between SSC and flow provides discussion and detailed examples from the data indicating that subsurface erosion processes are the dominant source of suspended sediment flowing from the Control gully. However, the Referee makes a good point that erosion processes in the catchment, possibly sourced from surface erosion, appear to be a major contributor of suspended sediment flowing through the gully systems and that the collection of accurate and representative catchment monitoring data is very important to understanding these dynamics. The authors will revise the existing commentary on catchment suspended sediment contribution, in the Results and Discussion and Conclusions sections, to provide emphasis on the importance of monitoring locations for the purpose of collecting representative catchment overland flow samples.

Note text has been added to the caption of Figure 1 regarding the placement of PASS samplers in the gully catchments.

***Line 138-140*:** "N.B. The overland PASS sampler in sub-catchment 3 of the remediated gully was deployed several metres away from the flow line inferred by surface geology due to the redirection of flow associated with vegetation and termite mounds."

Specific comment 3. "Also, how do the catchment areas compare? The total catchment area of the remediated gully is ~13ha but what is the catchment area above each PASS sensor in the sub-catchments and how does this play into the results? And the catchment area for each sub-catchment of the remediated gully."

RESPONSE: ***Acknowledge.*** The aim of measuring suspended sediment in water flowing overland into the gullies was to understand their contribution, in terms of suspended sediment concentration and particle size distribution, to the suspended sediment measured at the gully outlet. Because of this, the size of the catchment is less important as ensuring that the major catchment drainage inputs into the gully are monitored. For example, the remediated gully catchment drains into the gully from three separate locations, later mixing at a confluence within the gully. Thus, three monitoring locations were required to account for the majority of overland flows draining from the catchment. In contrast, the majority of catchment overland flows into the control gully drain through one location, thus, it was monitored at one location up-stream of the gully head. Evaluation of the influence of sub-catchment area on the contribution of suspended sediment to the gullies would require the estimation of suspended sediment loads from these sub-catchments. As discussed in the manuscript (Lines 290-295 and 463-466) the estimation of loads from these highly ephemeral systems, and their catchments, is very challenging and was not feasible for this study. The authors acknowledge the importance of the catchment area regarding overland flow sediment contributions and will provide commentary on this in the Results and Discussion section. Commentary regarding this was added to the Results and Discussion: ***Line 403-406*:** "In contrast, the PSD of suspended sediment samples collected from the outlet of the remediated gully (d50 of 5.84 µm) and samples collected from Catchment 2 (d50 of 5.52 µm) and 3 (d50 of 5.06 µm) of the three catchment areas draining into the gully were very similar, thus suggesting their sediment contributions would be similar, when normalised for differences in catchment area size."

Specific comment 4 . "If possible, I think a before remediation and after remediation DEM image (or DEM of difference maybe) would be a useful addition."

RESPONSE: ***Accept.*** Please refer to Figure 2.

Specific comment 5 . "Figure 7 and 8 seem to suggest that the fine fraction is coming from the catchments more so than the gullies? But there isn't much discussion about this? Maybe I'm interpreting the results wrong but if this is the case, I think it's one of the more interesting findings for discussion."

> *RESPONSE:* ***Clarify.*** Figure 7 and 8 demonstrate that the distribution of fine sediment (0.1-30 µm) in the suspended sediment samples collected from the catchments and gully outlets are similar. However, further investigation (e.g., geochemical tracing) would be required to differentiate the sources of fine sediment in the gully outlet sample. The authors agree with the referee's observation that the catchments samples appear to consist of mostly fine sediment as is indicated by in Figures 7 and 8 and Table 3 (d_{90} < 36 µm for all overland flow samples collected). Given this it could be suggested that the catchments contribute some of the fine suspended sediment measured at the gully outlet.
>
> This is discussed in Section 3.2.3 Particle size distribution, Lines 356-368: "The suspended sediment PSD characteristics of control gully catchment PASS samples was notably different to the gully outlet PASS samples (Table 3). This indicates the contribution of slightly coarser suspended sediment from gully erosion (d50 10.8 µm) is greater than the suspended sediment contribution of the catchment (d50 4.29 µm) in the control gully. In contrast, the PSD characteristics of suspended sediment samples collected from the outlet of the remediated gully (d50 of 5.84 µm) and samples collected from Catchments 2 (d50 of 5.52 µm) and 3 (d50 of 5.06 µm) of the three catchment areas draining into the gully were very similar (Table 3) (Figure 8). This suggests there is a notable contribution of sediment entering both gullies from their respective catchments.".

Specific comment 6. "In your abstract and conclusions you present a value of 80% as the sediment reduction achieved but it's not clear how this number is calculated? Is it the (SSC control – SSC remediated) / (SSC control)? Or some other number?"

> *RESPONSE:* ***Clarify.*** The sections the Referee mentions, state the following: Lines 22-23: "Suspended sediment concentrations were ~80% lower at the remediated site compared to the control site,…" and Lines 460-463: "The multiple lines of evidence from this water quality study indicate the application of intensive landscape-scale remediation on actively eroding alluvial gullies has the potential to reduce average suspended sediment concentrations by more than 80%." These statements imply that the SSCs of the different gullies were compared and the difference in concentration between the two was ~80%. This comparison is discussed in further detail in Section 3.2.1 Suspended sediment concentration. It is not uncommon to see statements such as these without detailed explanations of the exact formula used in the abstract conclusion sections of a scientific journal article.

Specific comment 7. "[Line] 52: "There are various types of gullies present in the GBR catchment region (e.g., hillslope, colluvial, ephemeral, and soft-rock badlands), however, alluvial gullies likely represent the largest source of sediment, accelerated by land use change, to the GBR." - Reference?"

> *RESPONSE:* ***Accept.*** The text now states:
>
> ***Line 63-65***: "Of the various types of gullies present in the GBR catchment region (i.e., hillslope, colluvial, ephemeral, and soft-rock badlands), alluvial gullies likely represent the largest source of sediment to the GBR (Brooks et al., 2013; Brooks et al., 2020a)"

Specific comment 8. " [Line] "90: "The study site topography is relatively flat." - Would be good to know average slope?"

> *RESPONSE:* ***Accept.*** The following commentary has been added:
>
> ***Line 112-113*****:** "The study site topography is relatively flat (average slope of the gullies and respective catchments at the site ranges from 8.6 – 9.7 m/m) with undulating gradients, surrounded by sandstone ranges."

Specific comment 9. " 101: "Erosion rates derived from repeated airborne LiDAR between 2009 and 2015 (before remediation activity), indicate the control gully produced slightly more sediment (61 t -1 ha-1 yr-1) compared to the remediated gully (50 t-1 ha-1 yr-1), based on gully catchment area." - Per unit area of gully or catchment?"

> *RESPONSE:* ***Clarify.*** The authors reference the sediment yields estimated by Brooks et al., 2016, where the unit area was inclusive of the gully and its associated catchment area.

Specific comment 10. [Line] **"**102 – 103: t-1 ha-1 yr-1 » t . ha-1 . yr-1 mass shouldn't be a reciprocal here.

> *RESPONSE:* ***Accept.*** The text now states:
>
> ***Line 125-128*****:** "Erosion rates derived from repeated airborne LiDAR collected before remediation was conducted (2009 to 2015), indicate the control gully produced slightly more sediment (61 t/ha/yr) compared to the remediated gully (50 t/ha/yr), based on gully catchment area (Brooks et al., 2016)."

Specific comment 11. [Line] "103: "Note, LiDAR does not account for the surface erosion generated from the catchment area of each gully, which would be expected to be comparable on an area normalised basis. Hence, the difference in specific yields between the treatment and control would be less than indicated by the LiDAR data alone (Brooks et al., 2016)." - I find this statement a little confusing. I think you either need to be clearer about what this means or not include it.

> *RESPONSE:* ***Accept.*** The authors decided to remove the statement.

Specific comment 12. [Line 169]: "time weighted average (TWA) SSC" – I can take a guess at what this is but it would be nice to have an equation.

> *RESPONSE:* ***Accept.*** The following text and equation have been added:
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> ***Line 224-230:*** TWA SSC of PASS samples was determined using equation 1:
>
> $$TWA\ SSC\ (mg/L) = \frac{M}{tF}$$
>
> Where the total mass of suspended sediment collected by the sampler (*M*; milligrams) is divided by the volume of water sampled during deployment (duration of sampler operation (*t*; minutes) multiplied by the pump flow rate (*F*; litres per minute))."

COMMENTS FROM REFEREE 3:

GENERAL COMMENTS FROM REFEREE 3:

General Comments 1. "GENERAL REMARKS The reviewed manuscript refers to the interesting topic on remediation measures used to decrease the negative impact of gully erosion. Such studies are highly needed, especially when they are carried out in one of the most valuable area around the world as the Great Barrier Reef. I appreciate that Authors tested different monitoring methods and evaluated them. These findings may be useful in other areas characterized by dispersive soils and intense short rainfall events. In my opinion this manuscript fits to the scope of Hydrology and Earth System Sciences journal. The methods are clearly presented (some minor remarks are marked below). The results and conclusions are generally clear, concise, and well-structured. Although, I think that this section can be improved. It would be great to see some comparison of remediation measures used in this study with studies from other regions. The figures are readable, and they correspond well with the data presented in supplement. In order to improve the quality of the paper, I include below some minor remarks."

> *RESPONSE:* ***Acknowledge***. The authors acknowledge this positive comment and have undertaken specific reconsideration to address the other key points raised by the reviewer (see below).

SPECIFIC COMMENTS FROM REFEREE 3:

Specific Comment 1. " Lines 1-4 Please, consider shortening the title."

> *RESPONSE:* ***Accept.*** The revised title is "Intensive landscape-scale remediation improves water quality of an alluvial gully located in a Great Barrier Reef catchment".

Specific Comment 2. "Lines 20-21 I suggest to include some information on methods to the abstract. Now you just wrote that novel monitoring network was used without any details."

> *RESPONSE:* ***Accept.*** The following statement was added to the abstract:
>
> ***Line 20-24:*** "The gully remediation method was a first attempt, in the region, to invest a high level of financial (total cost of remediation ~$90,000 AUD) and logistical effort (e.g., intensive earthworks including the establishment of an on-site quarry) to develop long lasting erosion mitigation measures (i.e., regraded, compacted and battered gully walls, rock armouring of banks and channel, and installation of rock check dams)."

Specific Comment 3. "Can you refer also to the studies on remediation measures in other areas, not only in the GBR catchments?"

> *RESPONSE:* ***Accept.*** Text has been added to the introduction that states:
>
> ***Line 71-79:*** " A recent review by Bartely and co-workers (2020) identified several scientific studies that evaluated the effectiveness of gully remediation on improving water quality in various regions around the world, including: the French Alps (Mathys et al., 2003), Southern regions of the United States of America (Polyakov et al., 2014; Nichols et al., 2016), Spain (Hevia et al., 2014), China (Rustomji et al., 2008; Wang et al 2011), and Ethiopia (Ayele et al., 2018; Dagnew et al., 2015). Bartely and co-workers concluded that remediation efforts generally decrease the sediment yield of eroding gullies and thus improve water quality conditions. However, water quality improvements were driven by the extent of remediation (catchment and gully) and the re-establishment of vegetation in the gully post-remediation (Bartely et al., 2020)."

Specific Comment 4. "Line 54 Slacking or slaking?"

RESPONSE: ***Clarify.*** The authors thank the Referee for pointing out this oversight. We believe the correct term is slaking sediments. This spelling mistake has been corrected.

Specific Comment 5. "Line 95 I'm confused. You wrote in the text that you used two gullies in the study, whereas in Figure 1 you marked three remediated gully catchments and one control gully catchment. Were these three gully catchments treated as one? Can you mark them together for instance with the same colour line or somehow marked them as one site?"

RESPONSE: ***Clarify/Accept.*** Please refer to the revised Figure 1.

Specific Comment 6. "Lines 120-129 I suggest to include some photos from the study area. I know that you present several photos in the supplement, but I think that some of them should be in the manuscript, e.g.., control gully, remediated gully before and after remediation."

