Suspended Sediment Monitoring in Remote Aquatic Environments: An Assessment of New and Existing Measurement Techniques in Alluvial Gully Systems

Nicholas J. C. Doriean

B.Sc (Hons)

A thesis submitted in fulfilment of the requirements of the degree of

Doctor of Philosophy

School of Environment and Science,
Griffith University, Australia

October 2019

Acknowledgments

Great thanks go to my supervisors: Dr William Bennett, Associate Professor Andrew Brooks, Professor Peter Teasdale, and Associate Professor David Welsh. I am tremendously grateful for all of your support and mentorship. Each of you have made time to comment on an idea, help out in the field, or review the latest version of a manuscript. I have particularly admired how all of you have been able to work so well with one another and provide me with clear guidance throughout my candidature. It is a great example of each of your skills as experts in your respective fields and as effective collaborators within a team. I believe you are all valuable assets to the scientific community, and I feel privileged to have worked with each of you over the last few years. Special thanks must go to Dr William Bennett who became my principal supervisor early in my candidature due to unforeseen circumstances. Your consistent and thoughtful support has been invaluable.

Thanks to Griffith University and the Australian Federal Government for the opportunity to study at a great institution and having received a PhD scholarship. I would also like to thank the Griffith University School of Environment and Science community for listening to my endless ideas and for being great friends: Ryan, Lana, Chris, Tyson, Emily, Ryo, Steve, and Chantal. Special thanks goes to John Spencer, for the countless hours working with me in the baking hot North Queensland sun or in the sodden monsoonal wet! Your steadfast attitude to complicated and tiring challenges was a true inspiration for me to always keep a level head and move forward. Thank you!

Final thanks go to my wife Jess, family, and friends, for your constant support of my endeavours, even at the cost of missed special occasions. Your faith in me and my abilities never wavers, even when I doubt them myself. It is because of you all that I am able to take risks, overcome challenges, and celebrate successes.

"…do the other things, not because they are easy, but because they are hard,
because that goal will serve to organize and measure the best of our energies and skills,
because that challenge is one that we are willing to accept…"

John F Kennedy

Statement of Originality

The material presented in this thesis has not been previously submitted in any University and, to the best of my knowledge, contains no material previously published or written by another person except where due acknowledgement is made in the thesis itself.

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Nicholas J. C. Doriean

October 2019

Abstract

Our current understanding of suspended sediment dynamics is often limited to accessible aquatic environments that can be monitored using existing techniques. Consequently, there is a lack of data from remote, ephemeral waterways, such as gullies, which are challenging to monitor using conventional approaches originally designed to operate in rivers and streams. Recent research suggests gully erosion is a significant driver of sediment pollution to aquatic environments; for example, greater than 40% of the sediment pollution to the Great Barrier Reef can be attributed to gully erosion.

Current deficiencies in our capability to monitor gully water quality require the development of affordable, autonomous monitoring methods that can be deployed at high spatial resolution across a gully network and that can also withstand harsh, remote environments. Therefore, a simple and robust time-integrated device for in situ suspended sediment sampling was developed; the pumped active suspended sediment (PASS) sampler. The PASS sampler operates by drawing water through a settling column using a peristaltic pump at a constant velocity, effectively concentrating the suspended sediment, into a time-integrated sample, from a large volume of sampled water into approximately 4 L. Laboratory testing showed the PASS sampler was capable of retaining over 90% of the suspended sediment in a sample dominated by silt and clay (median particle size = 6.98 µm). The device was tested alongside a suite of conventional suspended sediment monitoring techniques (flow proportional discrete sampling, automatic discrete sampling, passive single stage sampling and turbidity measurement) for application in alluvial gully systems and found to provide samples that accurately represented time weighted average suspended sediment concentration and particle size distribution.

The suite of evaluated methods was applied to investigate the effect of landscape-scale gully remediation on the water quality of a catchment draining into the Great Barrier Reef. The median suspended sediment concentration of the remediated gully (1429 mg L^{-1}) was greatly

reduced compared to a control gully (7123 mg L^{-1}). The application of a novel monitoring network using PASS samplers and other established measurement methods, in conjunction with suspended sediment-associated nutrient analysis, provided a detailed and robust account of the water quality improvements generated by landscape-scale gully remediation and the implications it could have for reducing sediment and associated nutrient pollution to the Great Barrier Reef. Ambient concentrations of pollutants considered most likely to impact the health of Great Barrier Reef ecosystems were also greatly reduced (~75% reduction of fine suspended sediment (< 63 µm) and a ~65% reduction in sediment-associated nutrients (nitrogen and phosphorus)).

Table of Contents

1 Thesis Structure

This study is written in a thesis by publication format in accordance with Griffith University policy (Appendix 1). The Introduction includes a review of the published literature relevant to the objectives of the thesis (Chapter 2). This is followed by two method development chapters (Chapters 3 and 4) and a field-based investigation (Chapter 5). Chapters 3 through 5 are written as manuscripts formatted to the requirements of the peer reviewed academic journals to which they have been submitted/published. Due to this, there is some repetition throughout these chapters, including in the descriptions of methods, study sites, and reference lists. There are also specific literature reviews at the start of each results chapter, per the requirements of the journals. The Conclusion and Future Research chapters (Chapters 6 and 7) reflect on the findings of the thesis and provide suggestions for future research priorities (Figure 1).

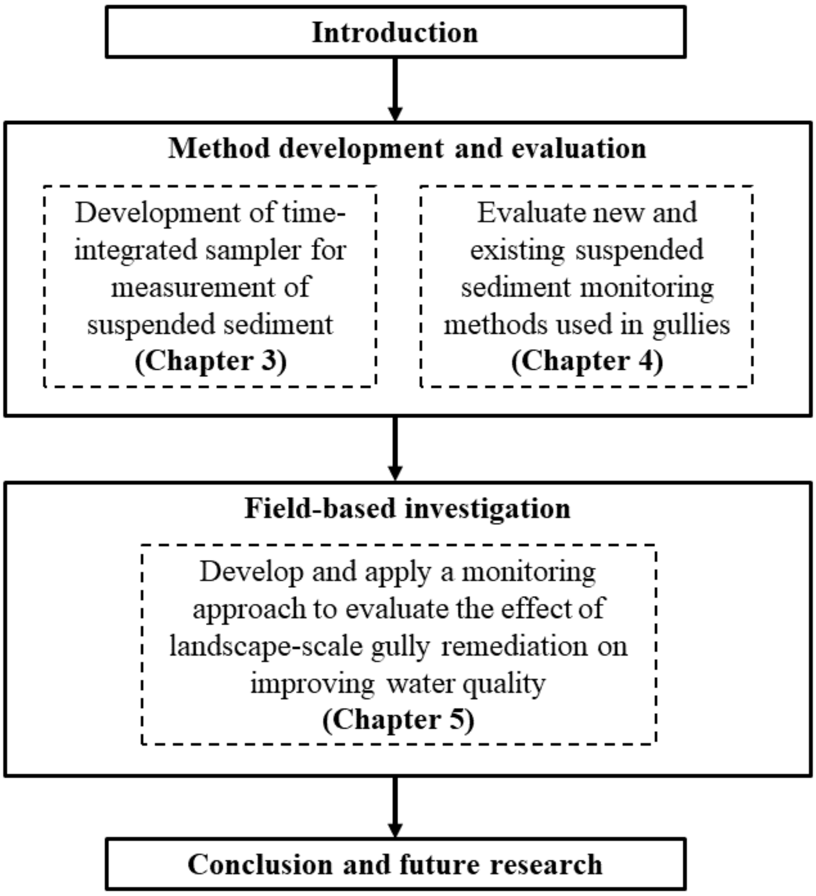

Figure 1. Conceptual outline of the thesis.

2 Literature Review

2.1 Suspended sediment in the aquatic environment

2.1.1. Physical properties

Suspended sediment is the inorganic and organic material suspended and transported in the water column of most natural aquatic environments [1, 2]. The composition of suspended sediment is determined by the geology/geomorphic process zone and/or source type from which the sediment originates [3]. For example, suspended sediment could be generated from erosion processes occurring in a stream channel, in a catchment (i.e., hillslope or gully erosion), or from anthropogenic sources (i.e., industrial or residential effluents in stormwater) [4]. The various inorganic and organic components of suspended sediment have different physical properties, which determine their behaviour and fate in the aquatic environment.

Inorganic suspended sediments typically consist of detrital geological materials that have been broken down into smaller particles by various physical weathering processes and then further eroded and transported by water, wind, or ice [3]. Suspended sediments are broadly categorised based on their size (Table 1), which is strongly linked to their chemical composition. The sediment size class most widely accepted in scientific literature was developed by Wentworth (1922) and refers to particles smaller than 63 µm as fine suspended sediments that are naturally cohesive, with cohesivity increasing with decreasing particle size [5]. This sediment class consists mostly of clay (<4 µm) and silt (4-63 µm) particles (Table 1). Clays include minerals such as kaolinite, montmorillonite, vermiculite, halloysite, illite, bentonite, and chlorite [6, 7]. Due to their small size and the presence of surface charges, clays are strongly affected by electrostatic interactions with water molecules and other suspended particles. These features also determine the cohesive properties of fine sediment. In contrast, sand particles (>63 µm), which generally consist of quartz, feldspar, mica and carbonates, do not possess the same degree of surface charge and are thus less affected by these electrostatic forces. The sand fraction in particular is much less cohesive than fine sediment because any electrostatic interactions are too weak to allow these larger particles to associate together [5, 8].

Table 1. Sediment particle size classification. The phi (*φ) scale represents a version of the particle size class using a constant of 1mm diameter as a reference for a log equation using the equivalent Wentworth class [9].* Source: Wenworth 1922 [10].

φ scale	*Size range (metric)*	*Aggregate name (Wentworth class)*	*Other names*
<−8	>256 mm	Boulder	
−6 to −8	64–256 mm	Cobble	
−5 to −6	32–64 mm	Very coarse gravel	Pebble
−4 to −5	16–32 mm	Coarse gravel	Pebble
−3 to −4	8–16 mm	Medium gravel	Pebble
−2 to −3	4–8 mm	Fine gravel	Pebble
−1 to −2	2–4 mm	Very fine gravel	Granule
0 to −1	1–2 mm	Very coarse sand	
1 to 0	0.5–1 mm	Coarse sand	
2 to 1	0.25–0.5 mm	Medium sand	
3 to 2	125–250 µm	Fine sand	
4 to 3	63–125 µm	Very fine sand	
8 to 4	4–63 µm	Silt	Mud
10 to 8	0.98–4 µm	Clay	Mud
20 to 10	0.95–977 nm	Colloid	Mud

The organic component of suspended sediment generally consists of bacteria, algae, or decaying matter from plants and/or animals and plays an important role in controlling some physical properties of suspended sediment [4]. Suspended sediment particles are rarely transported in isolation, rather, they often consist of composites of organic and inorganic materials known as flocs (i.e., they are derived from the process of flocculation) (Figure 2) [6, 11]. These highly complex structures are formed through electrochemical forces and by the adhesive nature of extracellular polymeric substances excreted by algae and bacteria [12]. These intricate configurations of particles determine the chemical carrying capacity, source potential, and manner of transport of suspended sediment particles in aquatic environments [4].