RESPONSE: ***Accept.*** Please refer to Figure 2.

Specific Comment 7. "Lines 187-192 Did you analyse the whole soil profiles or did you only take samples from the topsoil/subsoils? At which depth did you take samples? Why did you put this subsection (2.4.3. Soil sampling and analysis) into section 2.4. Monitoring methods? I suppose that you did these analyses only once and PSD in soils wasn't monitored."

RESPONSE: ***Acknowledge/Clarify.*** Whole soil samples were analysed for particle size distribution using hydrometer techniques. Soil samples were collected from the face the gully (i.e., the areas undergoing erosion) at depths ranging from the surface to 1 m. The soil sampling and analysis section was written as a separate section because these analyses were only conducted once and the authors thought it best not to group it under the water quality monitoring methods section.

The text now states:

Line 209-217**:** "Soil samples were collected as part of the design phase of the gully remediation project (Brooks et al., 2016; Brooks et al., 2018). Soil samples (1-2 kg) were collected from the face and walls of the gullies (i.e., the areas undergoing erosion) using a hand trowel and auger at depths ranging from the surface to 1 m. 21 and 9 samples were collected from the remediated and control gullies, respectively, prior to the remediation activities. The soil samples were analysed for particle size distribution using the soil hydrometer method (ASTM standard method 152H) (Brooks et al., 2016). Soil particle size distribution data was composited and treated as an average for the purpose of comparing gully soil to suspended sediment. This was done as soil to 1m deep can be eroded into suspended sediment during a flow event (e.g., gully wall collapse can impact large sections of the headscarp and expose deeper erodible soils) (Garzon-Garcia et al., 2016)."

Specific Comment 8. "Line 194 Which samples? I suppose that suspended sediments, but it should be clarified."

> *RESPONSE:* ***Accept/clarify.*** The authors thank the Referee for pointing out this oversight. The sentence now states the following in the revised manuscript:
>
> ***Line 221-223*****:** "Water samples collected from the Remediated and Control gullies were analysed for suspended sediment concentration (ASTM standard method D 3977-97), and particle size distribution using laser diffraction spectroscopy (Malvern Mastersizer 3000, Malvern Instruments)."

COMMENTS FROM PETER HAIRSINE:

GENERAL COMMENTS FROM PETER HAIRSINE:

General Comments 1. “This manuscript addresses a clear knowledge gap: the evaluation of a remediation technique for alluvial gullies in a tropical setting.”

> *RESPONSE:* ***Acknowledge***. The authors acknowledge this positive comment and have undertaken specific reconsideration to address the other key points raised by Peter Hairsine (see below).

SPECIFIC COMMENTS FROM PETER HAIRSINE:

Specific Comment 1. “The primary conclusion is given as "The multiple lines of evidence from this water quality study indicate the application of intensive landscape-scale remediation on actively eroding alluvial gullies has the potential to reduce average suspended sediment concentrations by more than 80%.” This conclusion is made on the basis of a comparison of 2 wet seasons of suspended sediment measurement using 4 different types of water samplers for a single control (3.3 hectares catchment area) and single treated catchment (13.7 hectares catchment area) - noting that 3 treatment catchment areas are labelled in figure 1.”

The recent review of gully remediation efficacy of Bartley et al. (2020) demonstrates other similar studies have combined multi-year monitoring, pre-treatment measurement and replication in a range of settings. No study was found to provide a "gold standard" BACI, multi-decadal and replicated study but conclusions and attribution were normal reduced as a result.”

> *RESPONSE:* ***Clarify.*** The authors thank Peter for notifying the authors of the recent study completed by his colleagues (Bartely et al., 2020). This manuscript was submitted to HESS prior to the publication of the Review article Peter mentions. The authors have included the findings of the review in the revised manuscript literature review.
>
> ***Line 72-79*****: “**A recent review by Bartely and co-workers (2020) identified several scientific studies that evaluated the effectiveness of gully remediation on improving water quality in various regions around the world, including: the French Alps (Mathys et al., 2003), Southern regions of the United States of America (Polyakov et al., 2014; Nichols et al., 2016), Spain (Hevia et al., 2014), China (Rustomji et al., 2008; Wang et al 2011), and Ethiopia (Ayele et al., 2018; Dagnew et al., 2015). Bartely and co-workers concluded that remediation efforts generally decrease the sediment yield of eroding gullies and thus improve water quality conditions. However, water quality improvements were driven by the extent of remediation (catchment and gully) and the re-establishment of vegetation in the gully post-remediation (Bartely et al., 2020).”

Specific Comment 2. “I looked for "multiple lines of evidence" but only found the suspended sediment sampling with 4 devices arranged side by side.”

> *RESPONSE:* ***Acknowledge/Clarify.*** For context, Peter is referring to Line 460 “The multiple lines of evidence from this water quality study indicate the application of intensive landscape-scale remediation on actively eroding alluvial gullies has the potential to reduce average suspended sediment concentrations by more than 80%.”
>
> In this statement authors are referring to the collection of water quality data using different monitoring methods (i.e., four different methods for collecting water quality data) to assess the effect of gully remediation on water quality. Each of the water quality monitoring methods used collect a sample in a manner that is independent compared to the others, thus, evidence is provided by four separate lines of data gathering. Furthermore, the use of different water quality analyses provides further relevant lines of evidence, that are complimentary to the separate collection methods, (i.e., suspended sediment concentration, particle size distribution, and nutrient and carbon analyses).
>
> The authors acknowledge that the term “multiple lines of evidence” may mislead some readers to thinking that complimentary data (i.e., Lidar soil loss estimates) are referenced here. Thus, the authors have revised the text to state:
>
> ***Line 505-507:*** “The water quality data collected during this study, using multiple monitoring methods, supports the application of intensive landscape-scale remediation to significantly reduce suspended sediment concentrations in actively eroding gullies.”

Specific Comment 3. “The two years of sampling does not enable any assessment of whether the hydrological forcing can be interpreted in terms of long term rainfall variability. Furthermore this sampling does not necessarily represent the long term (decades) performance of the remediation measures.”

> *RESPONSE:* ***Acknowledge.*** The authors agree with Peter in that there is a need for more monitoring data, over longer time scales, to evaluate the effects of long term stressors (i.e., rainfall variability and backwater flooding effects). The authors infer this sentiment in the final statement of the conclusion section Line 477: “ However, more information is needed, particularly sediment load estimates and information on remediation longevity over decadal timescales.”
>
> The following statements have been added to the results and discussion and conclusion sections:
>
> ***Line 319-321*: “**However, because this study only includes two wet seasons of data it should be considered preliminary until it is further validated by continued monitoring of the remediated gully for several additional wet seasons.”
>
> ***Line 506-509*:** “Further monitoring at the site should be conducted over longer timescales (i.e., decades) to evaluate the longevity of the erosion mitigation controls used as part of the gully remediation works.”

Specific Comment 4. "The difference in performance between the control and treatment gullies is well summarised in terms of the suspended sediment concentrations and the particle size distributions. The difference between these measures is then attributed to the treatment effect. While this step is intuitive, it is not formally supported given the many limitations of the methodology as noted above."

> *RESPONSE:* ***Clarify.*** The aim of the study was to determine if gully water quality conditions were improved by landscape-scale remediation using water quality monitoring methods that employ sampling processes that are unique from one another. This was done so that limitations of one or more of the monitoring methods used could be accounted for when evaluating the effectiveness of the remediation measures. The water quality of the overland flow waters draining into the Remediated and Control gullies from their respective catchments is relatively similar. The overland flow water represents the major transport mechanism for suspended sediment within the gully system. Thus, the lower concentrations of suspended sediment and associated nutrients and carbon in the Remediated gully compared to the Control gully can only be attributed to the reduction in sediment and nutrient sources (i.e., erodible soil) from within the gully itself. This is not an intuitive assessment, rather, it is an interpretation of the data gathered. Furthermore, the authors have provided before and after photographs and digital elevation imagery of the remediated gully that demonstrates how erosion of the gully system has been greatly reduced, since remediation. This complimentary line of evidence will further support the conclusions made regarding the effectiveness of the remediation measures used at the Remediated gully.

Intensive landscape-scale remediation improves water quality of an alluvial gully located in a Great Barrier Reef catchment

Nicholas J.C. Doriean,[1,2] William W. Bennett,[1] John R. Spencer,[2] Alexandra Garzon-Garcia[3], Joanne M. Burton[3], Peter R. Teasdale,[4,5] David T. Welsh,[1] and Andrew P. Brooks[2,*]

[1] Environmental Futures Research Institute, School of Environment and Science, Griffith University, Southport, 4215, Queensland, Australia
[2] Griffith Centre for Coastal Management, Griffith University, Southport, 4215, Queensland, Australia
[3] Department of Environment and Science, Queensland Government, Brisbane, 4102, Australia
[4] University of South Australia, UniSA STEM, Scarce Resources and Circular Economy (ScaRCE), SA, 5000, Australia.
[5] University of South Australia, Future Industries Institute, SA, 5000, Australia.

Correspondence to Andrew P. Brooks (andrew.brooks@griffith.edu.au)

Abstract. Gully erosion can be a major disruptor to global fluvial sediment budgets. Gully erosion in the catchments of the Great Barrier Reef is attributed to~40% of fine suspended sediment pollution to the freshwater and marine ecosystems downstream. Mitigating this source of erosion will have a lasting positive impact on the water quality of connected rivers and the receiving marine environment. Here we conduct a preliminary evaluation of the ability of intensive landscape-scale gully remediation to reduce suspended sediment and associated nutrient export from a catchment draining to the Great Barrier Reef. The gully remediation method was a first attempt, in the region, to invest a high level of financial (total cost of remediation ~$90,000 AUD) and logistical effort (e.g., intensive earthworks including the establishment of an on-site quarry) to develop long lasting erosion mitigation measures (i.e., regraded, compacted and battered gully walls, rock armouring of banks and channel, and installation of rock check dams). A novel suspended sediment monitoring network, comprised of a suite of new and established automated monitoring methods capable of operating in remote environments, was used to evaluate the water quality of a remediated gully, a control gully and their respective catchments. The recently developed pumped active suspended sediment (PASS) sampler optimised to sample ephemeral water flows was deployed in gully outlets and catchment runoff flow paths. This study demonstrates how the combination of low and high cost water quality monitoring techniques can be deployed in a configuration that ensures sample collection redundancy and complimentary data collection between methods. Samples collected from the remediated gully had significantly lower suspended sediment concentrations compared to the control gully, providing preliminary evidence that the remediation works were successful in stabilising erosion within the gully. Dissolved and particulate nutrient concentrations were also significantly lower in the remediated gully samples, consistent with the decreased suspended sediment concentrations. The novel combination of suspended sediment measurements from both the gully channels and overland flows in the surrounding gully catchments suggests that sediment and nutrients at the remediated site are likely sourced from erosion processes occurring within the catchment of the gully (at relatively low concentrations). In contrast, the primary source of suspended sediment and associated nutrients at the control gully was erosion from within the gully itself. This study demonstrates the potential of landscape-scale remediation as an effective mitigation action for reducing suspended sediment and nutrient export from alluvial gullies. It also provides a useful case study for the monitoring effort required to appropriately assess the effectiveness of this type of erosion control.

1 Introduction

Gully erosion is a significant contributor to the increase in global soil erosion rates and is a major driver of suspended sediment-related impacts on downstream aquatic systems (Poeson et al 2011; Bartely et al 2020). This is particularly relevant for water quality conditions in the Great Barrier Reef (GBR), which is negatively impacted by fluvially sourced pollutants; primarily suspended sediment, dissolved and particulate nutrients, and agrochemicals (Bainbridge et al., 2018; Bartley et al., 2014; Brodie et al., 2012; Fabricius 2005). Land use change, such as, mining, agriculture (grazing and cropping) and urbanisation associated with European settlement in the region since the 1860s has increased the output of fine sediment and nutrients from the catchments draining into the GBR (Bartley et al., 2018; Kroon et al., 2016). Catchment tracing studies have consistently identified sub-surface erosion processes, particularly from stream banks and gullies, as the dominant source of fine sediment delivered to the GBR (Olley et al., 2013; Wilkinson et al., 2015a). Gully erosion in particular has been identified as the largest single source of suspended sediment, estimated to contribute more than 40% of all fluvially transported sediment entering the GBR (McCloskey et al., 2017). Recent research suggests that these sediments, particularly from grazing lands, also act as a source of bioavailable nitrogen (Garzon-Garcia et al., 2018a; Garzon-Garcia et al., 2018b).

Gullying occurs when unconsolidated soils and sediments become exposed and eroded by fast flowing storm runoff (Brooks et al., 2018; Casalí et al., 2009). Gully erosion is a natural process, however, land use changes have increased the rate of gully erosion and subsequent sediment export (Prosser et al., 1994; Shellberg et al., 2016). The tropical climate of the GBR catchment region creates intense rainfall events (often > 40 mm h^{-1}) that can rapidly erode tonnes of soil from an actively eroding gully during a single storm (Brooks et al., 2015; BOM, 2020). Of the various types of gullies present in the GBR catchment region (i.e., hillslope, colluvial, ephemeral, and soft-rock badlands), alluvial gullies likely represent the largest source of sediment to the GBR (Brooks et al., 2013; Brooks et al., 2020a). Alluvial gullies consist of mostly fine (<63 µm) dispersive and/or slaking sediments and are located on the floodplains or terraces of river systems, thus increasing the chance of sediment transport to major rivers and marine receiving environments (Brooks et al., 2013; Brooks et al., 2016; Brooks et al., 2019). These characteristics, coupled with the high connectivity of the gullies to river channel networks, mean that a large proportion of the eroded fine sediment and associated nutrients from alluvial gullies will be exported to coastal waters (Brooks et al., 2009; Brooks et al., 2018; Shellberg et al., 2013).

A recent review by Bartely and co-workers (2020) identified several scientific studies that evaluated the effectiveness of gully remediation on improving water quality in various regions around the world, including: the French Alps (Mathys et al., 2003), Southern regions of the United States of America (Polyakov et al., 2014; Nichols et al., 2016), Spain (Hevia et al., 2014), China (Rustomji et al., 2008; Wang et al 2011), and Ethiopia (Ayele et al., 2018; Dagnew et al., 2015). Bartely and co-workers concluded that remediation efforts generally decrease the sediment yield of eroding gullies and thus improve water quality conditions. However, water quality improvements were driven by the extent of remediation (catchment and gully) and the re-establishment of vegetation in the gully post-remediation (Bartely et al., 2020). Until recently, studies of gully remediation effectiveness in GBR catchments have focussed on smaller scale gullies (i.e., hillslope gullies), with the application of low intensity erosion controls such as cattle exclusion fencing, revegetation, and the manual installation of tree branch and/or geotextile fabric check dams (Bartley et al., 2017; Wilkinson et al., 2015b; Wilkinson et al., 2013; Wilkinson et al., 2018). These strategies are effective at reducing erosion in smaller gullies, however, they are not well-suited for stabilising the much larger alluvial gullies that are present in many GBR catchments.

Recent research suggests alluvial gullies in GBR catchments require the intervention of intensive landscape-scale remedial efforts to stem further erosion and reduce sediment export (Brooks et al., 2016; Brooks et al., 2018; Carey et al., 2015; Howely et al., 2018). There are several alluvial gully erosion mitigation projects currently underway in major GBR catchments (e.g., the Normanby and Burdekin catchments), which are trialling various remedial works, including: large-scale earthworks (i.e., reshaping of active gully head-scarps and sidewalls); rock chutes, including the application of geotextile matting; rock-capping and mulching of potentially erodible soils; and the installation of bed control and water velocity reducing measures (e.g., check dams). Stock exclusion and revegetation are also important mitigation measures implemented in these gully remediation projects, often in concert with other treatments. The overall aim of these remedial trials is to ascertain the control measures that are capable of permanently reducing alluvial gully erosion and associated sediment, as well as particulate nutrient export (Brooks et al., 2016; Brooks et al., 2018; GA, 2019, Brooks et al., 2020b).

Here we aim to assess the effectiveness of landscape-scale remediation in improving the water quality of an alluvial gully situated in the tropics of Queensland, Australia, which flows to the Great Barrier Reef. We apply a recently developed gully water quality monitoring approach that facilitates accurate measurements while meeting the financial and operational requirements of monitoring in remote locations. This work, although done on a limited spatial and temporal scale, provides a critical foundation for developing and evaluating landscape-scale remediation of alluvial gullies in the Great Barrier Reef region.

2 Methods

2.1 Study site

The study site is located on a cattle station in the Cape York Peninsula region of Queensland, Australia. There are several gullies that have formed in the alluvial floodplain and terrace of the Laura River (Figure 1). The tropical climate of the region is characterised by wet (October to April) and dry (May to September) seasons. Approximately 95% of the annual rainfall (regional mean annual rainfall is 936 mm) occurs during the wet season (Brooks et al., 2014a; BOM 2020). The study site topography is relatively flat (average slope of the gullies and respective catchments at the site ranges from 8.6 – 9.7 m/m) with undulating gradients, surrounded by sandstone ranges. The alluvial sediments comprising the floodplain/terrace are derived from the Laura River catchment, which is dominated by the Ordovician Hodgkinson Formation meta-sediments, late Jurassic/early Cretaceous Gilbert River sandstones, and Quaternary/Neogene Maclean Basalts (Brooks et al., 2013; Brooks et al., 2014b) (Figure 1).

Two gullies were used to evaluate the effectiveness of the remediation works. The remediated gully is the larger of the two which encompasses several gully lobes that drain into a central channel. The gully treatment area is ~0.6 ha, with a catchment area of 13.7 ha. The catchment of the remediated gully is a conglomerate of three sub-catchments (Sub-catchments 1-3) (Figure 1). The active secondary incision of the control gully is ~0.2 ha while the gully catchment, which drains directly into the headscarp, has an area of 3.3 ha. Both gullies are situated in highly-dispersible and slaking sodic alluvium. Prior to remediation, both gully catchments would have undergone similar erosion processes (i.e., scalding, sheet erosion, rilling in the gully catchment and tunnel erosion, head scarp mass-failure, and gully sidewall erosion within the incised part of the gully). Erosion rates derived from repeated airborne LiDAR collected before remediation was conducted (2009 to 2015), indicate the control gully produced slightly more sediment (61 t/ha/yr) compared to the remediated gully (50 t/ha/yr), based on gully catchment area (Brooks et al., 2016). Comparison of particle size distribution (PSD) (Section 3.2.3) from readily erodible soil collected from the two gullies, prior to remediation activities, showed there was no significant difference between the two gullies. It is likely that these soils would have eroded into suspended sediment in a similar manner, thus, it is assumed that the suspended sediment concentration (SSC) and PSD from the two gullies would have been similar, pending any significant differences in water velocity.

The remediation of the larger gully complex was designed to halt the highly active erosion within the rapidly incising part of the gully and slow the scalding and sheet erosion processes within the broader gully catchment through destocking and the construction of contour berms (Brooks et al., 2018)

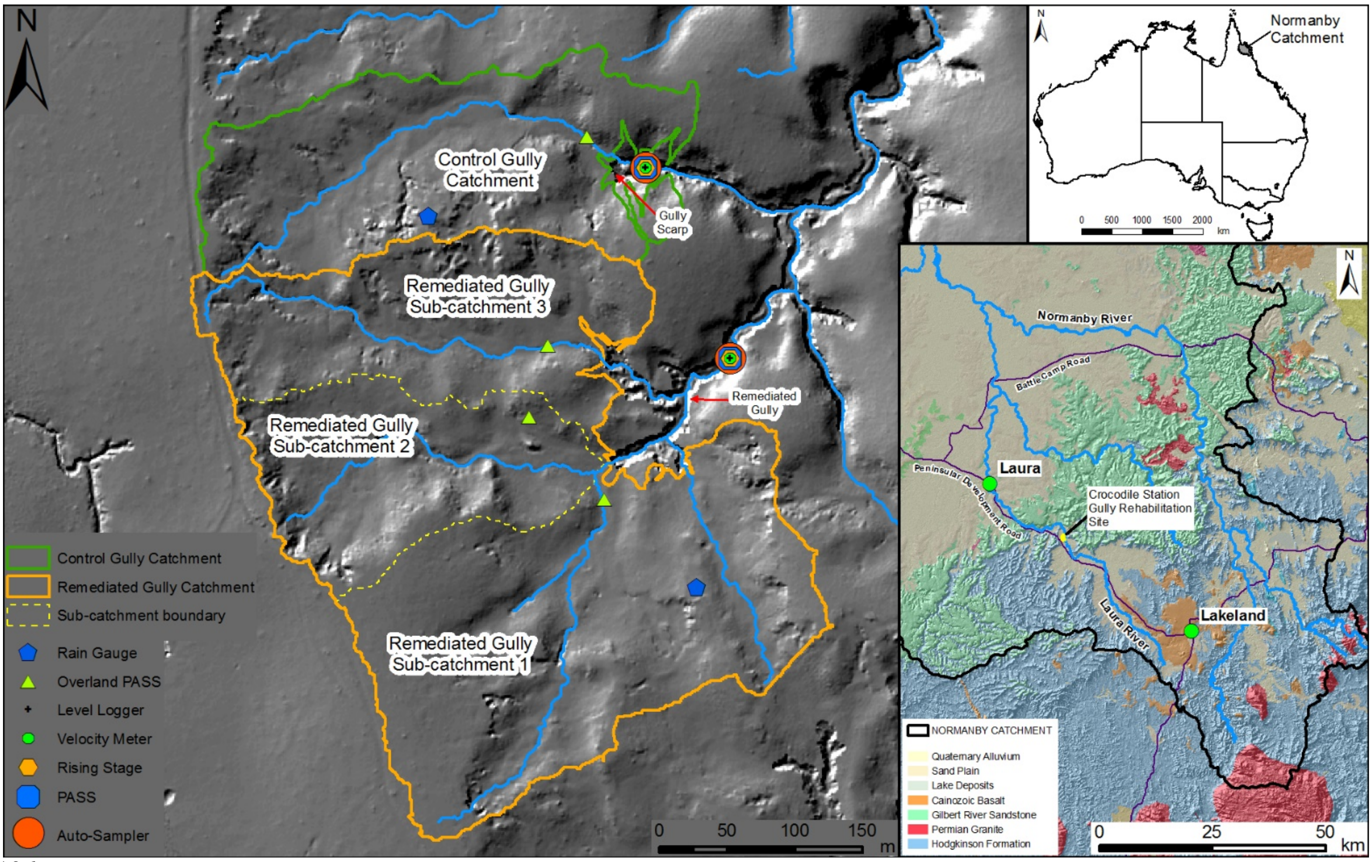


Figure 1: Topographic map of the study site, including surface geology and gully locations. Source: (Geoscience Australia., 2019). PASS = Pumped active suspended sediment (PASS) sampler, Overland PASS = a PASS sampler used to sample water flowing overland (i.e., runoff), Rising stage = Single stage sampler (i.e., rising stage sampler). N.B. The overland PASS sampler in sub-catchment 3 of the remediated gully was deployed several metres away from the flow line inferred by surface geology due to the redirection of flow associated with vegetation and termite mounds.

2.2 Gully remediation

The large actively eroding alluvial gully complex was remediated using various intensive, landscape-scale gully erosion control earthworks during the 2016 dry season. The entire gully complex was regraded and compacted using heavy machinery. Gypsum was added during this process to reduce soil dispersibility (Liu et al., 2017), and geofabric covering was applied over the former gully head scarp and held in place by a coarse sandstone surface capping. The rest of the gully complex was capped with locally sourced shale rock. Check dams were installed at regular intervals (approximately every 40 m) in the three major channels that replaced the original gully lobes (SI-1). After this, the entire gully complex was seeded with native vegetation and livestock were excluded from the gully and its surrounding catchment. No remedial efforts were applied to the control gully, other than the exclusion of livestock (SI-1) (Brooks et al., 2018). Time-lapse footage of the remedial works is available online at https://www.youtube.com/watch?v=dCbV1BggnKI (CYNRM, 2017).