Figure 2. Microscope images of a floc (left panel, scale bar = 0.5 μm) and group of flocs (right panel). Source: Walling et al. 2016 [4].

The specific gravity of a sediment particle coupled with its size and shape determines the amount of force required for suspension in the water column to occur. Clay particles are often platy in their morphology, being very thin relative to their width and length (Figure 2). Silt and sand commonly have more uniform size dimensions, tending towards the cuboid shape class. However, these particles shapes are often made irregular by the weathering forces exerted upon them. Thus, to compare and understand the different suspended sediment shapes and sizes their dimensions are determined by relating their length to an equivalent sphere size with a similar settling velocity as the actual particle (Figure 3). This allows for the standardised estimation of suspended sediment particle movement through water.

Figure 3. Particle shape factor of suspended sediment. Sp = sphericity, la, lb, and lc = measurement of the longest, intermediate, and shortest axis measurement, respectively. Source: Julien 2010[8].

2.1.2. Transport processes

Suspended sediment is transported by the natural processes of erosion, suspension (i.e., transport) and sedimentation (Figure 4) [5, 8]. These processes occur in a wide range of aquatic environments (e.g., rivers, streams, wetlands, and oceans) and are driven by the velocity of water or by differences in biogeochemical processes (e.g., vertical transport of clay particles in a lake due to physiochemical changes in the water column) [13, 14]

[redacted]

Figure 4. Processes of erosion, transport, and sedimentation of suspended sediment. Source: Julien 2010[8].

The interaction of forces that cause a sediment particle to become suspended are complex. Shear stress is the overriding force on a sediment particle in the form of flowing water. However, the density of the individual particle, the specific drag caused by its shape, and fluid viscosity and turbulence all interact to determine the suspension and transport of particles. The interactions of these influences determine the particle size and concentration distribution of suspended sediment throughout the water column (Figure 5) [8].

Figure 5. Shields diagram of suspended sediment transport interactions. *u_** = shear velocity of water, where *ω* is the settling velocity of a particle, *Re_**= Reynolds number (a measure of flow turbulence), and grains shield parameter is the rational force for incipient movement of a particle. Source: Shields 1936[15, 16]. Note, these relationships are most influential on particles >63 µm. Fine particles <63 µm are influenced more by flocculation and electrostatic interactions [17].

Sediment is transported as either bed load or suspended sediment. Bedload consists of mostly non-cohesive sediment >63 µm, whereas, suspended sediment is categorised as either suspended load (mostly cohesive fine sediment <63 µm) or washload (mostly clay particles (<4 µm) that are effectively in permanent suspension (Figure 6). Bedload usually occupies a thin zone above the sediment bed and is dominated by the slower moving transport process of saltation, where particles are suspended for a short time only to rapidly settle out due to insufficient shear stress to keep them in suspension [18]. The suspended load is characterised by a relatively uniform horizontal distribution of particle sizes (not accounting for friction and drag caused by channel banks and debris), whereas the vertical distribution is determined by gravitational and turbulent forces. The very small sediment particles of the washload are kept in permanent suspension as part of the suspended load or by electrochemical processes. These particles only undergo sedimentation when they are incorporated into flocs [18]. These three modes of transport determine the movement of suspended sediment through aquatic systems.

Bed load can take years to be transported from its source and often becomes entrapped in sediment sinks (e.g., wet lands) [19]. Suspended load, in contrast, can be rapidly transported over small to large distances depending on the hydrological processes occurring in the aquatic system (i.e., water velocity and flow duration). For example, in the catchments of the Great Barrier Reef (GBR) fine suspended sediment (<16 μm) sourced from subsurface gully and stream bank erosion can travel hundreds of kilometres through streams and rivers, driven by a single large storm event (e.g., a tropical cyclone), before extending out into the ocean [20].

Figure 6. Conceptual diagram of suspended sediment transport processes. Note, the washload is part of the suspended load in this diagram. Source: Marshak 2015 [21].

2.1.3. Chemical properties

The size and electrostatic properties of a suspended sediment particle are often related to its affinity for binding various solutes, with decreasing suspended sediment particle sizes associated with increasing chemical affinity [5, 7, 22, 23]. For example, Pacini and Gächter (1999) found that phosphorus concentrations associated with clay-sized particles (<4 μm) were approximately 10-fold higher than with sand-sized particles (> 63 μm) (Figure 7). This is due to the high surface area to volume ratio (ranges typically measured in $m^2\ g^{-1}$) of clays compared to silts and sands (ranges typically measured in $cm^2\ g^{-1}$), coupled with the abundance of binding sites available for ion-exchange reactions [24, 25]. This does not mean coarser particles of silt and sand do not interact with solutes, rather, they do so to a lower extent compared to clays and very fine silts [7, 23].

Figure 7. Particulate phosphorus concentrations over a range of particle sizes from samples collected from the Kleine Aa River in Central Switzerland. Source: Pacini and Gächter 1999 [22].

The physical and chemical factors that affect the interaction of suspended sediment with solutes are diverse and can change depending on the prevailing conditions [7, 23]. These include physical conditions (i.e., grain size, cation exchange capacity, and magnetic properties), chemical mechanisms (e.g., adsorption, precipitation, or mineralisation), and chemical phases (e.g., carbonation, water chemistry, and presence or absence of organic matter) [7]. The sorption and desorption of reactive compounds (e.g., nutrients and organic compounds), for example, can vary widely with the changes in pH or salinity that often occur throughout a catchment [26, 27]. Whereas, more unreactive compounds and elements (e.g., trace metals) tend to remain unchanged as suspended sediment is transported through a catchment, depending on their chemical stability or if they are sorbed or incorporated into the sediment particle [28, 29]. For example, in the catchments of the Great Barrier Reef, suspended sediment associated nutrient compounds (mainly organic nitrogen) remain relatively unaltered from their source state during transport through freshwater systems, however, the flocculation of these particles with organic matter and their movement into estuarine waters initiates physiochemical reactions that cause the nitrogen compounds to speciate (Figure 8) [30].

[redacted]

Figure 8. Conceptual diagram of the processes and controls that determine the bioavailability of the different fractions of particulate nitrogen in sediment. The physiochemical change of freshwater to brackish water often results in the generation of new bioavailable species of nitrogen (e.g., oxidised nitrogen and ammonium). Source: Garzon-Garcia et al., 2018[30].

The physical and chemical water quality conditions of many aquatic systems are determined by the balanced supply, movement and accumulation of sediment and associated elements and compounds [4, 14, 31]. As a consequence of these interactions the role of suspended sediment as a vector and source of contaminants and nutrients is often in a state of flux through aquatic environments. For example, in the Mississippi River Basin suspended sediment accounts for 30-50% of the annual flux of nutrients and at least 75% of the annual flux of trace/major elements [32].

2.1.4. Environmental impacts

Suspended sediment is found in any aquatic environment that is part of or connected to a catchment system, including: wetlands, overland runoff, gullies, urban infrastructure, streams, rivers, and oceans. However, the unique characteristics of these systems determines the type of suspended sediment they have and its role in the catchment [1, 4, 14]. Systems with dynamic flow (e.g., catchments, streams, and rivers) often act as conduits for suspended sediment traveling from a source to a receiving environment, however, these systems can also contribute, alter, or accumulate suspended sediment. Oceans, wetlands, bays and lakes are typically suspended sediment sinks due to their lower flow velocities compared to rivers and streams, which results in the sedimentation of coarser particles and the persistence of fine particles in suspension throughout the water column [18, 19, 33]. Often these receiving systems are the most at risk of detrimental ecosystem impacts associated with increases or decreases in suspended sediment export from catchments [34].

The physical environmental impacts of suspended sediment can be detrimental to aquatic ecosystems. Sediment smothering and decreased light penetration is caused by the increase of fine suspended sediment input to receiving waters with lower water velocities (e.g., lakes, wetlands, or coastal bays), which results in the prolonged suspension of fine sediment in the water column followed by the gradual accumulation of settling sediment particles across entire ecosystem surfaces. These impacts are particularly detrimental to sessile fauna and flora. For example, coral reefs are more susceptible to disease, predation, and lower re-colonising after coral bleaching as the result of being smothered in fine sediment [20, 35, 36]. Additionally, seagrass meadows can experience severe decreases in photosynthetic activity, due to water column turbidity and deposition of sediment on leaf surfaces [37, 38]. Furthermore, excessive amounts of fine suspended sediment in the water column increases the mortality of fish and invertebrates via gill clogging and disruption to feeding and breeding habits (Figure 9) [39, 40]. Suspended sand can also be detrimental to the environment; for example, excessive loads of suspended sand can completely bury benthic communities in receiving waters and scour established channel systems and riparian communities during high velocity flows (i.e., flooding) [41].

[redacted]

Figure 9. Summary of the effects of fine suspended sediment (i.e., suspended particulate matter (SPM)) on coral reef and seagrass habitats. Note, TEP stands for transparent exopolymer particles. Source: Bainbridge et al., 2018 [40].

Suspended sediment often plays a major role in transporting various contaminants and nutrients in aquatic environments. Sediment particles are the major transport vector for a variety of anthropogenic contaminants, such as, petrochemical compounds, polychlorinated biphenyls, trace metals, and organo-metals (e.g., mercury). In the United States of America, for example, suspended sediment is the second highest cause of river and stream degradation, chiefly due to its direct association with 65% of the 126 priority pollutants identified by the United States Environmental Protection Agency [42, 43]. These suspended sediment-associated contaminants are transported through various ecosystems and can negatively affect various trophic levels [5]. For example, fine sediment bearing contaminants may settle in a receiving coastal environment and become a source of contaminant exposure to the numerous bioturbators present, and their predators [5]. These exposures, while infrequently acutely toxic, can have a variety of chronic effects such as reduced growth, reduced feeding efficiency, shortened life expectancy, and birth defects [39].

Suspended sediment-associated nutrients are a vital component of the health of an aquatic ecosystem, however, excessive amounts of these particulate nutrients can have long-lasting environmental consequences [44-46]. Excessive loads of sediment-associated nutrients can cause eutrophication in lakes, rivers and estuaries [47], and the input of suspended sediment-associated nutrients from large river systems to coastal zones can shift the biogeochemical balance of multiple ecosystems. For example, fluvial fine sediment and associated nutrient loads to the waters of the GBR have increased as a result of anthropogenic activities and severely impacted the water quality of the coastal zone (Section 2.3.4)[48]. This has created an environment that encourages the proliferation of generalist marine species (e.g., crown of thorns starfish and harmful algae), which are detrimental to coral reef ecosystems [35, 49, 50]. These environmental impacts are best avoided or mitigated through the effective management of catchments, which can only be achieved through the collection of representative suspended sediment monitoring data [51, 52].

2.2 Suspended sediment monitoring techniques

The suitability of a suspended sediment monitoring method is determined by the flow regime, suspended sediment dynamics, site access, and the empirical data requirements. There are several manual or automated methods available for sampling and measuring suspended sediment in aquatic environments, the majority of which were designed for monitoring fluvial systems.