2.3 Monitoring design

While gullies commonly share similar patterns of formation and erosion, there are many variables that need to be considered before implementing a monitoring plan to evaluate water quality within a gully system. Ideally, it is best to identify the factors that will have the greatest influence on gully water quality and monitor them prior to any remediation, in-order to establish a baseline of water quality conditions (i.e., a standard Before After Control Impact (BACI) design). Any water quality monitoring assessment of a gully, particularly those being used to evaluate the effectiveness of remediation efforts, should provide a representative measure of the following parameters:

- Rainfall: the primary driver of continued gully erosion (Castillo et al., 2016).
- Soil: characterising basic soil physico-chemical parameters will aid in understanding the transformation of soil into suspended sediment and how that may affect water quality (Brooks et al., 2016; Brooks et al., 2018).
- Water quality: it is recommended that at least two different means of water sample collection/measurement are used to ensure a representative measure of SSC and PSD. Entire flow events should also be monitored if possible (e.g., a time-integrated sample of an event is most representative). If possible, samples should be collected from water flowing into the point of erosion (i.e., above the head scarp) and within the gully after the point of erosion (i.e., downstream of the head scarp) (Doriean et al., 2020).

In this instance the remediation project was required to implement the treatments and monitor the responses within a three-year timeframe, thus, a full BACI design was not possible. Instead, a control/impact design was used in which remediation effectiveness was evaluated against a nearby comparable un-remediated control gully (SI-2). Three repeat airborne LiDAR surveys were collected over a six-year period, which enabled normalised baseline erosion rates to be calculated for the two sites, demonstrating the comparability of the treatment and control gullies (Brooks et al., 2016).

2.4 Monitoring methods

2.4.1 Hydrological and meteorological monitoring

Two rainfall gauges (Hydrological Services tipping bucket rain gauges - 0.2 mm/tip with Hobo data logger) were placed in the catchments of the remediated and control gullies (Figure 1). The rain gauges were programmed to provide a near continuous account of rainfall for the sampling period (2017/2018 and 2018/2019 wet seasons). Water level loggers (In-situ rugged troll 100®) were programmed to measure every two minutes and were secured on the surface of a straight section of channel just downstream of each gully head (Figure 1). A barometric logger (In-situ barotroll®) was placed underneath the remediated gully rainfall gauge and set to record atmospheric pressure every 15 minutes.

2.4.2 Sample collection and monitoring

The original monitoring plan to evaluate the water quality conditions, focusing on suspended sediment, was limited by funding and available measurement techniques, which resulted in only the outlets of both gullies being monitored for the first wet season (2017/2018). The successful modification of a recently established suspended sediment monitoring method, the pumped active suspended sediment (PASS) sampler, to operate in gullies (Doriean et al., 2020) allowed for the monitoring network to expand spatially and thus, enable monitoring of the time weighted average (TWA) SSC and PSD of sediment entering each gully from their respective catchments during the 2018/2019 wet season.

Four different suspended sediment monitoring methods were used to collect water samples in the gullies: PASS samplers (Dorian et al., 2019), modified for gully deployments (Doriean et al., 2020); rising stage (RS) samplers (Edwards et al., 1999); autosamplers (Edwards et al., 1999); and turbidity loggers (Gray et al., 2009 and Doriean et al., 2020). Several monitoring methods were used in this study to provide multiple lines of evidence to determine the effectiveness of the remediation activities in reducing suspended sediment and nutrient export, as well as providing insight into the performance of the different monitoring methods. Each of the monitoring methods used in the control and remediated gullies were recently described and comprehensively evaluated by Doriean and co-workers (2020). The turbidity measurements recorded from the two gullies did not provide useful information for comparison of the gullies and there were few instances where turbidity measurements correlated with physically collected samples. Therefore, turbidity measurement data collected from the gullies are not reported further here (see Doriean et al., 2020). The TWA SSC and PSD of overland flows (i.e., catchment runoff) into the gullies was measured from samples collected using PASS samplers, configured to operate in ephemeral waterways (Doriean et al., 2020). The natural slope of the land flowing into the gullies had several depressions or low points that collected water as it flowed over the land – PASS samplers were installed at these locations with the intake and float switch located 0.09 m above the ground (SI-2).

2.4.3 Soil sampling and analysis

Soil samples were collected as part of the design phase of the gully remediation project (Brooks et al., 2016; Brooks et al., 2018). Soil samples (1-2 kg) were collected from the face and walls of the gullies (i.e., the areas undergoing erosion) using a hand trowel and auger at depths ranging from the surface to 1 m. 21 and 9 samples were collected from the remediated and control gullies, respectively, prior to the remediation activities. The soil samples were analysed for particle size distribution using the soil hydrometer method (ASTM standard method 152H) (Brooks et al., 2016). Soil particle size distribution data was composited and treated as an average for the purpose of comparing gully soil to suspended sediment. This was done as soil to 1m deep can be eroded into suspended sediment during a flow event (e.g., gully wall collapse can impact large sections of the headscarp and expose deeper erodible soils) (Garzon-Garcia et al., 2016).

2.5 Sample analysis and statistics

Water samples collected from the remediated and control gullies were analysed for suspended sediment concentration using gravimetry (ASTM standard method D 3977-97) and particle size distribution using laser diffraction spectroscopy (Malvern Mastersizer 3000, Malvern Instruments). Samples were screened using a 2 mm sieve prior to analysis to remove any large debris or detritus. TWA SSC of PASS samples was determined using equation 1:

$$TWA\ SSC\ (mg/L) = \frac{M}{tF} \quad (1)$$

Where the total mass of suspended sediment collected by the sampler (M; milligrams) is divided by the volume of water sampled during deployment (duration of sampler operation (t; minutes) multiplied by the pump flow rate (F; litres per minute)).

Sediment used for particle size analysis was not chemically treated and was kept in suspension using mechanical dispersion methods (i.e., a baffled container with an impellor stirrer) (Doriean et al., 2020). Nutrient analyses were conducted on a select group of samples. The samples were analysed for total and dissolved organic carbon (5310 TOC and DOC 2017), and total and dissolved nitrogen and phosphorus (4500-Norg D and 4500-P B). Dissolved nutrient species (ammonium, oxidised nitrogen, and phosphate) were analysed using segmented flow analysis methods: 4500-NH3, 4500-NO3, and 4500-P (APHA 2005; Garzon-Garcia, Bunn, et al., 2018; Garzon-Garcia et al., 2015). Due to the remoteness of the field sites and sporadic nature of flow events, it was only possible to retrieve nutrient samples from the autosampler within 48h of initial collection on the 24th of January 2018 and the 6th of February 2019. Nutrient samples were not retrieved from the other instruments (Manual, RS, or PASS samplers) because the samplers contained samples from previous flow events, or the samples could not be collected and processed within the 48-hour timeframe. Consequently, the percentage of sand was likely underestimated in the samples collected by the autosampler, which were analysed for nutrients (Doriean et al., 2020).

GraphPad-Prism® was used for statistical analysis of sample data following an evaluation for equality of group variances using Brown-Forsythe and Bartlett’s tests before being analysed using paired t-tests to assess differences between sample groups (p = 0.05). The data was found to be normally distributed. Pearson's correlation analysis was also used to assess the relationship between SSC and nutrient concentrations.

2.6 Data quality and uncertainty

Throughout this study we attempt to acknowledge the uncertainty associated with the various monitoring techniques. A previous evaluation of the sample collection methods was used during this study to determine the approximate uncertainty associated with each method (Table 1) (Doriean et al., 2020). These uncertainties were accounted for when interpreting data from the various methods.

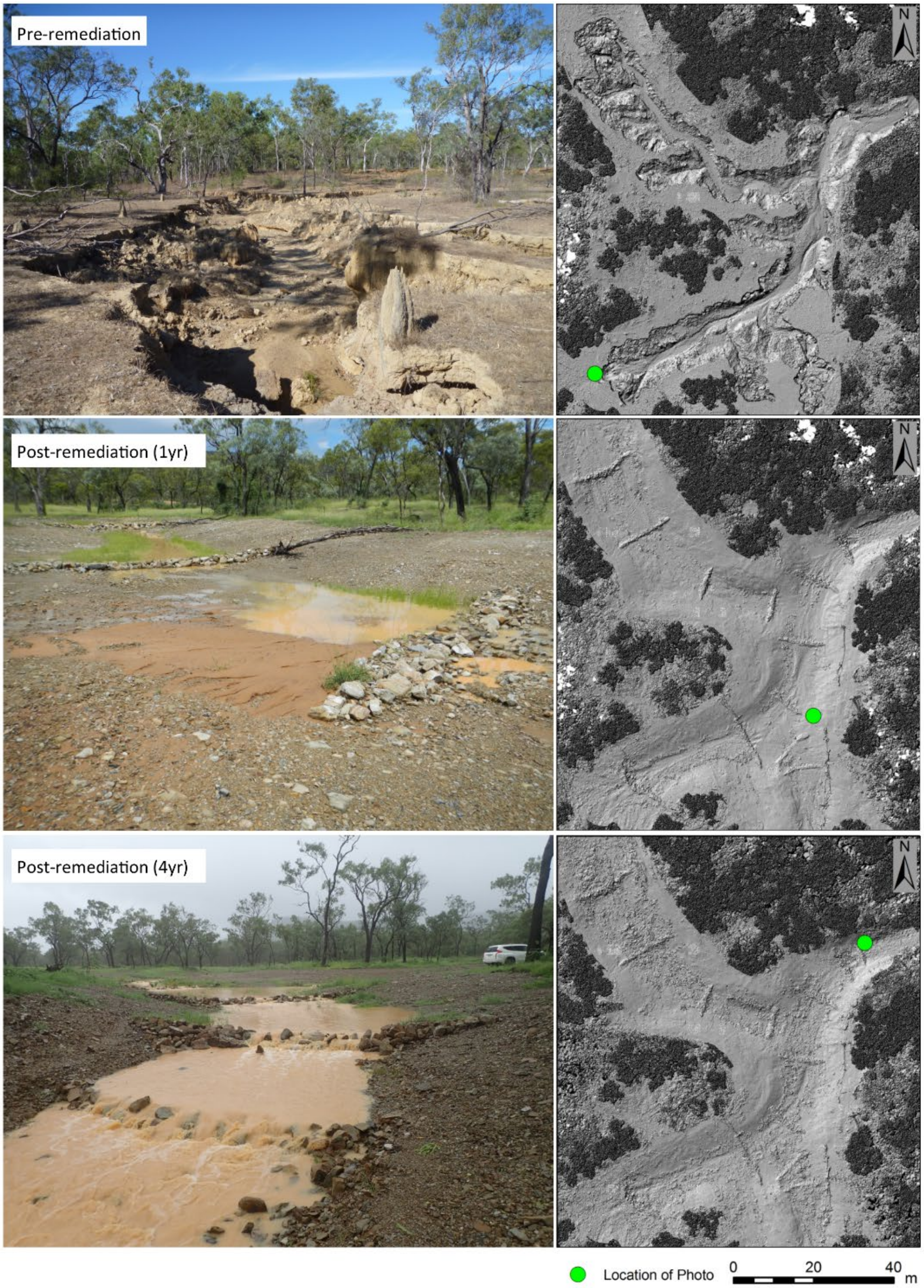
Table 1. Uncertainties, of either SSC or PSD measurement, associated with suspended sediment monitoring methods used in alluvial gullies. Source: (Doriean et al., 2020).

Sampler type	***Uncertainty (%)***			
	TWA SSC*	***PSD d_{10}***	***PSD d_{50}***	***PSD d_{90}***
Autosampler	25 (± 10)	10	25	45
RSS	20 (± 10)	9	12	2
PASS sampler	9 (± 5)	10	20	20

TWA SSC = time weighted average SSC. RSS = rising stage sampler.

3 Results and Discussion

Repeat airborne and terrestrial Lidar imaging suggest the erosion controls deployed in the remediated gully had no significant failures and that sediments are being retained behind the check-dams (Figure 2). Samples were collected from approximately half (5-6) of all flow events (> 0.2 m peak water level) recorded for the 2017/2018 wet season. Fewer events (3-4) were sampled during the 2018/2019 wet season due to two major backwater flooding events at the study site, caused by high water levels in the Laura River (see SI-3 for hydrographs of all sampled events). These flood events damaged equipment and contaminated samples with flood water. However, the flood events did not appear to affect the erosion mitigation structures of the remediated gully (SI-4). Despite the challenges of monitoring these remote systems and the unpredictable nature of flow events, sufficient samples were collected from a range of flow event types (i.e., intensity, length, time of year; SI-3) to meet the objectives of the study.



270 Figure 2. Before and after photos (left panels) of the remediated gully and repeat Lidar images (right panels) of the remediated gully for years 2016 (unremediated), 2017 (post-remediation (1yr)), and 2019 (post-remediation (4yr)). Note, the aggradation of sediment in the gully. Green dots show location of photographs. Modified from Brooks et al., 2020b

3.1 Rainfall and major hydrological events

Rainfall totals at the study site for the 2017/18 (920 mm) and 2018/19 (915 mm) wet seasons were not significantly different from the yearly average (943 ± 283 mm) of the permanent rain gauge operated by the Queensland Department of Natural Resources, Mines and Energy (DNRME), located at Coal Seam Creek, ~13 km from the study site. The on-site and DNRME rain gauges were in broad agreement (R^2=0.50; SI-5), although the variability in the relationship confirms that on-site rainfall gauges should always be deployed to achieve accurate rainfall intensity data. While there were many intense storms that resulted in flow events in the studied gullies, there were two major flood backwatering events that occurred in the 2018/19 wet season as a result of high-intensity rainfalls in the region surrounding the study site (SI-3). Review of historical DNRME stream gauge water level data of the Laura River at Coal Seam Creek showed that these backwatering events typically occurred with a ~3-year frequency over the 20-year dataset (DNRME, 2019).

3.2 Impact of remediation on suspended sediment characteristics

Soil characteristics and erosion estimates for the control and remediated gullies (prior to remediation) based on catchment size, area of readily erodible gully soil, and repeat Lidar aerial measurements suggest the control and remediated gullies likely had similar suspended sediment dynamics (Brooks et al., 2013; Brooks et al., 2016). The following sections describe how PSD, SSC, and most nutrient concentrations of samples collected from the remediated gully were significantly different/lower than the control gully for both wet seasons (2017/2018 and 2018/2019). A time series of all monitored flow events is included as supporting information (SI-3).

3.2.1 Suspended sediment concentration

The remote location and challenging monitoring conditions, which are, typical of alluvial gullies meant that multiple suspended sediment sampling methods were used to ensure the most representative data were collected throughout both wet seasons (Doriean et al., 2020). Overall, the SSC range of samples collected by each method, from the outlet of the remediated gully were significantly lower compared to those collected from the outlet of the actively eroding, control gully (Table 2).

PASS sampler data were used to compare time-weighted average (TWA) SSC and other suspended sediment characteristics (i.e., PSD and SSC by sediment particle size class) of the remediated and control gullies because the method collected samples with the most representative PSD and TWA SSCs (Doriean et al., 2020), and monitored the most flow events during both wet seasons (SI-3). The low temporal resolution of PASS sample data, theoretically, allows for the potential underestimation of SSC when very high SSCs are present at high flow rates for only short periods over the duration of a flow event (Doriean et al., 2019). However, comparable SSC data collected by manual flow proportional sampling, autosamplers, and RS sampler methods, which have high temporal resolution, corresponded well with the SSC range of the PASS samples from both gullies (Table 2), indicating that the PASS samples were representative of the measured events.

The median TWA SSC of PASS samples collected from the control gully (7123 ± 2670 mg L^{-1}) was ~5-fold higher than the median TWA SSC of samples collected from the remediated gully (1429 ± 411 mg L^{-1}) (Table 3, Section 3.2.3). This, and statistical analysis, suggests there was significantly ($p<0.001$) more sediment export due to erosion within the control gully than in the remediated gully. The TWA SSC of the catchment water flowing into the remediated (461-3556 mg L^{-1}) and control gullies (485-2709 mg L^{-1}) validate the assumption of similar contributions of suspended sediment from the two gully catchments during the monitoring period (see Table 4, Section 3.2.3). Comparison of remediated and control gully TWA SSC by sediment particle size class indicates the remedial works reduced the concentration of suspended sand (by 96%), silt (by 76%), and clay (by 73%) (Figure 3). Bulk densities of the different sediment size fractions were very similar (~0.1 g L^{-1} difference), and thus an average density was used to determine the different SSCs by size class (SI-6). The reduction in SSC across different sediment particle size classes indicates the remedial works are effectively reducing erosion and sediment export from the remediated gully. However, because this study only includes two wet seasons of data it should be considered preliminary until it is further validated by continued monitoring of the remediated gully for several additional wet seasons.

Table 2. Descriptive statistics of SSC samples collected from the control and remediated gullies, during the 2017/2018 and 2018/2019 wet seasons.

Sampling method	***Remediated Gully***				***Control Gully***			
	AS	***FP***	***RSS***	***PASS****	***AS***	***FP***	***RSS***	***PASS****
Number of samples	79	7	18	6	61	10	18	8
Minimum (mg L^{-1})	350	364	378	1150	4146	3823	5675	5948
25% percentile (mg L^{-1})	827	421	906	1201	5055	4829	7874	6103
Median (mg L^{-1})	1063	493	1502	1280	6180	5761	9177	7348
75% percentile (mg L^{-1})	1492	688	2736	2011	8162	6631	11278	8472
Maximum (mg L^{-1})	3035	842	5278	2044	53086	8550	28696	14125
Range (mg L^{-1})	2685	478	4900	895	48939	4728	23021	8177
Mean (mg L^{-1})	1204	562	1860	1495	7773	5858	10560	7963
Std. Deviation (mg L^{-1})	542	177	1275	411	6669	1331	5167	2670
Std. Error of Mean	61	67	300	168	854	421	1218	944
Lower 95% CI of mean	1083	398	1226	1064	6065	4906	7990	5730
Upper 95% CI of mean	1325	725	2494	1927	9481	6811	13129	10195
Coefficient of variation	45%	31%	69%	28%	86%	23%	49%	34%

Sampler type	***Are the control and remediated gullies significantly different? (α = value)***
AS	Yes ($p < 0.0001$)
FP	Yes ($p = 0.0001$)
RSS	Yes ($p < 0.0001$)
PASS	Yes ($p = 0.0007$)

AS = autosampler, FP = flow proportional sampling, RSS = rising stage sampler, PASS = PASS sampler. * = PASS samples represent the time weighted average suspended sediment concentration for the time the sampler was deployed.

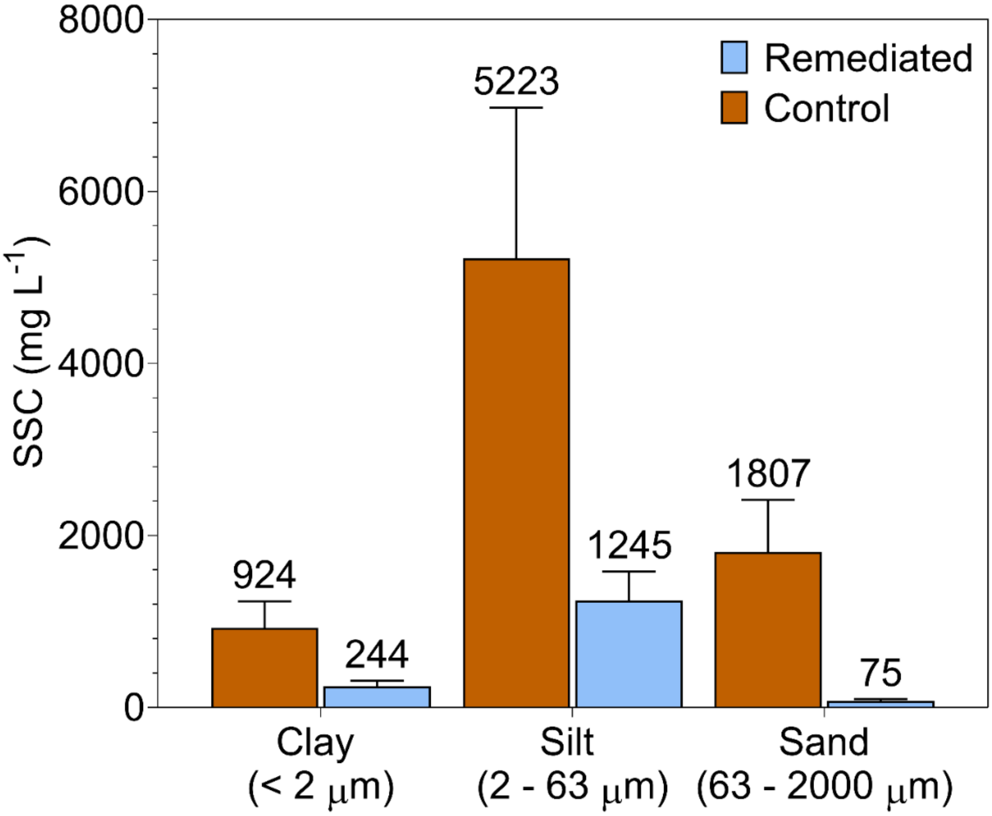


Figure 3. Median SSC by sediment size class for PASS samples collected from the control (brown) and remediated (blue) gullies during the 2017/2018 and 2018/2019 wet seasons. Error bars represent sample standard deviation. Autosampler and RS sampler SSC by PSD are included in SI-7.

3.2.2 Relationship between SSC and flow

There is currently insufficient water discharge data to accurately estimate the sediment loads of the two gullies monitored in this study. The unstable nature of gully banks and bed features means the channel cross-section can change dramatically during a single event, thus obtaining an accurate measurement of the gully channel cross section over a wet-season is rarely feasible. As a result, the use of a discharge related rating curve based on a single measure of channel cross-section will have high uncertainty (Malmon et al., 2007). Furthermore, manual measurements of water velocity are dangerous due to the risk of rapid water level rise (e.g., the control and remediated gullies often encounter water level changes of 0.5 m in under 5 minutes) and the potential for bank collapse in the control gully. Automated methods for determining velocity or discharge (e.g., acoustic doppler velocimeters/acoustic doppler current profilers) offer an alternative to manual measurements, however, these methods are expensive and are limited to waters where SSC is typically less than 15000 mg L^{-1}, without additional site-specific calibration (Sottolichio et al., 2011). For these reasons it takes considerable time and effort to collect sufficient data to accurately determine gully discharge and, therefore, sediment load. Once an adequate amount of gully water discharge data are collected, sediment load estimates for the remediated and control gullies will be calculated and published.

In the absence of water velocity data, comparison of water levels (and thus shear stress), likely to show similar trends to velocity and SSC, show that there was no obvious relationship for the control gully. However, SSC trends in the remediated gully, particularly in the 18/19 wet season, may be linked to water level, likely as a function of velocity (Figure 4) (SI-3). Additional flow event data, including water velocity measurements are needed to confirm this.

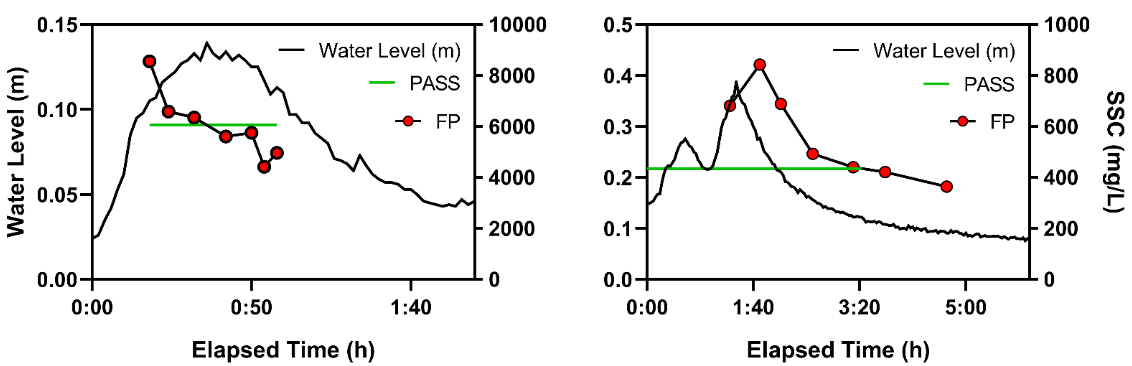


Figure 4. Relationship between SSC and stream height for single flow events in the control (left panel, flow event B) and remediated (right panel, flow event F) gullies, that occurred during the 2018/2019 wet season (SI-3). Water level (black line), PASS TWA SSC (green line), and flow proportional (FP) sampling (red circles with black line).