2.2.1. Manual sampling

The requirements of manual sampling for suspended sediment should not be confused with those of manual sampling for other forms of water quality monitoring. Direct sampling of suspended sediment using a standard sampling cup or pump can often create sample bias to coarser grained sediment (>63 μm) due to the inherent complexities associated with how suspended sediment is transported through the water column with dynamic velocities [53]. Rather, the most representative sample of suspended sediment is collected using isokinetic (i.e., flow proportional) sampling methods. Isokinetic samplers collect a representative sample of suspended sediment by ensuring water entering the sampler does not change in velocity. This is achieved by the use of a sampler equipped with a small valve designed to exhaust air at the same rate that water flows into the sampler or using a sample devoid of air (i.e., a collapsible bag), thus, the sampling velocity matches the ambient water velocity (Figure 10) [54].

[redacted]

Figure 10. Relationship between sampling velocity and suspended sediment concentration (>63 µm) for isokinetic and non-isokinetic samplers. Source: Wilde 2006 [54].

There are over 22 types of isokinetic samplers designed for the collection of suspended sediment samples from fluvial environments. The most commonly used samplers include (Figures 11 and 12):

- DH-48: Hand held sampler that uses a small valve to allow air to escape at the same rate as water is sampled into a sample bottle. Designed for collecting suspended sediment from small streams [55].
- DH-81: Hand held sampler that uses the same fundamental design as the DH-48, except its sampling components are coated in Teflon to reduce the risk of sample contamination by the sampler materials [55].
- DH-95: Similar in design to the DH-81, except designed for use in deeper waterways (3-9.5 m) using a reel. The sampler is stabilised by hydrodynamic fins at the rear of the sampler body [55].

- D-95: Same design as the DH-95, except more suited to sample in higher water velocities – this is achieved by the sampler being much heavier (32 kg), requiring suspension from a winch or crane [55].
- D-96 and D-99: Similar exterior design to the other samplers, however, these samplers collect sediment into a collapsible bag devoid of air. This design allows for the collection of samples from greater depths (e.g., the D-96 for depths between 9.5-15 m and the D-99 for depths >30 m) [55].

Figure 11. Diagram of DH-48 isokinetic sampler. Source: Wilde 2006 [54].

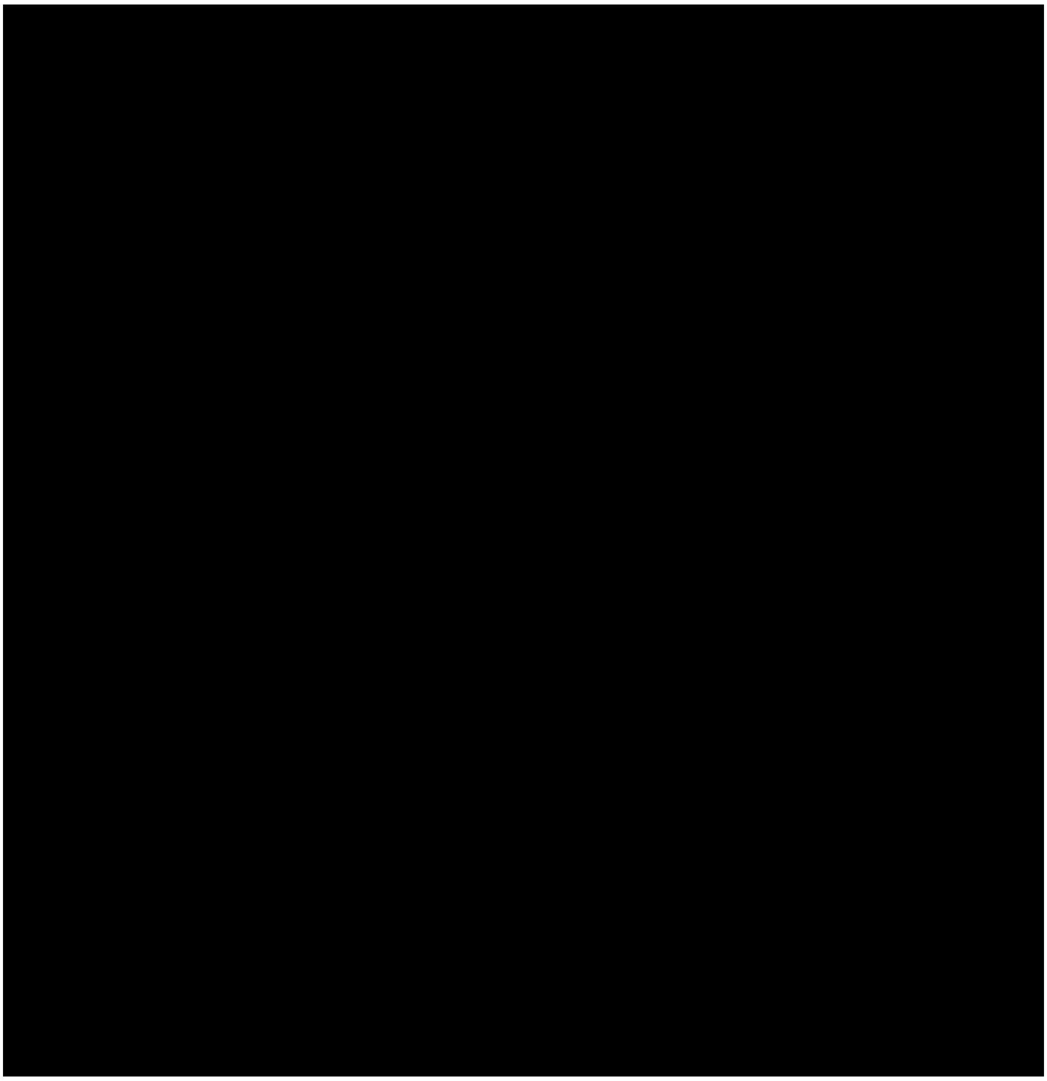

Figure 12. Diagrams of commonly used isokinetic samplers. Source: Wilde et al., 2014 [56].

Ensuring flow proportional samples are collected is not the only concern when attempting to collect representative suspended sediment samples. As previously discussed, suspended sediment often flows in a heterogenous manner vertically through a waterway. Thus, in-order to gain a representative sample it must be collected using the combination of depth integrated and flow proportional sampling. Further, to account for any horizontal suspended sediment heterogeneity multiple depth-integrated samples must be collected along a channel cross section, unless the channel is very narrow (i.e., < 0.5 m) [53, 55]. The number of samples required for a particular channel is determined by calculating the equal discharge increment (i.e., samples collected within variably-space zones of different velocities but the same discharge) or the equal width increment (i.e., samples collected from within several equally spaced zones, determined by the distribution and concentration of flow) (Figure 13) [53, 55].

[redacted]

Figure 13. Diagram of equal discharge (top) and equal width (bottom) sampling principle. Source: Edwards and Glysson 1999[53].

Despite its high level of accuracy, manual sampling is difficult to conduct due the following constraints: (1) intense flow events often preclude personnel from entering the water due to safety concerns, thus limiting sampling to locations with safe access points (e.g. bridges); (2) considerable amounts of financial and technical support are required to execute manual sampling over large spatial and temporal scales; and (3) flow events are often sudden and difficult to predict [2]. For these reasons, routine monitoring of waterways often requires the application of automated sampling approaches [56].

2.2.2. Automated sampling

Automated sampling methods are often applied when manual sampling is infeasible. These methods commonly have a single point of measurement and do not collect flow-proportional samples. Manually collected samples are often required to calibrate automatically collected single point samples to improve their accuracy [52, 56]. Automated samplers can be broadly categorised as pumped, single stage, or time-integrated, and include surrogate measurements such as turbidity.

2.2.2.1. Pumped sampling

Pumped automatic samplers (or autosamplers) consist of a fixed intake point connected via a tube to a pump and distributor, which is controlled by a computer that allows for the collection of either discrete individual samples (commonly up to 24 individual 1 L samples) or composite samples (commonly 20 x 1 L composite sample) (Figure 14) [57]. An additional method of pumped sampling is to use a peristaltic pump (commonly an autosampler) providing a constant flow of sample water for a continuous-flow centrifuge (CFC). This method is more representative of suspended sediment dynamics when sampling over long periods, compared to discrete autosamplers, because it continuously samples, whilst separating water and retaining only sediment. This method is effective at capturing fine to coarse sediment [54]. Generally, the CFC outflow water should contain <2% of sediment mass sampled with a median particle size of 0.5 µm, indicating it captures everything except colloids. This method is very useful; however, it requires technical expertise to operate and can be expensive ($20,000-$100,0000 AUD) (54, 57).

Figure 14. Diagram of an autosampler with a water level sample trigger. Source: Electdata 2019 [58].

Autosamplers tend to be moderately to highly expensive ($3500 to $30,000 AUD [57]) and are commonly used as a component of water quality stations (i.e., stream gauges) located on rivers and streams with high environmental value [59]. They need to be connected to an external sensor (i.e., water level actuator, flow meter, or water quality sonde) and programmed to sample once a predetermined set of conditions are met (e.g., sampling begins once water level and flow velocity reach certain values) [56]. Studies that have evaluated autosamplers for collecting suspended sediment from fluvial and urban waterways have shown that autosamplers collect representative samples of fine suspended sediments (< 63 µm). For example, a study conducted in the Tualatin River in Oregon, USA, successfully predicted suspended sediment discharge using a combination of autosamplers and surrogate monitors (Figure 15). The study noted that the autosamplers did generally provide good data, however, the samplers were prone to reliability issues.

Figure 15. Example of the high-resolution suspended sediment concentration data obtainable using an autosampler. Source: Anderson and Stewart 2010 [60].

Autosamplers may also collect samples that underrepresent the proportion of ambient coarse-grained sediments (>63 µm). This underestimation is commonly low (<10%) and mostly due to the non-isokinetic design of the sampler [52]. However, this bias is worsened when the sampler is significantly elevated (> 2 m) above its sample intake, as coarser particles settle out in the transfer tube during sample pumping. For example, previous studies have shown that an autosampler elevated above its intake (>2 m) can underestimate very fine sand (63-120 µm) by ~20% and fine to medium sands (125-500 µm) by up to 50% (Figure 16) [61, 62]. The under-sampling of coarse sediments can be accounted for by calibrating the suspended sediment concentration and particle size distribution of the samples collected using an autosampler with samples collected using a more representative method (e.g., isokinetic manual sampling) [60].

Figure 16. Effect of autosampler intake elevation on the particle size distribution of collected samples. Note the d_{50} represents the median of the sample particle size distribution. Source: Clark et al., 2009 [61].

2.2.2.2. Single stage sampling

The single stage sampler (i.e., rising stage (RS) sampler) is a simple *in situ* autonomous non-isokinetic sampling device, made from affordable materials, developed by the United States Geological Survey [63]. The RS sampler is placed in a channel above the ambient water level and once the water level exceeds the highest point of the sampler intake a pressure difference is created and the sampler siphons water, collecting a sample, until an air lock is created in the exhaust outlet of the sampler (Figure 17) [53, 56].

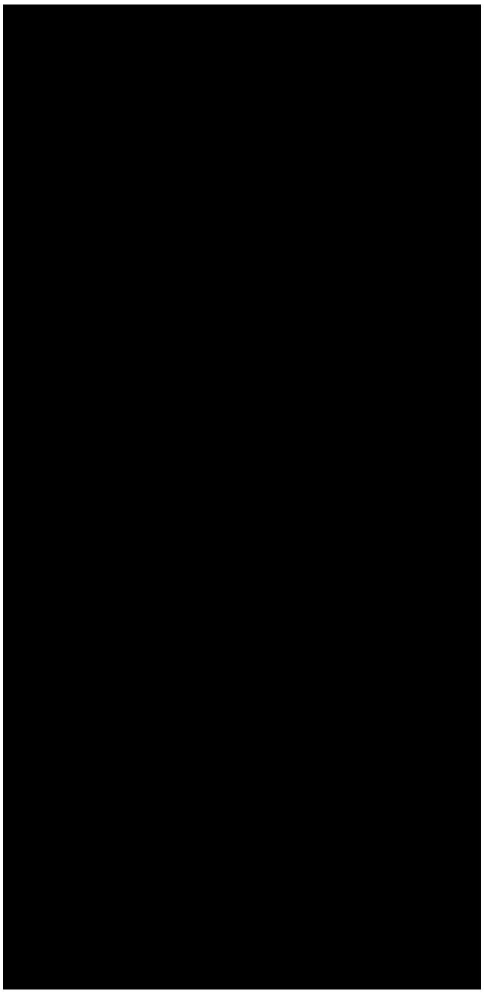

Figure 17. Diagram of a rising stage sampler. Sampling is initiated when the water level rises above the highest point of the intake tube. Source: Wilde et al., 2014 [56].

The RS sampler can be installed at different vertical and horizontal locations in a channel to measure vertical and horizontal suspended sediment particle size and concentration. They are commonly used in remote aquatic environments due to their durability and low cost [2]. However, the RS sampler has several limitations, including: 1) there is no guarantee that the siphon rate will match the ambient flow rate, thus, the sample collected is not flow proportional; 2) samples can only be collected from systems where the water level changes and it can only collect samples on the rising stage of a flow event; 3) the sampler body can accumulate small amounts of water from condensation, which can bias the measured sediment concentrations; and 4) re-submergence of the sampler in deep waters (>5 m) above the sampler can cause sample contamination with subsequent flow events [53, 56, 63, 64]. Despite these limitations, evaluation of RS samplers in small streams dominated by fine sediment (<63 μm) demonstrated that it collects samples with suspended sediment concentrations and particle size distributions that agree to within 10% of manual iso-kinetic sampling [63, 65]. Similar evaluations in large rivers, however, have noted that suspended sediment concentration data collected using RS samplers can differ from manual sampling data by 10 – 20% [2, 63]. For example, RS samplers were used as a complimentary technique to estimate the fine sediment budget of a catchment in North Queensland, Australia, that drained into the Great Barrier Reef (Figure 18). The study showed how RS samplers corresponded well to manually collected samples and predicted suspended sediment concentrations based on turbidity measurements. However, there was evidence that some samplers may have sampled multiple events and thus were biased to high concentrations – this was likely due to the greater depths of subsequent flow events that resulted in the water pressure exceeding the ability of the airlock to prevent further water ingress, resulting in contamination of the original sample [64].

[redacted]

Figure 18. Suspended sediment rating curves for the East Normanby River in Northern Queensland, Australia. Source: Brooks et al., 2013 [64].

2.2.2.3. Time-integrated sampling

Sampling methods discussed thus far are only capable of collecting discrete samples. This limitation means that samples must be collected at a very high frequency to account for the dynamic nature of suspended sediment during flow events. However, high frequency monitoring using these approaches is often not feasible for safety, technical, or financial reasons and thus in its absence uncertainty is introduced. In contrast, time-integrated methods continuously sample the aquatic system and therefore account for the suspended sediment dynamics in the sample they collect. The most commonly used time-integrated sampling method for suspended sediment was developed by Phillips and co-workers in 2000 [66]. The Phillips sampler is a single-point, partial flow-proportional sampler that traps suspended sediment flowing through it by reducing the water velocity within the sampler body compared to ambient water velocities (Figure 19). Due to the reliance on the reduction of water velocity inside the Phillips sampler, it is not capable of isokinetic sampling [67].

[redacted]

Figure 19. Diagram of time-integrated suspended sampler designed by Phillips and co-workers (2000). Source: Phillips et al., 2000 [66].

The Phillips sampler collects a sample of suspended sediment representative of the deployment duration (e.g., a single flow event over one day or multiple flow events over a month). The low cost of the Phillips sampler makes it an effective sampling method for qualitative studies conducted over large spatial scales, such as sediment fingerprinting or tracing at the catchment scale [68-73]. For example, Phillips samplers were used to compare the seasonal variation of suspended sediment-associated lead concentrations throughout an urban catchment (Figure 20) [70].

[redacted]

Figure 20. Example of Phillips-sampler data used to compare seasonal suspended sediment-associated lead concentrations in an urban catchment. Source: Hutchinson et al., 2008 [70].

However, Phillips samplers are not suitable for the measurement of suspended sediment concentration because there is no way to determine how much water passes through the sampler [66]. Furthermore, evaluation studies of the Phillips sampler note that not all of the sediment sampled is retained under high flow conditions, thus biasing the mass and particle size distribution of the sediment sampled [67, 74, 75]. For example, an evaluation study of the Phillips sampler using kaolinite clay and natural river sediment showed the sampler would oversample coarser fractions of very fine kaolinite (d_{50} = 6.8 µm) and under-sample the fine sediment fraction of river sediment (d_{50} = 99.5 µm) (Figure 21). Also, the flow dependent design of the sampler means turbulent water flows can affect its sampling ability [74, 75].

[redacted]

Figure 21. Comparison of suspended Kaolinte (Kao.) and River (Riv.) suspended sediment median particles size of samples collected using isokinetic (white bars) and Phillips samplers (black bars). Error bars represent ±1% standard error. Source: Smith and Owens 2014 [75].

2.2.2.4. Surrogate suspended sediment measurements

Surrogate measurements describe the indirect measurement of suspended sediment concentration through either turbidity (i.e., the loss of water transparency) or other light refraction parameters (Figure 22). Some techniques are also capable of estimating particle size distribution *in situ*.

[redacted]

Figure 22. Examples of a turbidity logger (left) and laser scattering logger (right). Source: Charlesworth et al., 2010 [76].

Numerous studies have evaluated the effectiveness of surrogate measurements in different waterways (e.g., oceans, rivers, streams, and wetlands) and found the approach to work well in combination with the physical collection of samples [4, 26, 77-79]. This is required to establish a predictive relationship between the surrogate measurement and actual measurements of suspended sediment concentration or particle size distribution. Systems that have relatively consistent suspended sediment concentrations and particle size distributions are the most suitable for this approach (Figure 23). The USGS, for example, uses turbidity sensors to supplement physical sample collection for the estimation of suspended sediment in several North American rivers [78].

[redacted]

Figure 23. Comparison of isokinetic sample suspended sediment concentration and estimated suspended sediment concentration using streamflow and turbidity (A) of the James River at Cartersville, Virginia, USA. Estimated values were calibrated using the linear relationship between isokinetic sample suspended sediment concentration and turbidity measurements (B). Source: Gray and Gartner 2009 [78].

However, measurement bias can occur when suspended sediment characteristics change (e.g., particle size or source) and physical samples are not collected to account for them. The direct measurement of suspended sediment concentration and particle size using more complex laser or ultrasonic resonance technology has also been proven to work well in rivers and streams. However, these instruments are susceptible to instrument sensor saturation during periods of high suspended sediment concentration (e.g., 2-5 g L^{-1} SSC) (Table 2), which may limit their application in certain systems.

Table 2. Summary of attributes for turbidity and laser surrogate measurement technologies. Source: Gray and Gartner 2009 [78].

Attribute	*Turbidity logger*	*Laser refraction logger*
Price (AUD)	\$5,000	\$50,000
Concentration range	0-2 g L^{-1} (higher concentration ranges can be attained with custom models)	0-10 g L^{-1} (particle size dependent)
PSD measurement range	Does not measure PSD	0.0025 - 0.5 mm or 0.00125 - 0.25 mm
Reliability and robustness	Scratching/fouling of optics can result in lower accuracy. Sensor may saturate at high concentrations.	
Region of measurement	Fixed point	
Accuracy as SSC surrogate	When used in moderately consistent PSD. Operates well when SSC is in range.	

Surrogate techniques have a high purchase cost (\$5,000 to \$ 50,000 AUD), which limits their application in remote environments and across large spatial scales. Furthermore, they provide no information on important parameters associated with suspended sediments (e.g., suspended sediment-associated contaminants or nutrients) [4, 56], which reduces their utility in cases where this information is an objective of sampling. Overall, surrogate techniques are most suitable as a complementary method to the collection of actual samples.

2.3 Suspended sediment monitoring in remote gully environments

2.3.1. Introduction to gully erosion

Gullies form where overland flows (i.e., runoff), concentrated by gradients in the land surface, reach a velocity where the vegetative cover (if present) and soil become incised and begin to erode. These incisions then coalesce and form an incipient channel. Further erosion then focuses at the head of the initial incision, where steep sloped (nearly vertical) scarps develop. Supercritical flows begin to occur at the base of the scarp causing a deepening of the channel and the undermining of the headwall, which eventually leads to mass failure (i.e., collapse and retreat of the scarp upslope). Sediment is made available by erosion and weathering of the gully banks and bank collapse and by erosion of the channel (Figure 24) [3]. If surface erosion processes are slow moving or the soil has stronger cohesive properties rills will form rather than gullies. Rills are small eroded channels (< 30 cm wide) that often occur in agricultural lands and can be rectified by low intensity earthworks (i.e., tilling). Gullies, however, are larger channels that cannot be restored by such methods [3, 81, 82].