The SSC of samples collected from the control gully, using RS samplers and autosamplers, suggest there is a general decreasing trend in SSC following the initiation of flow ($R^2 = 0.61$), regardless of changes in flow event length or stage height (SI-3) (Figure 5). This trend is likely the result of instream processes, such as the rapid mobilisation of readily erodible soil from the gully and deposited fine sediment from previous flow events. This contributes to a high initial SSC followed by a steady decrease in SSC to an equilibrium between the scouring of erodible gully soil source material and the transport capacity of the water flowing through the gully (Malmon et al., 2007). These processes have been observed in other ephemeral waterways and may be an inherent feature of these systems (Dunkerley et al., 1999; Malmon et al., 2002). In contrast, there was no relationship ($R^2 < 0.01$) between SSC and time after the initiation of flow in the remediated gully (Figure 5). The SSC trend in the remediated gully is no longer symptomatic of an actively eroding system, rather, it is a relationship similar to that of streams transporting sediment sourced from the catchment (Doriean et al. 2019; Nistor and Church 2005). This suggests gully erosion is no longer a dominant sediment source and the gully may now be a conduit for suspended sediment sources from erosion processes occurring in the catchments.

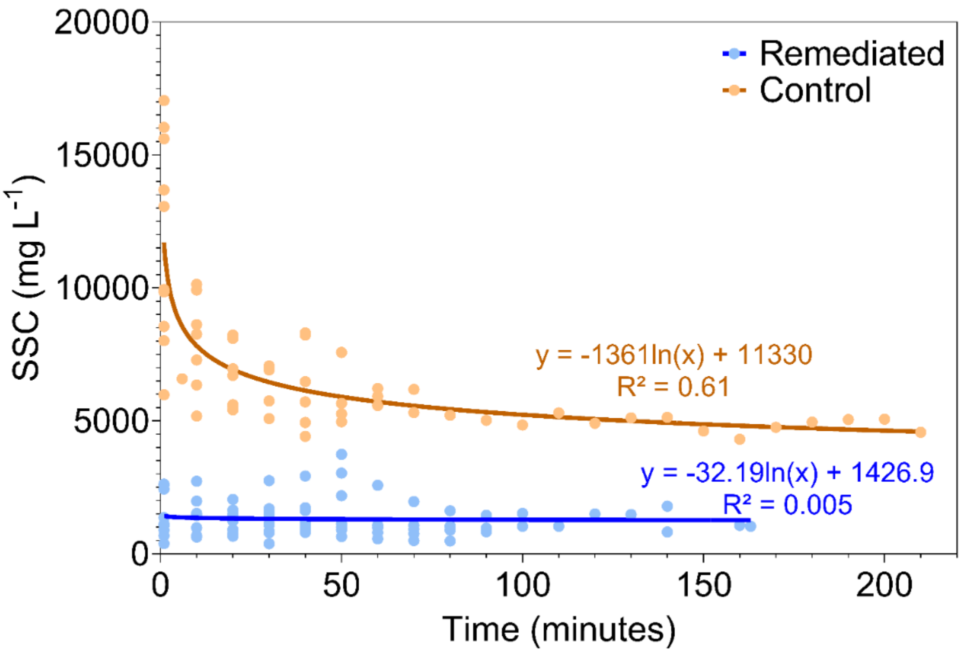


Figure 5. Relationship between time after initiation of flow and SSC of samples collected from the control (brown) and remediated (blue) gullies using autosamplers and RS samplers during the 2017/2018 and 2018/2019 wet seasons. Trend lines represent logarithmic regression models.

3.2.3 Particle size distribution

The PSD of erodible soil collected from both the control and remediated gullies, prior to remediation, were not significantly different (SI-8) (Figure 6). For both gullies, ~45% of readily erodible soil from the gully head scarp was comprised of sand, with the remainder being silt (~35%) and clay (~20%) (Figure 6). The near identical PSD characteristics of the readily erodible soil from both gullies is consistent with their proximity and indicates that the control gully provides an appropriate comparison to evaluate the effectiveness of remedial works at the remediated gully.

Suspended sediment samples from the control gully, collected using a PASS sampler, demonstrate the alteration in PSD of the gully soil when it becomes suspended under flow, mixed with sediment from the catchment and selectively transported downstream (Figure 7). This change in PSD is expected because the sediment particles will distribute in the water column based on their physical and chemical characteristics, such as shape, size, mass, and affinity to flocculate into composite particles (Vercruysse et al., 2017; Walling et al., 2016). Hence, lighter and finer particles (clay and silt) were dominant in the suspended sediment samples. The bulk of the sand in the eroded gully soil is likely transported as bed load, with the proportion in the suspended fraction dependant on periods of high flow-velocity (Horowitz, 2008). The presence of large deposits of sand within the control gully channel bed supports this interpretation (SI-9).

Comparison of the average PSD of suspended sediment samples collected from the remediated and control gullies show that silt and clay were dominant in both, however, sand was almost completely absent (<6%) in the remediated gully samples (Figure 8). There was no visual evidence of bedload sediment (i.e., sand) settling in the remediated gully channel, rather, these coarser sediment particles (>63 μm) appeared to be trapped behind flow reduction structures (i.e., check dams) (SI-9). This is consistent with observations of check dam performance in similar applications (Nyssen et al., 2004; Rustomji et al. 2008; Wei et al., 2016; Bartely et al., 2020). Comparison of suspended sediment PSD characteristics (10th (d10), 50th (d50), and 90th (d90) percentiles) of PASS samples collected from the control and remediated gullies show that the suspended sediment from the remediated gully (d50 of 5.84 μm) was significantly finer than that of the control gully (d50 of 10.8 μm) (Table 3).

The PSD of control gully catchment PASS samples shifted to smaller sizes compared to the gully outlet PASS samples (Table 3), which indicates that the contribution of slightly coarser suspended sediment from gully erosion (d50 10.8 µm) is greater than the suspended sediment contribution of the catchment (d50 4.29 µm) in the control gully. In contrast, the PSD of suspended sediment samples collected from the outlet of the remediated gully (d50 of 5.84 µm) and samples collected from Catchment 2 (d50 of 5.52 µm) and 3 (d50 of 5.06 µm) of the three catchment areas draining into the gully were very similar, thus suggesting their sediment contributions would be similar, when normalised for differences catchment area size (Table 3) (Figure 9). The lack of similarity in suspended sediment PSD characteristics between the remediated and control gullies outlets, and similarity in the PSD of the remediated gully and its catchments, indicates gully subsoil (i.e., sand and coarse silt) is no longer a significant source of the suspended sediment flowing from the remediated gully. It also indicates that the dominant PSD component of fine suspended sediment (i.e., clay and silt) in the remediated gully is now primarily sourced from the gully catchments. This finding supports the key conclusions of the recent review conducted by Bartely et al., (2020), which found that remediation of both the gully and its catchment(s) will generate a more immediate and effective reduction in sediment yield than remediation of the gully alone.

Table 3. Time-weighted average suspended sediment concentration and particle size distribution data of samples collected, using PASS samplers, from the remediated and control gullies during the 2017/2018 and 2018/2019 wet seasons. Note catchment samples (n=2 per sampling location) were only collected during the 2018/2019 wet season.

Sampling location	***TWA SSC (mg L^{-1})***	***PSD (µm)***		
		d_{10}	***d_{50}***	***d_{90}***
Control gully	7123 (± 2670)	1.79	10.8	175
Control catchment	485-2709	1.04	4.29	26
Remediated gully	1429 (± 419)	1.40	5.84	27
Remediated catchment 1	337-563	1.71	8.11	36
Remediated catchment 2	461-1517	1.27	5.52	30
Remediated catchment 3	808-3556	1.27	5.06	24

Please note, each catchment PASS sample TWA SSC represents the average SSC of several flow events.

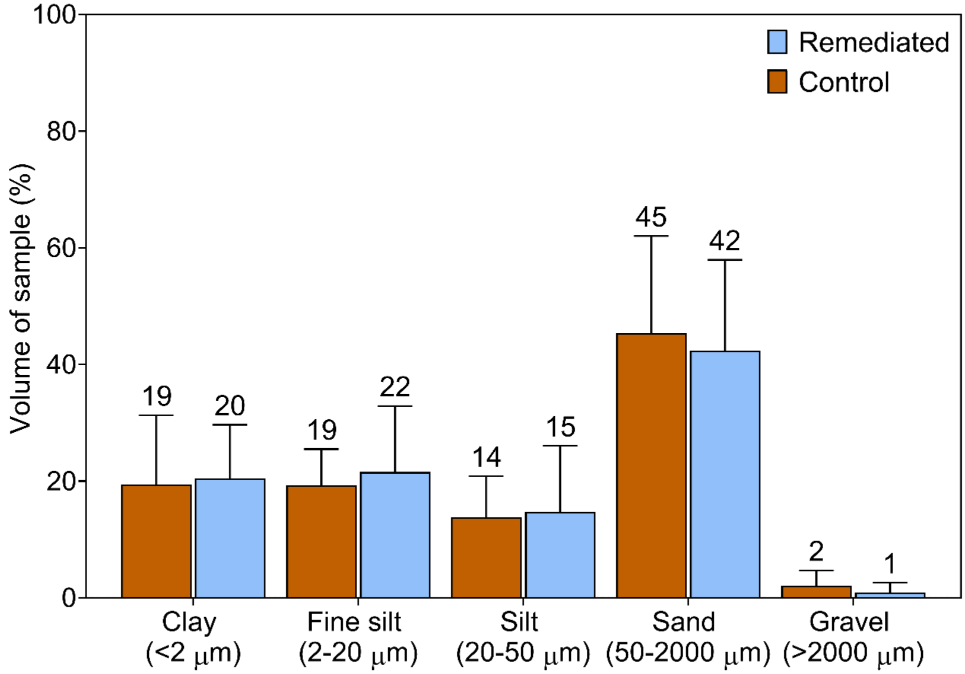


Figure 6. Average PSDs, by size class, of soil collected from the control (brown) and remediated (blue) gullies, prior to remedial works. Error bars represent the standard deviation of each class. Control n=4 and remediated n=14.

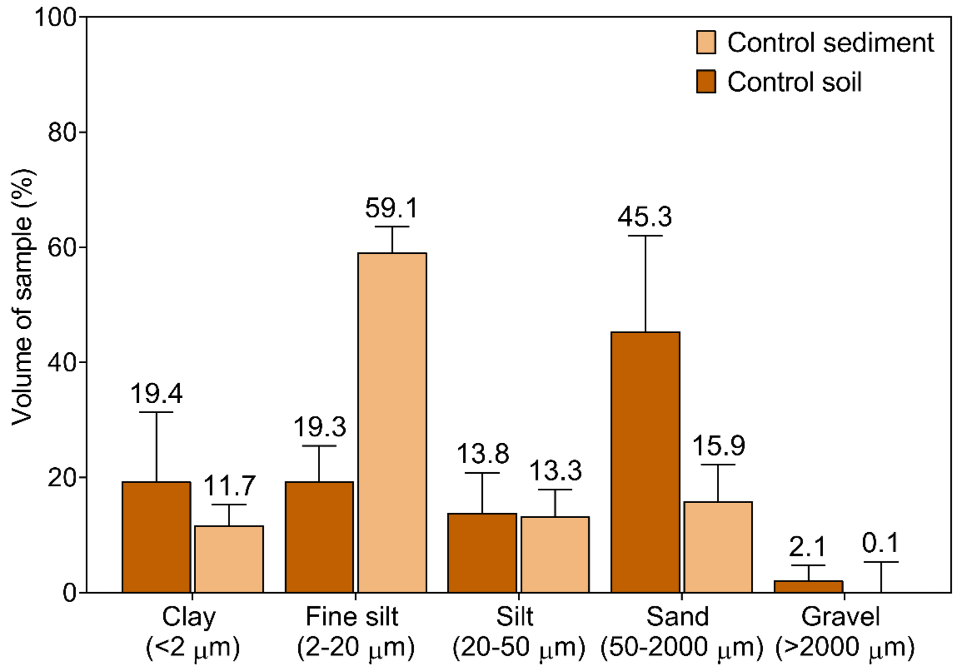


Figure 7. Control gully soil (brown, n=4) and control gully suspended sediment (light brown, n=6) PSD by size class. Error bars represent error as standard deviation for the soil and sediment PSDs respectively.