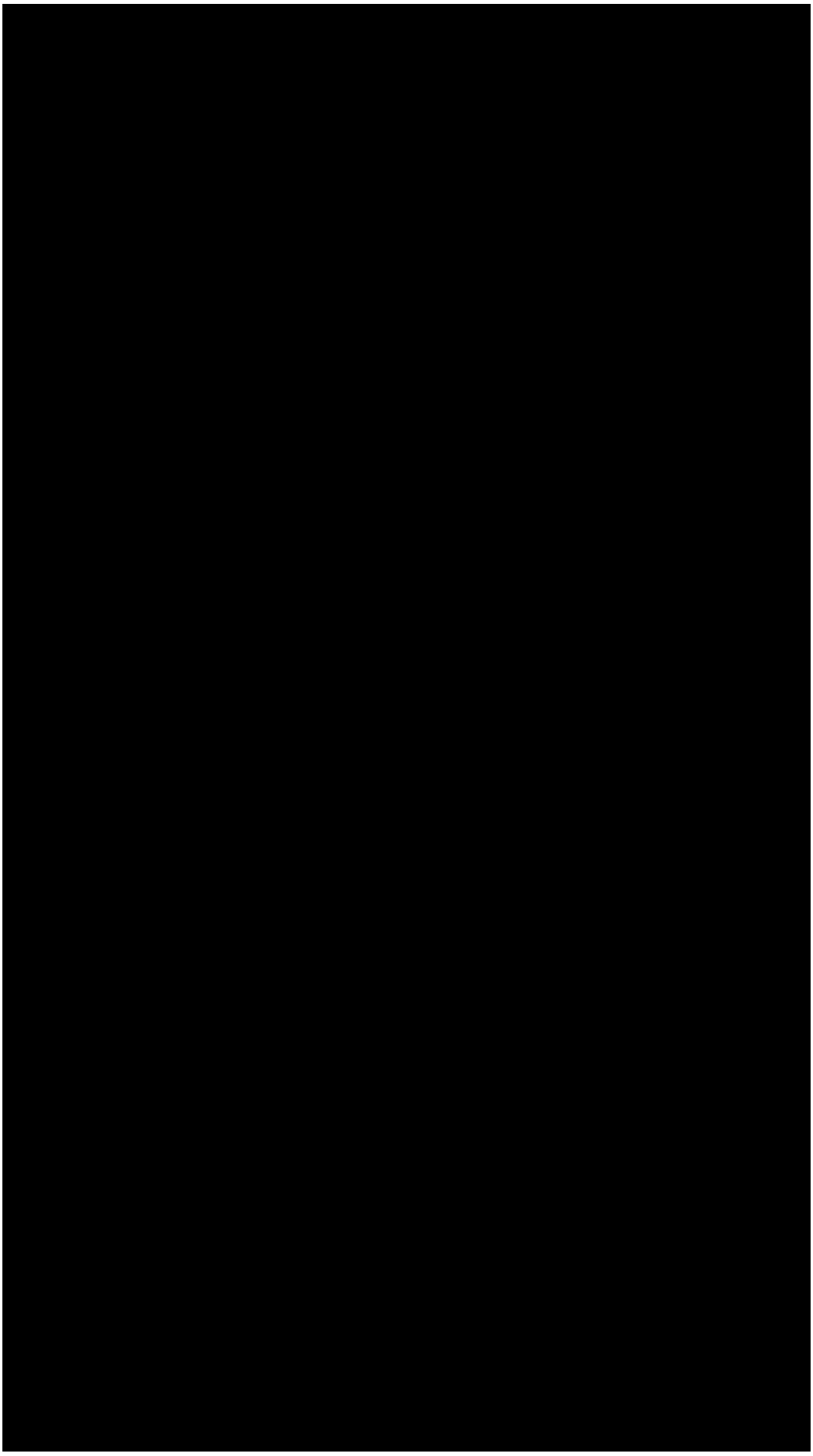

Figure 24. Stages in the formation of a hillside gully. Source: Leopold 1964 [80].

Gullies can vary in shape and size from small and sometimes transient trenches formed in recently tilled farmland (i.e., ephemeral gullies) to the much larger types formed on hillslopes and alluvial floodplains (i.e., permanent gullies) (Figure 25). Gully erosion is a global problem that occurs in every climate region except polar environments [81-84].

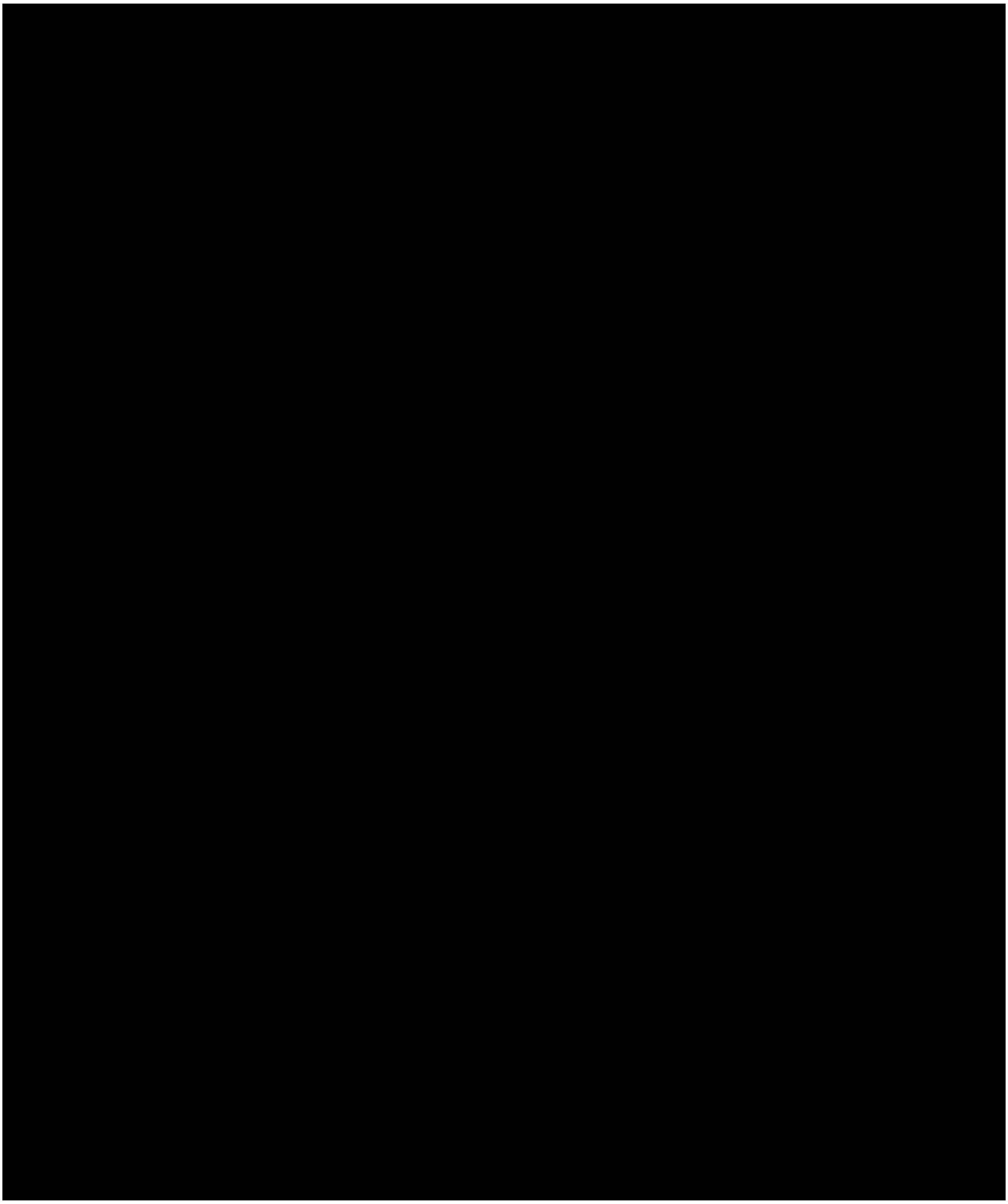

Figure 25. Ephemeral (top) and permanent (bottom) gullies. Source: Di Stefano et al., 2013 [84] and Shellberg and Brooks 2012 [85].

From a hydrological view point, gullies are ephemeral waterways that are created and maintained by intense periods of rainfall [82]. Gully erosion is a natural process and usually occurs in landscapes with limited vegetative cover and poor soil properties (e.g., sodic soils with little cohesion). It is widely accepted that unsustainable land use practices (e.g., intensive land clearing, agricultural practices using introduced species, and poorly planned infrastructure) have greatly increased the formation of gullies and rates of gully erosion. For example, a review of the last century of gully research found that the dominant driver of gully erosion severity was from human land uses (Figure 26) [81-83, 86, 87]. Once a gully system of considerable size (e.g., a permanent alluvial gully) forms it is often the dominant source of soil loss and sediment production [81]. For example, increased gully erosion in the catchments draining into the Great Barrier Reef is so significant that it is now considered to be the single biggest contributor to suspended sediment pollution affecting the water quality of the GBR [88].

Figure 26. Summary of long term (> 15 year) gully erosion studies over the last century. Increasing levels of gully erosion severity are shown in darker shading. Symbols indicate the driver for change in gully erosion severity. Source: Castillo 2016 [82].

2.3.2. Challenges of monitoring gullies

Permanent gully erosion often spreads through a landscape forming a network of actively eroding head scarps (the major points of gully erosion) connected by channels. These gully networks can either flow into a shared channel or drain directly into a stream or river. Permanent gullies also form quite steep and sometimes unstable channel banks, which increases the risk of hazardous access and egress from these systems (Figure 27) [80, 89, 90].

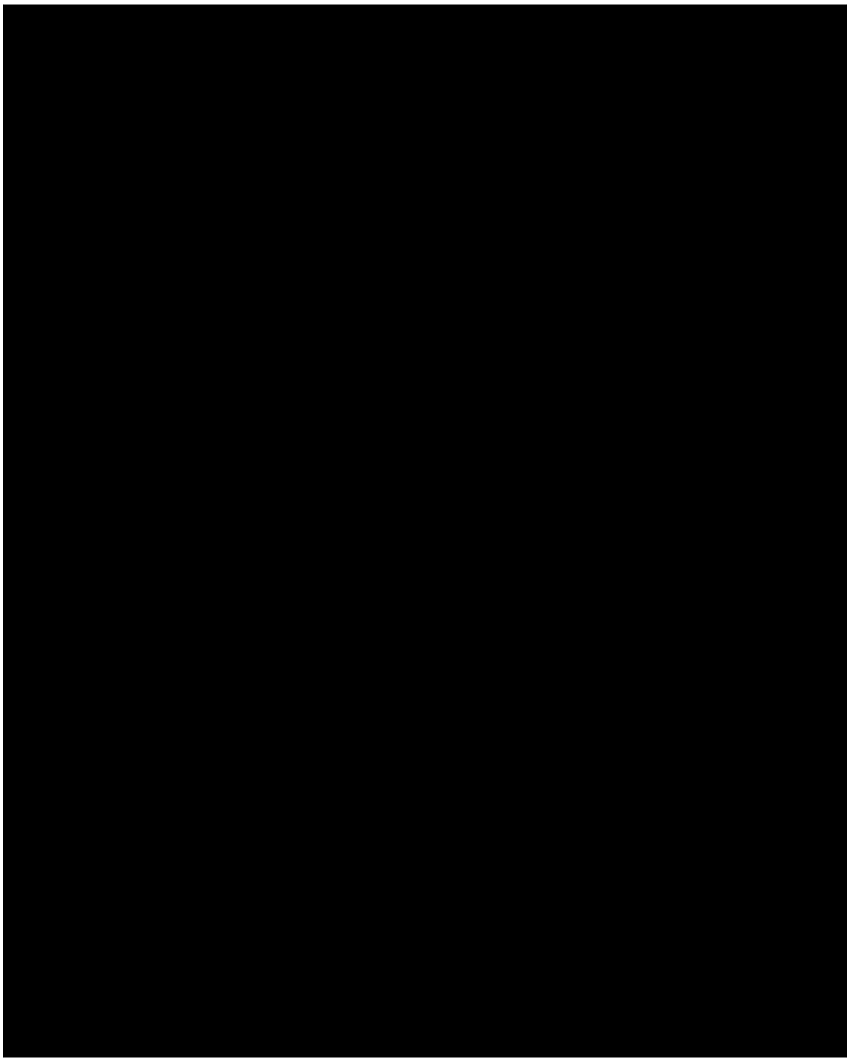

Figure 27. Example of the steep walls often formed in permanent gullies. These structures increase the risk of unsafe access and egress during flow events, which occur during periods of intense rainfall. For reference, the gully sidewall in this picture is >2 m in height. Source: Shellberg and Brooks 2012 [85]

A comprehensive review of gully research published between 1900 and 2016, identified grazing and other forms or agriculture as the land uses most associated with gully erosion (40.5% and 43.2% respectively) with the remaining land uses being forested and other undeveloped lands (13.2%) and urban sprawl (3.1%) [82].This means the majority of eroding gullies (~83.7%) are located in rural areas where access is likely to be difficult, particularly during intense rainfall events.

There is a wealth of gully erosion data developed from remote sensing technologies and temporal observations of gully expansion [82, 91-93]. However, there is a distinct lack of hydrological information from sites of gully erosion [94]. This is because the collection of representative suspended sediment data from gully systems is challenging under the best conditions [94]. The often-complex arrangement of gully networks, un-safe conditions when under flow, often remote location, and dependency on high intensity rainfall to initiate flow events makes these systems extremely challenging to monitor using currently available manual and automated suspended sediment measurement methods. For example, a study designed to use manual sampling and an array of automated monitoring methods (telemeted gauging, turbidity logging, RS samplers, and autosampling) to estimate the suspended sediment load from a remote gully in the dry-tropical region of northern Australia sampled <30 samples during the four measurable flow events (Figure 28) [95]. This demonstrates the level of investment both technically and financially that is required to capture these short lived and highly unpredictable events.

Figure 28. An example of the limited opportunities to collected suspended sediment samples from a flowing gully. Only four flow events were high enough (>125 mm depth) to be measurable over a 6-month period. Source: Bartley et al., 2017[96].

2.3.3. Existing monitoring approaches

Manual sampling of suspended sediment from gullies is often infeasible due to challenging logistics, hazardous conditions, and remoteness. Furthermore, the often-networked configuration of eroding gullies across a landscape means it is impossible to collect manual samples from each eroding gully or even a gully system using these manual techniques (Figure 29). To address this issue, gullies are often monitored using automated suspended sediment monitoring methods, which from a logistical and financial perspective result in the same limitations as using manual sampling (i.e., limited spatial coverage). As a result, often only the end of gully network outlets are monitored, which results in reduced spatial resolution of suspended sediment dynamics across the gully network [20, 96, 97].

Figure 29. Examples of the different gully networks that can form in a landscape. Note, the multiple outlets for each individual gully. Source: Shellberg and Brooks 2012 [85]

Remote sensing technologies (e.g., light detection and ranging) are used to fill the gaps in the current suspended sediment monitoring data. Remote sensing is commonly conducted using aerial and terrestrial surveys to estimate soil loss over long time scales (e.g., yearly or decadal).

However, considerable error can be introduced when these technologies are used to estimate the loss of specific fractions of the soil (e.g., fine sediment < 63μm). The error is dependent on the assumptions that are made, including: a reliable relationship between physically collected soil samples and remote sensing data; no change to the particle size distribution during suspension in water; and the resolution of the remote sensing data being sufficient to accurately estimate soil loss [91, 92, 98]. Furthermore, remote sensing technologies cannot provide information on the dynamics of suspended sediment transport, the distance suspended sediment fractions are likely to travel downstream, or the concentrations of associated contaminants and nutrients associated with the eroded gully soil. This information is critical to understanding the effect of gully erosion on downstream aquatic environments, thus necessitating the application of suspended sediment monitoring techniques to collect physical samples [4].

2.3.4. Case Study: Great Barrier Reef catchment, Australia

The GBR is the receiving environment for 35 river basins with a combined discharge of 29 cubic km of water, annually [99, 100]. The health of the Great Barrier Reef ecosystem is degrading due to increased bleaching events, ocean acidification, and deteriorating water quality conditions [101]. From an environmental management perspective, the improvement of water quality is a priority because it can be addressed by relatively local efforts (in contrast to climate change, for example) and can improve the resilience of the reef ecosystem to other stressors. The flow of suspended sediment and dissolved and particulate (i.e., suspended sediment-associated) nutrients from the land to the ocean determines the water quality conditions in the GBR. Fine sediment pollution has a widespread impact within the GBR, as demonstrated by the large plumes of suspended sediment that are frequently observed by remote sensing observations (Figure 30) [102].

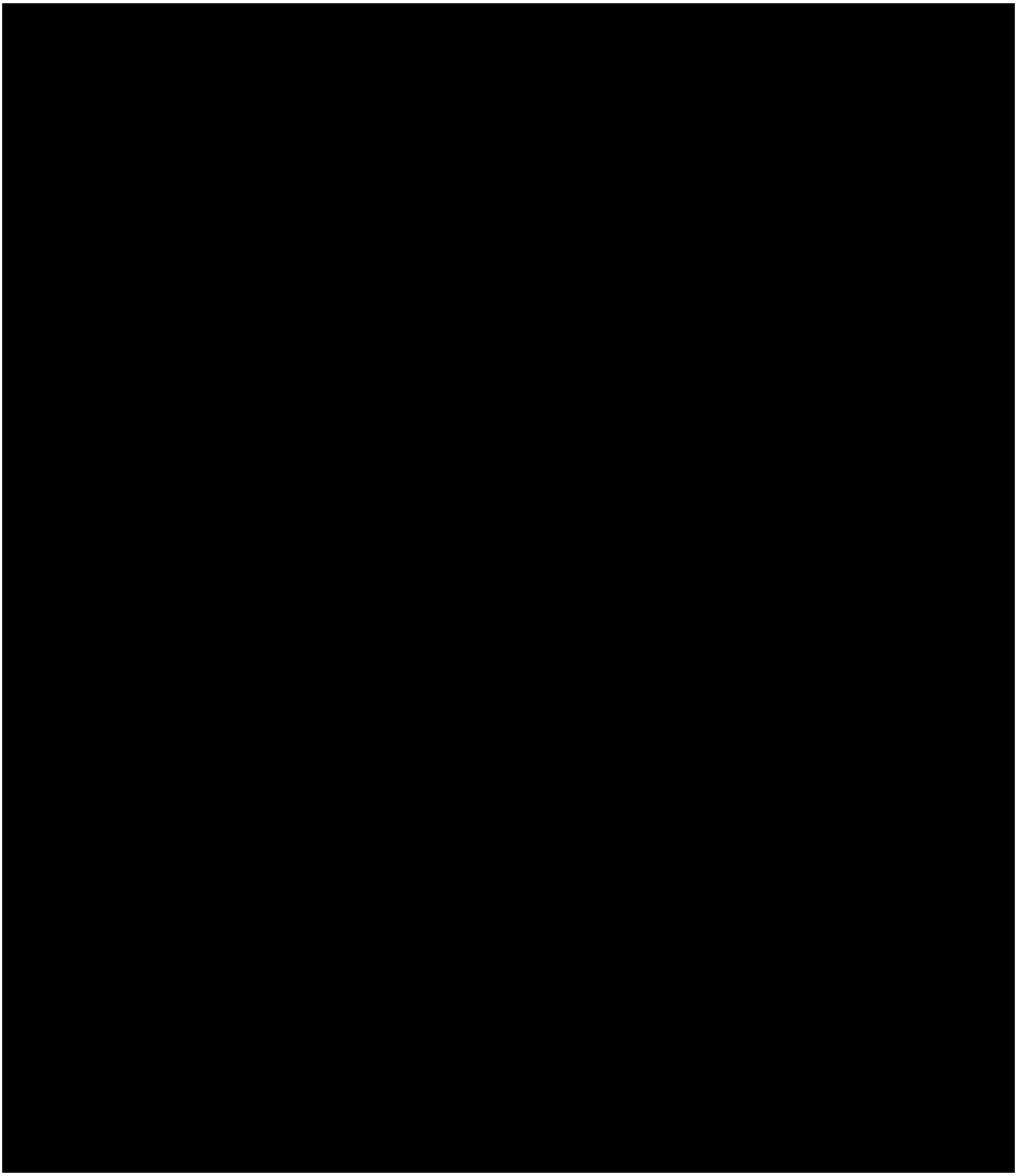

Figure 30. Extent of annual total suspended solids averages (TSS) (i.e, fine sediment and organic matter) throughout the GBR (total area of 344, 400 km^2) from 2004 to 2017. Note the large plumes of TSS exported from the catchments to the coastal zone. Source: Waterhouse et al., 2018 [102].

Catchment modelling done in 2016 estimated that ~9.9 million tonnes yr^{-1} of fine sediment (<63 μm) is discharged into the GBR, of which 80% is estimated to originate from erosion sources caused by anthropogenic land use change (e.g., agriculture (particularly grazing) and, infrastructure) initiated during European settlement in the region in the mid to late 1800s [40, 99, 102, 103, 104]. Gully and stream bank erosion is the single largest source of suspended sediment exported from catchments into the GBR (~4 million tonnes yr^{-1}) [105]. This increase in fine suspended sediment and associated nutrients has resulted in coral smothering, reduction in light penetration, impairment of coral and fish resilient to disease, and the bloom of harmful macro algae and generalist predatory species populations (e.g., the crown-of-thorns starfish, *Acanthaster planci*, a predator that feeds on coral) [35, 48-50, 106, 107].

The Australian Federal and State governments are currently targeting a 50% reduction in sediment pollution to the Great Barrier Reef, from priority catchments, by 2025 [108]. This target will only be met if we fully understand the erosion processes and subsequent suspended sediment dynamics of the largest sediment contributors – actively eroding gully systems. The Australian Federal and State Governments have between 50 to 100 automated water quality stations deployed at end of catchment locations across the catchments draining into the GBR (total area of 423,000 km^2) [102]. Whilst the current monitoring network covers the major fluvial outlets it is inadequate for the empirical assessment of suspended sediment pollution sources and trends across the region. For example, it is estimated there are approximately 87,000 km (linear length) of gullies and small ephemeral channels in the GBR catchment region and only a handful (<0.1%) are actively monitored for suspended sediment [109]. The identification of suspended sediment sources and their contribution to fluvial sediment loads will play an important role in reaching the target of reducing suspended sediment pollution to the GBR by 50% before 2025 (Figure 31).

[redacted]

Figure 31. Example of potential hillslope and river channel suspended sediment sources. The current extent of permanent monitoring efforts in the GBR catchments is equivalent to monitoring the river channel suspended sediment load in this framework (River channel suspended sediment load). Source: Collins and Walling 2004 [110].

The current water quality monitoring approaches used in the catchments of the GBR are effective at measuring overall sediment loads from the catchments and identifying sediment sources on a broad scale. However, this is not sufficient to allow the targeting of gully rehabilitation efforts to those areas where they will achieve the greatest reductions in suspended sediment export – this requires high-resolution spatial data at the sub-catchment scale. New low-cost automated suspended sediment monitoring methods, which can be deployed at high spatial resolution within catchments, are needed to address this current limitation in monitoring capability.