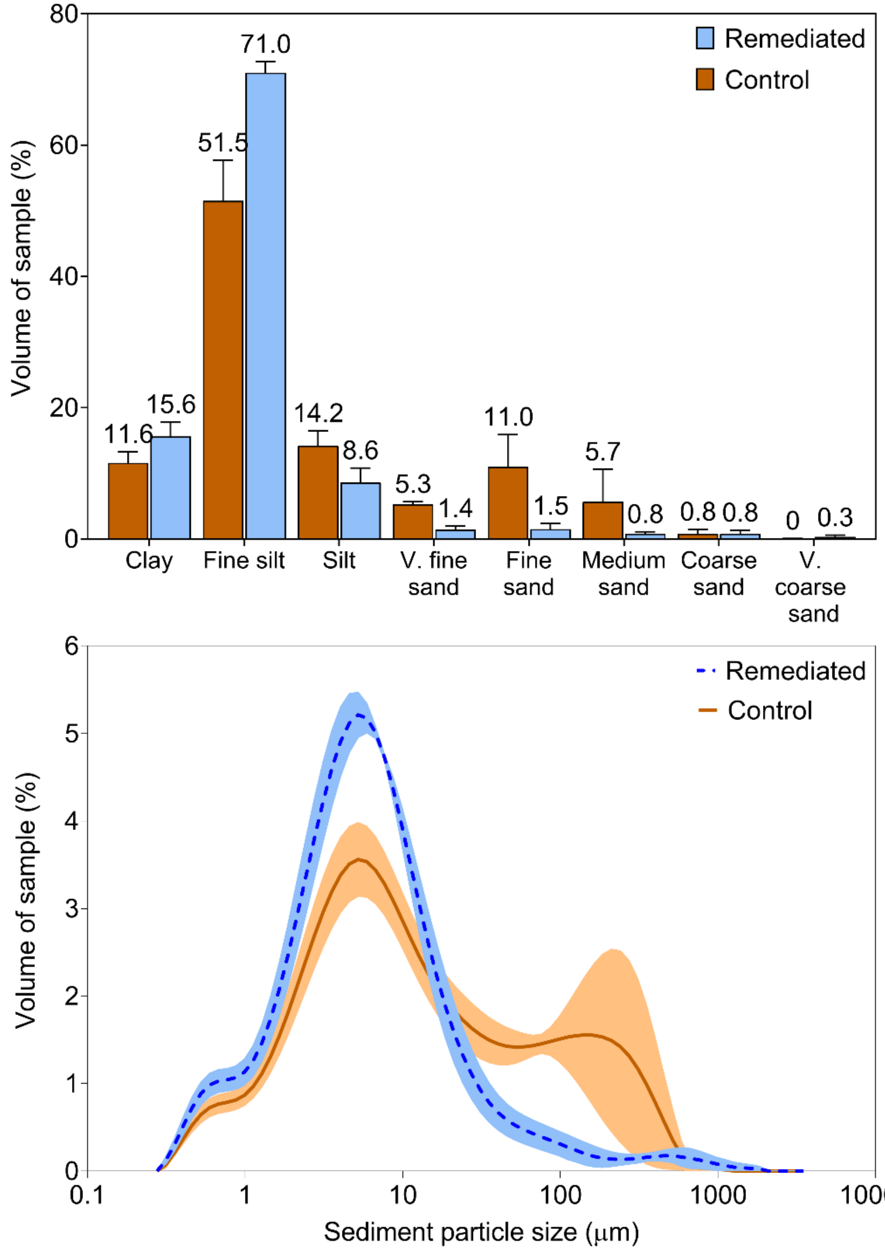


Figure 8. Average suspended sediment PSD by sediment size class (left panel) and plotted by frequency (right panel) for PASS samples collected from the control (brown) and remediated (blue) gullies during the 2018/2019 and 2018/2019 wet seasons. Error bars (left panel) and shading (right panel) indicate error as standard deviation. Clay = <2 µm, Fine silt = 2-20 µm, Silt = 20-63 µm, very fine sand = 63-100 µm, fine sand = 100-250 µm, medium sand = 250-500 µm, coarse sand = 500-1000 µm, very coarse sand = 1000-2000 µm.

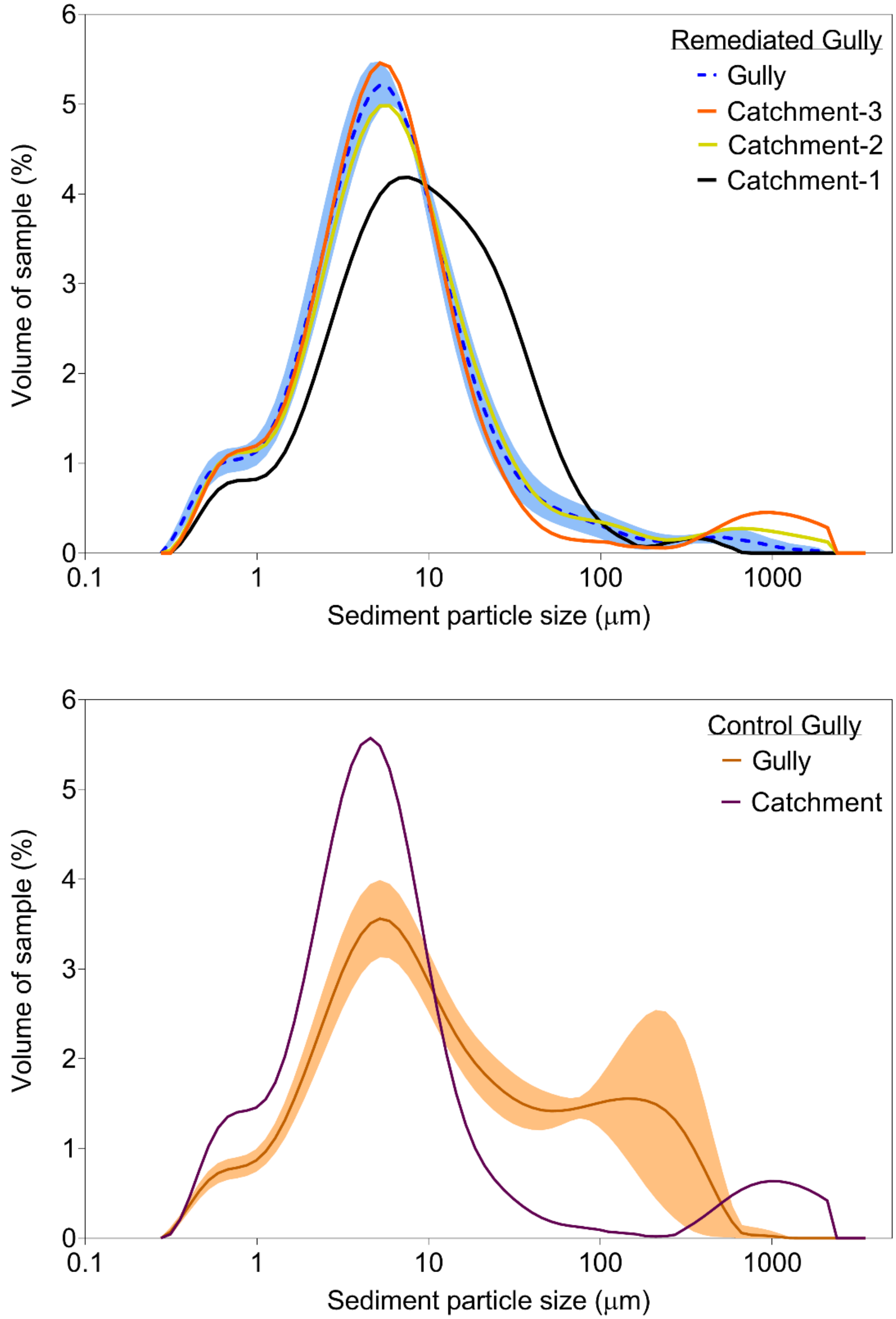


Figure 9. Average PSDs of PASS samples collected from the remediated gully (blue) and catchments (orange, yellow, and black) and control gully (brown) and catchment (purple) suspended sediment PSD frequency plots, during the 2018/2019 wet season. Shading around gully PSDs represents error as standard deviation.

3.3 Particulate and dissolved nutrients

Three opportunities occurred during the study period (24/01/2018, 15/12/18, and 05/02/2019) where samples were able to be retrieved from the remote sampling site within a time frame that allowed them to be processed (i.e., refrigerated, and samples filtered and frozen within 48 hours of collection) and analysed. A total of 40 samples were collected from the remediated (n=14) and control (n=26) gullies for nutrient analysis. The hydrographs and SSC trends of these sampling events indicate they were representative of the other flow events observed in the two gullies (SI-3) and provide enough data for a preliminary assessment of nutrient transport trends within the gullies. Note, the SSC of these samples were likely underestimated by ~15% because they were analysed using the total suspended solids (TSS) analysis method rather than the SSC method (Gray et al., 2000).

The bulk of total organic carbon and nutrient (nitrogen and phosphorus) concentrations, for both gullies, consisted of particulate fractions (Figure 10). Organic carbon and nutrient concentrations of samples collected from the remediated gully were significantly lower than control gully samples for both dissolved and particulate fractions, except for dissolved organic carbon and nitrogen during the 2018/2019 wet season (Table 4; Figure 10).

Dissolved nutrients are influenced by numerous biogeochemical processes that occur in the catchment and the gully, with some of these processes occurring rapidly (i.e., instantly or within several minutes) and significantly altering nutrient chemical speciation (Garzon-Garcia et al., 2016; Garzon-Garcia et al., 2015; Lloyd et al., 2019). We do not currently have sufficient information to investigate the effect these processes have on dissolved nutrient trends occurring in the gullies and their catchments, thus, our interpretation of this data will be limited. However, particulate nutrients and carbon are more stable, taking days or weeks to undergo large changes due to biogeochemical processes once initial leaching of soluble components has occurred (Garzon-Garcia et al., 2018a; Waterhouse, et al., 2018). Therefore, we can assume that the particulate nutrients are relatively stable and representative of their source when sampled from the gully outlet.

For the samples collected during flow events on the 23rd of January 2018, the SSC and particulate nutrient concentrations showed a significant correlation in the control gully ($r = 0.68$ to 0.78; $p < 0.01$), whereas there was no significant correlation ($r = 0.23$ to 0.48; $p > 0.05$) between SSC and particulate nutrient concentrations in the remediated gully (Figure 11; SI-10). The strong positive relationship between SSC and nutrient concentrations in the control gully supports the hypothesis that erosion processes within the gully are acting as the dominant source of suspended sediment and particulate nutrients. In contrast, the poor relationship between SSC and nutrient concentrations in the remediated gully is likely due to the much lower rates of gully erosion at this site, which limits the range of SSCs over which the relationship can be evaluated. It may also indicate multiple sources (i.e., sediment and detritus inputs from the catchment) are contributing to particulate nutrient export. The remediated gully suspended sediment had a significantly higher nutrient proportion by mass than that from the control gully (SI-11), consistent with the higher proportion of fine suspended sediments observed in the remediated gully, as a result of reduced subsoil erosion effects (Figure 8) (Horowitz 2008). Reliably differentiating fine suspended sediment and associated nutrients sourced from either the catchment or the gully itself is challenging without dedicated sediment tracing data (e.g. stable or radioisotopes, biomarkers), and/or a distributed network of event samplers within the catchment. Despite this, our PSD data is consistent with a dominant catchment source of suspended sediment and particulate nutrient sources in the remediated gully. In contrast, the significant relationships between SSC and particulate nutrients in the control gully demonstrates that eroding subsoil was likely a major source of particulate nutrients in the control gully. Future work should seek to investigate the specific sources of suspended sediment and associated nutrients at the study sites.