2.4 Objectives

This research aims to further our understanding of suspended sediment dynamics in remote aquatic systems through the development and evaluation of new and existing automated monitoring approaches. Meeting this aim will address an important gap in knowledge and measurement capability that is currently hindering the ability of environmental managers to identify and monitor suspended sediment sources at the sub-catchment scale. A combination of laboratory and field evaluations will be applied to evaluate the selected methods. Specifically, I aim to:

1. Develop and evaluate an automated and affordable time-integrated suspended sediment sampler suitable for use at high spatial resolution.
2. Evaluate the capabilities of this new sampler with existing suspended sediment monitoring approaches for remote gully systems with highly erratic flow regimes and harsh climatic conditions.
3. Apply the evaluated suspended sediment monitoring approaches to investigate the effect of landscape-scale gully remediation on water quality in a Great Barrier Reef catchment.

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3 Evaluation of a simple, inexpensive, in situ sampler for measuring time-weighted average concentrations of suspended sediment in rivers and streams

Hydrological Processes, 2019, 33, 678-686

This chapter consists of a co-authored published paper. The bibliographic details of the co-authored published paper, including all authors, are:

Nicholas J.C. Doriean, Peter R. Teasdale, David T. Welsh, Andrew P. Brooks, and William W. Bennett. (2019). Evaluation of a simple, inexpensive, in situ sampler for measuring time-weighted average concentrations of suspended sediment in rivers and streams. Hydrological processes, 2019, 33(5), 678-686

https://doi.org/10.1002/hyp.13353

My contribution to the published paper involved:

Initial concept and experimental design.

Collection and analysis of data.

Preparation of manuscript.

[redacted]

Nicholas J. C. Doriean

[redacted]

Corresponding author of published paper: William W. Bennett

[redacted]

Supervisor: William W. Bennett

Received: 20 June 2018 | Accepted: 22 November 2018
DOI: 10.1002/hyp.13353

RESEARCH ARTICLE

WILEY

Evaluation of a simple, inexpensive, in situ sampler for measuring time-weighted average concentrations of suspended sediment in rivers and streams

Nicholas J.C. Dorien[1] | Peter R. Teasdale[2,3] | David T. Welsh[1] | Andrew P. Brooks[4] | William W. Bennett[1]

[1] Environmental Futures Research Institute, School of Environment and Science, Griffith University, Southport, Queensland, Australia

[2] Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, Adelaide, South Australia, Australia

[3] Future Industries Institute, University of South Australia, Adelaide, South Australia, Australia

[4] Griffith Centre for Coastal Management, Griffith University, Southport, Queensland, Australia

Correspondence
William W. Bennett, Environmental Futures Research Institute, School of Environment and Science, Griffith University, Southport, Queensland 4215, Australia.
Email: w.bennett@griffith.edu.au

Abstract

The accurate measurement of suspended sediment (<200 μm) in aquatic environments is essential to understand and effectively manage changes to sediment, nutrient, and contaminant concentrations on both temporal and spatial scales. Commonly used sampling techniques for suspended sediment either lack the ability to accurately measure sediment concentration (e.g., passive sediment samplers) or are too expensive to deploy in sufficient number to provide landscape-scale information (e.g., automated discrete samplers). Here, we evaluate a time-integrated suspended sediment sampling technique, the pumped active suspended sediment (PASS) sampler, which collects a sample that can be used for the accurate measurement of time-weighted average (TWA) suspended sediment concentration and sediment particle size distribution. The sampler was evaluated against an established passive time-integrated suspended sediment sampling technique (i.e., Phillips sampler) and the standard discrete sampling method (i.e., manual discrete sampling). The PASS sampler collected a sample representative of TWA suspended sediment concentration and particle size distribution of a control sediment under laboratory conditions. Field application of the PASS sampler showed that it collected a representative TWA suspended sediment concentration and particle size distribution during high flow events in an urban stream. The particle size distribution of sediment collected by the PASS and Phillips samplers were comparable and the TWA suspended sediment concentration of the samples collected using the PASS and discrete sampling techniques agreed well, differing by only 4% and 6% for two different high flow events. We should note that the current configuration of the PASS sampler does not provide a flow-weighted measurement and, therefore, is not suitable for the determination of sediment loads. The PASS sampler is a simple, inexpensive, and robust in situ sampling technique for the accurate measurement of TWA suspended sediment concentration and particle size distribution.

KEYWORDS

in situ, particle size, suspended sediment concentration, suspended sediment sampler

1 | INTRODUCTION

Suspended sediment (typically <200 µm), and particularly fine suspended sediment (<63 µm), can cause negative impacts to aquatic environments by affecting two primary ecosystem functions. First, elevated concentrations of suspended sediment contribute to increased turbidity that decreases light transmission through the water column (Newcombe & Jensen, 1996). Low-light conditions decrease the productivity and influence the composition of primary producer communities, potentially altering ecosystem structures (Fabricius & De'ath, 2001; D. E. Walling & Collins, 2016). For example, disrupted light conditions, from excess fluvial suspended sediment, is causing extensive damage to seagrass ecosystems, on a global scale (Orth et al., 2006; Waycott et al., 2009). Similarly, increased ambient sediment concentrations in coral reefs (including Australia's Great Barrier Reef) associated with anthropogenic influences is a contributing cause of declining coral health due to reduced light penetration and direct smothering of coral (Bartley et al., 2017; Brodie et al., 2012).

Second, suspended sediment acts as a transport vector for nutrients and a wide range of contaminants (Horowitz, Clarke, & Merten, 2015). This transport process occurs because the chemically reactive surfaces of fine sediment particles readily adsorb chemical compounds, (e.g., nutrients, metals, and pesticides), thus concentrating and transporting them downstream (Horowitz, Stephens, Elrick, & Smith, 2012; D. E. Walling & Collins, 2016). In the United States, suspended sediment is either primarily, or exclusively, linked to up to 65% of the 126 priority pollutants listed and is considered to be the second highest cause of river and stream impairment, nationally (US-EPA, 1982, 2016). The impacts of suspended sediment-associated nutrients and contaminants are best mitigated through effective catchment management, which is evaluated and refined using spatially and temporally representative suspended sediment monitoring data (Horowitz et al., 2012).

The most common approach to measuring suspended sediment is to collect discrete water samples on a regular but infrequent basis (e.g., monthly) using manual or automated sampling methods. This is insufficient to provide a representative measure of suspended sediment concentration trends in dynamic systems, where changes in sediment concentration occur in unpredictable ways or where traditional sampling methods are impractical (e.g., high flow events, such as, intense rain storms and major floods; Horowitz, 2008; D. E. Walling & Collins, 2016). Monitoring regimes that rely on manual discrete sampling by workers, particularly in remote areas, cannot capture all of the high flow events that may occur (due to logistical or health and safety requirements) and will typically generate data biased to lower flow periods with lower suspended sediment concentrations (Horowitz et al., 2015; M. Perks et al., 2017). This can lead to inaccurate assessments of suspended sediment transport mechanisms and the potential risks of sediment-associated pollutants (Evans, Gibson, & Rossell, 2006).

Alternative monitoring techniques, such as on-site automated discrete sampling, can overcome these issues by sampling frequently over a storm hydrograph. However, the high cost of installation, maintenance, and analysis associated with this approach means they can usually only be deployed, in minimal numbers, at high priority sites (e.g., receiving waters with high ecological value; Jordan, Cassidy, Macintosh, & Arnscheidt, 2013; D. E. Walling & Collins, 2016). For example, in the 423,000 km^2 of catchments draining into the Great Barrier Reef World Heritage Area, which are the focus of a major water quality management programme by the Australian and Queensland Governments, only 43 automated sampling stations are in operation across the entire area (Wallace et al., 2016). In an attempt to overcome these limitations, various studies have used in situ turbidity data loggers to measure turbidity at high temporal resolution as a surrogate for suspended sediment concentration (Cassidy & Jordan, 2011; Conn et al., 2016; Dekker & Hestir, 2012; Evans et al., 2006; M. Perks et al., 2017; Rasmussen, Gray, Glysson, & Ziegler, 2009). This form of monitoring is more cost-effective than on-site sampling and can be deployed at multiple sites within a catchment. However, the data must be calibrated using manually collected samples and turbidity measurements provide no information on the chemical composition or particle size distribution of the sediment.

Passive, time-integrated, in situ sampling techniques, such as that developed by Phillips and coworkers (Phillips, Russell, & Walling, 2000; Phillips sampler), are more representative than infrequent discrete sampling (i.e., they collect sample continuously over the deployment period) and are more affordable than on-site automated discrete samplers and turbidity data loggers (D. E. Walling & Collins, 2016). However, they are primarily designed for qualitative sampling purposes, such as suspended sediment source fingerprinting, rather than for determining suspended sediment concentrations (Phillips et al., 2000; Smith & Owens, 2014). This is because the total volume of sampled water is unknown and the flow-dependent design of the Phillips sampler can result in preferential retention of coarser sediments at higher flow rates (approximately >0.5 m s^{-1}). This also creates bias when assessing sediment-associated contaminants, because the more reactive, fine particles can be underrepresented in the collected sample (Perks, Warburton, & Bracken, 2014; Phillips et al., 2000; Smith & Owens, 2014).

An alternative approach to the Phillips sampler is to continuously sample water at a defined flow rate (e.g., using a pump), which allows the total volume sampled to be controlled and facilitates genuine time-weighted average (TWA) measurements. This approach was first developed by Nunny (1985), although this specific sampler (NBT-82, which used a vertically oriented settling column) is no longer readily available. The NBT-82 has been used by researchers and referred to in published studies (Maddrell, 1996; Wilkinson & Wainwright, 1983; Williams, 1988) but to our knowledge has not undergone comprehensive evaluation in the peer-reviewed literature. In contrast, the Phillips sampler has been widely used and is the subject of several published evaluations (Perks et al., 2014; Russell, Walling, & Hodgkinson, 2000; Smith & Owens, 2014).

In this study, we present a detailed evaluation of a new version of the NBT-82 sampler type, the pumped active suspended sediment (PASS) sampler. The PASS sampler has the potential to address many limitations of commonly used methods to measure suspended sediment concentrations and, owing to its affordability, ease-of-construction and robustness, can be deployed at high resolution on the catchment scale. In this study, we have evaluated the PASS sampler, in both laboratory and field settings, to characterize its performance compared with other commonly used suspended sediment sampling techniques.