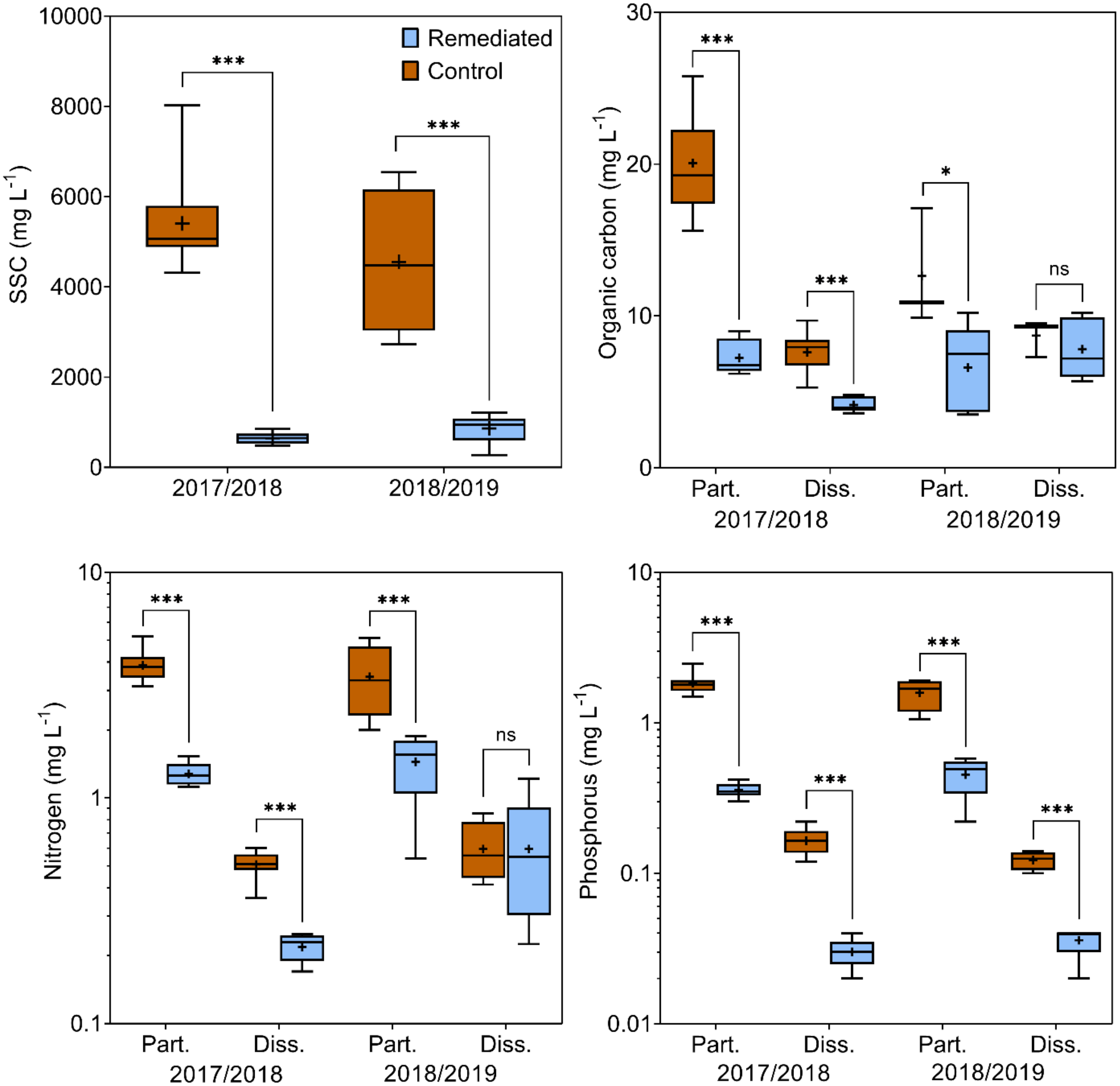


Figure 10. SSC and nutrient concentrations of samples collected during flow events in the 2017/2018 and 2018/2019 wet seasons. Note, the 2017/2018 data represents a single flow event and the 2018/2019 data represent multiple flow events. Box plots represent the minimum, maximum, 25th and 75th percentiles, median (horizontal line in box), and mean (cross). Brackets represent the results of paired t-tests, where $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), or $p > 0.05$ (ns).

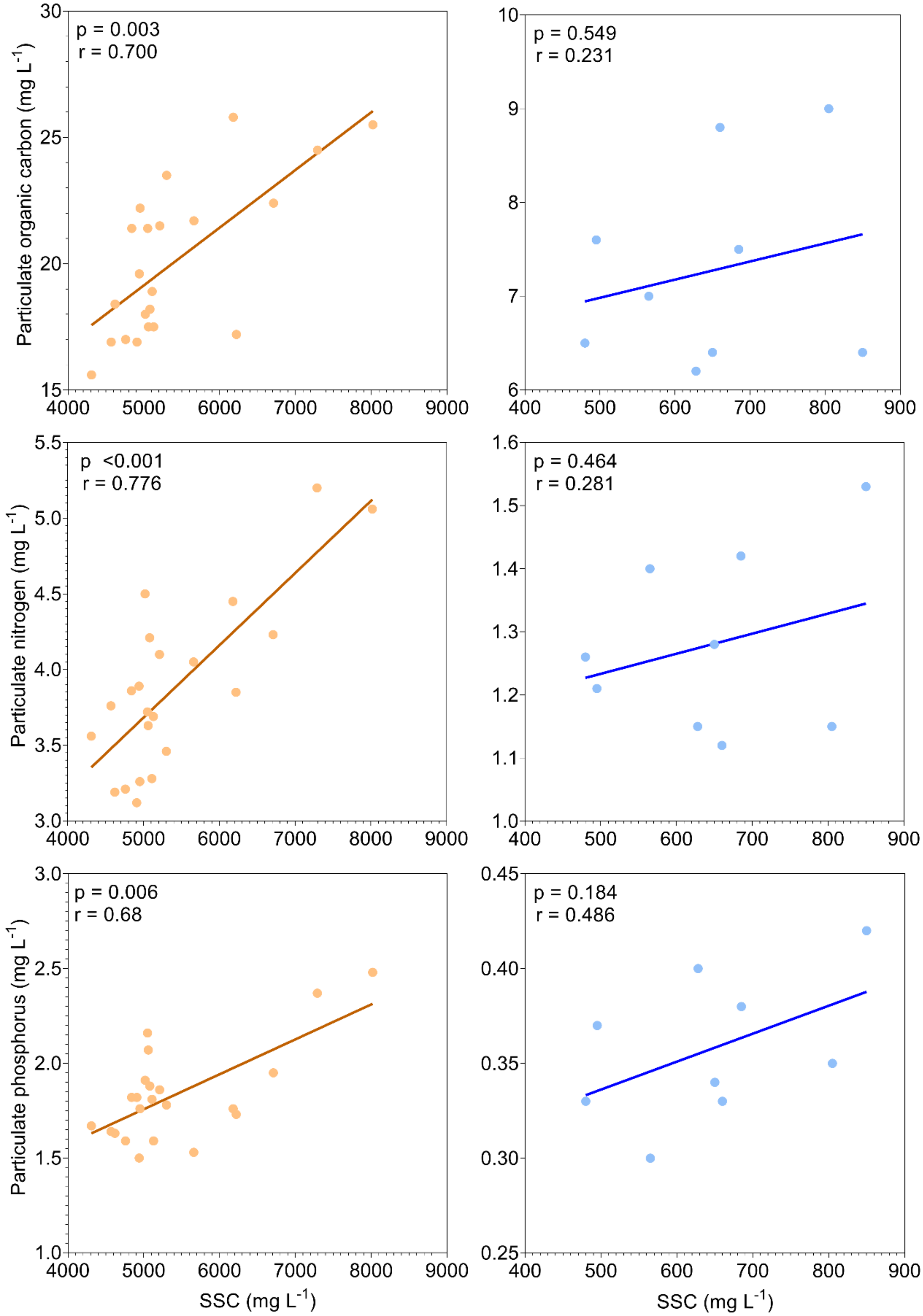


Figure 11. Relationships between SSC, and POC and nutrient concentrations in the control (brown) and remediated gully (blue) from single flow events on the same day during 2017/2018 wet season.

3.4 Monitoring approach assessment

The large investment in monitoring effort reported in this study was necessary in-order to properly assess the effect of landscape scale remediation on alluvial gully water quality, as well as to test the effectiveness of the different monitoring methods. It is imperative that environmental managers apply robust monitoring plans when conducting gully erosion control measures to ensure their effectiveness is appropriately evaluated. This study identified several important factors to consider when implementing a gully water quality monitoring plan:

(1) The combination of a small number of high-cost monitoring methods (i.e., autosamplers) complemented by low-cost automated methods (i.e., RS and PASS samplers) allows for both redundancy and more representative data collection at key monitoring locations, such as gully outlets. For example, the PASS sampler collected samples from events that occurred after the RS and autosamplers were at capacity; the RS samplers provided important information on in-stream suspended sediment heterogeneity over the rising stage; and the autosampler provided important discrete sample data used to evaluate suspended sediment dynamics (e.g., SSC and water-level hysteresis).

(2) The application of low-cost methods (e.g., the PASS sampler) allows for the establishment of a wider spatial monitoring network. In this study the PASS sampler was deployed at several monitoring locations, in both gully catchments and outlets, which would commonly not be a feasible approach with the other runoff monitoring methods.

(3) A complete conceptual model of potential inputs and outputs of a gully should be established before monitoring begins. Failure to do so could lead to inconclusive results and a poor evaluation of gully remediation effectiveness. For example, the lack of catchment data for the 2017/2018 wet season needed to be addressed for the following wet seasons in order to account for all the potential influences acting on the suspended sediment dynamics occurring in the gullies.

4 Conclusion

The water quality data collected during this study, using multiple monitoring methods, supports the application of intensive landscape-scale remediation to significantly reduce suspended sediment concentrations in actively eroding gullies. This is accompanied by the added benefit of significant reductions in nutrient (nitrogen and phosphorus) and carbon concentrations in gully discharge. Further monitoring at the site should be conducted over longer timescales (i.e., decades) to evaluate the longevity of the erosion mitigation controls used as part of the gully remediation works. Development of gully flow velocity or discharge measurement capabilities should be conducted to address the current limitations of discharge measurements in these often-remote locations. Future studies should also investigate the speciation of particulate and dissolved nutrients in remediated and active alluvial gully systems to better understand the effects of landscape-scale gully remediation on the reduction of bioavailable nutrient export.

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7 Data and Code availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

8 Author contribution

- **NJCD:** Designed the experiments, carried them out, sample and data analysis, investigated the data, and prepared the manuscript with contributions from all co-authors.
- **WWB**: Provided guidance in experimental design, method development, interpretation of results, and provided assistance with preparation of the manuscript.
- **JRS**: Provided assistance in method development, carried out field work, and interpretation of results.
- **AGG and JMB**: Provided sample and data analysis, interpretation of results, and assistance with preparation of the manuscript.
- **PRT and DTW**: Provided interpretation of results, and assistance with preparation of the manuscript.
- **APB**: Provided study supervision, guidance in experimental design, carried out field work, interpretation of results, and assistance with preparation of the manuscript.

9 Competing interests

The authors declare that they have no conflict of interest.