2 | METHODS

2.1 | PASS sampler design and operation

The main body of the PASS sampler is made from schedule 40 polyvinyl chloride (PVC) pipe (450 mm long, 100 mm internal diameter [ID]) with a volume of approximately 4 L (Figure 1). The PVC pipe is closed at each end with threaded PVC caps fitted with rubber O-ring seals. Teflon tape is applied to the threaded ends to ensure the sampler is watertight. The inlet of the sampler is a brass-threaded barb (2.5 mm ID; 35 mm length) located halfway along the longitudinal section of the sampler. A polyvinyl tube (4 mm ID; 200 mm long) runs from the sample inlet to the bottom of the sampler. The polyvinyl tube ensures that sediment collected at the inlet is deposited at the bottom of the sampler, furthest away from the outlet. The outlet, a brass fitting identical to the inlet, is threaded into the PVC cap at the top of the sampler. The inlet and outlet configuration can be altered to ensure the sampler inlet is at an optimal height for sampling. If necessary, the components of the sampler can be made of inert materials if the sediment collected by the sampler is going to be used for chemical analysis (e.g., for use in trace-element analysis polypropylene threaded barbs could be used instead of brass). The outlet is

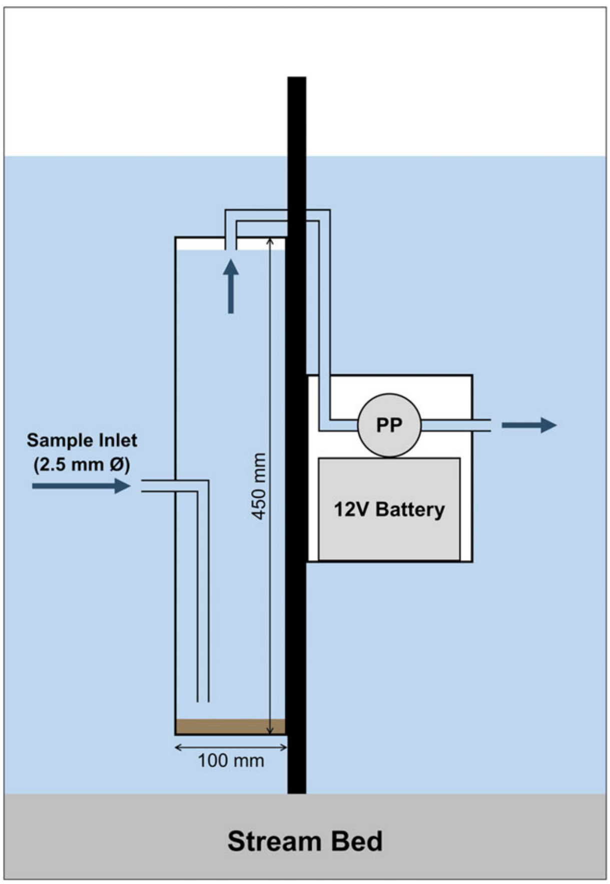

FIGURE 1 Schematic diagram of the PASS sampler. PP: peristaltic pump

connected, with 4 mm ID polypropylene tubing, to a Verderflex® M025 peristaltic pump, equipped with a 1.6 mm ID Teflon coated silicone pump tube assembly, and powered by a 12 V sealed lead-acid battery. The pump and battery are housed within a waterproof case that is submerged alongside the sampler, thus resulting in zero head from the inlet to the pump (although head of up to 9 m can be tolerated by the peristaltic pump tested). The pump can operate at different flow rates depending on the peristaltic pump tube diameter and supplied voltage. Please refer to the pump datasheet, supplied as Data S1, for additional pump specifications. The consistency of the pump flow-rate was tested several times during laboratory (flow rate was measured frequently during tests) and field testing (flow rate was measured daily during field deployments, using tubing attached to the output of the pump). Field testing of pump flow rates found them to vary by up to 5%, although this was only observed during long deployments (e.g., >1 week). An alternative to the peristaltic pump is the flap-valve pump, used by the NBT-82 (Nunny, 1985); however, this was not evaluated in this study.

Water from the sample site is used to fill the device before submerging it at the desired depth. For example, in a small stream, the PASS sampler can be secured to a post embedded in the streambed with the inlet facing cross flow at approximately 60% of the mean water depth. This is done to ensure the best possible location to compare the different sampling techniques. The location of the sampler inlet in other systems is dependent on what the operator wants to monitor. For example, the inlet can be lowered to accommodate streams with lower ambient levels than those used in this study. Also note that the main body of the sampler can be only partially immersed provided that the inlet is submerged and the sampler is full of water prior to sampling.

Similar to the Phillips sampler, the PASS sampler relies on the reduction of flow velocity when water enters the main body of the sampler to induce sedimentation of suspended solids within the sampler (Phillips et al., 2000). The key difference between the PASS and Phillips samplers is that the flow rate in the PASS sampler is controlled by a pump rather than relying on ambient flow. The controlled flow of the PASS sampler negates issues associated with flow-dependent suspended sediment sampling and allows for the measurement of the volume of water sampled, which can be used to estimate a representative TWA suspended sediment concentration.

2.2 | Laboratory testing of the PASS sampler

Channel-bed sediment, collected from Loders Creek in Queensland, Australia (Section 3.1), was used for all laboratory studies (Sections 2.2 and 2.3) and is hereafter referred to as the source sediment. Prior to being used for laboratory testing, the source sediment was wet sieved to less than 63 μm, treated with 30% hydrogen peroxide (Chem Supply® AR grade) at approximately 70 °C until all organic material was removed, and then shaken for 24 hr in a dispersant solution (0.4% m/v sodium hexametaphosphate, Analytical Reagent Grade, Sigma Aldrich). The source sediment was pretreated to reduce heterogeneity. This was done to minimize the potential bias associated with different sediment characteristics when using the source sediment for replicated evaluation and comparison tests. Please note that untreated sediment would likely settle faster, due to flocculation of smaller particles with organic detritus (Droppo & Ongley, 1992). This would result in the PASS and Phillips samplers retaining a greater percentage of the sediment mass sampled; in this sense, our laboratory experiments represent a conservative estimate of the performance of the PASS and Phillips samplers.

Sediment retention efficiency of the PASS sampler design was assessed by evaluating sediment mass retention under two different flow rates, 27 and 4 ml min^{-1}, determined by different pump tubing ID. This was achieved by sampling 4 L (the equivalent volume of the sampler capacity) of well-stirred suspended sediment in solution, with a known concentration of source sediment (1,000 mg L^{-1} in 0.001 mol L^{-1} NaCl). This concentration was used to minimize the potential error associated with collecting and comparing low sediment masses. It should also be noted that because sediment settling rate is a function of concentration the sampler may be less efficient at trapping sediment at low concentrations (Michaels & Bolger, 1962). Once the source sediment was completely sampled, it was immediately followed by sampling 4 L of sediment-free 0.001 mol L^{-1} NaCl solution, to ensure a full exchange of water had occurred inside the sampler, and thus determine the potential for sediment loss from the sampler when sampling volumes exceed the sampler volume. A 0.001 mol L^{-1} sodium chloride (NaCl) solution was used, as a synthetic freshwater, to prefill the samplers before the tests commenced. Subsamples of the source sediment, sediment inside the sampler, and sediment expelled from the sampler were collected for suspended sediment concentration and particle size analysis, using a 1,000 L min^{-1} submersible pump to homogenize the sample prior to collecting a subsample. The suspended sediment concentration of the subsamples was measured via sample filtration and drying as per Method 2540D of the APHA standard methods (APHA, 1989). Particle size distributions were measured under mechanical and ultrasonic dispersion via laser diffraction using a Malvern Mastersizer 3000. Each of the flow-rate tests were conducted in triplicate. GraphPad-Prism® was used for statistical analysis of all sample data. Sample data were first evaluated for equality of group variances using Brown–Forsythe and Bartlett's tests before being analysed using a paired *t*-tests to assess differences between sample groups.

2.3 | Laboratory evaluation of the Phillips sampler

Sediment retention efficiency of the Phillips sampler was evaluated using the same method as that used to evaluate the PASS sampler, described in Section 2.2. A suspended sediment solution (8 L; the capacity of the Phillips sampler) with a known concentration (1,000 mg L^{-1}) was sampled, immediately followed by sampling water (8 L) containing no sediment, to ensure a full exchange of the water inside the sampler. Using the same testing method developed by Phillips et al. (2000), a pump was attached to the outlet of the Phillips sampler to draw water through the sampler, thus simulating water passing through the sampler as it would when deployed in a flowing stream. Two flow rates (27 and 242.1 ml min^{-1}) where used to simulate the low and high flow rates that a Phillips sampler would commonly encounter when deployed in a fluvial environment (equivalent to 0.3 and 0.6 m s^{-1}, respectively). These flow rates were used by Phillips et al. when they first developed the Phillips sampler (Phillips et al., 2000; Russell et al., 2000). The flow rates used to evaluate the Phillips differ from that used for the PASS sampler (4 and 27 ml min^{-1}) because the PASS sampler relies on the pump rather than stream flow to move water through the sampler. Subsamples of the source sediment, sediment inside the sampler, and sediment expelled from the sampler were collected and analysed for suspended sediment concentration and particle size distributions, using the previously described methods.

2.4 | Field evaluation of PASS and Phillip samplers

Loders Creek is a small, lowland, subtropical stream, and estuary located in the Gold Coast, Queensland, Australia. The stream begins as freshwater and transitions to estuarine before entering an intercoastal lagoon, known as the Broadwater (Waltham, 2002). The freshwater catchment spans approximately 10 km^2, where the majority of land use is light industrial and urban or residential (Waltham, 2002). Most of the freshwater reaches of Loders Creek have been heavily modified to mitigate potential flooding of the catchment area. This has resulted in reduced riparian vegetation as well as certain sections of the creek becoming seasonally ephemeral due to being transformed into storm water drains (Waltham, 2002). An area plan of Loders Creek and its surrounding catchment area is provided in Data S2.

Triplicate sets of the Phillips and PASS samplers were placed in the middle of the stream channel cross section with the sampler inlets set at an approximate depth of 60% of the ambient stream height. Phillips and PASS samplers were deployed prior to and for the duration of two intense storm events, resulting in deployment periods of approximately 14 and 53 hr, with rainfall totals of approximately 20 and 75 mm, respectively, in the Loders Creek catchment area (BOM, 2018). Each PASS sampler was set to sample at a flow rate of 4.2 ml min^{-1}. Discrete samples were collected regularly during base flow conditions prior to the storm and then collected frequently (i.e., every 1–3 hr) during high flow conditions. A YSI ProDSS multiparameter meter was used to measure physicochemical parameters (dissolved oxygen, oxidation reduction potential, pH, specific conductivity, turbidity, and temperature), and stream velocity was measured whenever a discrete sample was collected using a Flowatch® water velocity meter (JDC Electronics, Switzerland). A HOBO U20L level logger was also deployed to measure stream height, at 1-min intervals, for the duration of the deployment. Upon retrieval of the PASS and Phillips samplers, the contents of the samplers were emptied into 10-L plastic containers. The individual Phillips and PASS samples were homogenized using a 1,000 L min^{-1} submersible pump prior to the collection of subsamples for analysis of total suspended solids (TSS), via sample filtration and drying as per Method 2540D of the APHA standard methods (APHA, 1989). The remaining sample solutions were placed in cold storage (4 °C) for 5 days, to allow suspended solids to settle, after which the supernatant was removed, and the remaining sample was analysed for particle size distribution by laser diffraction (Malvern Mastersizer 3000).

3 | RESULTS AND DISCUSSION

3.1 | Laboratory evaluation of PASS sampler and comparison with the Phillips sampler

Approximately 79% (±6) and 91% (±2) of the sampled sediment mass was retained in the PASS sampler at the 27 and 4 ml min^{-1} flow rates, respectively. These results suggest the PASS sampler is retaining the majority of sediment sampled, even under the worst-case scenario of unnatural sediment dispersion conditions (organics removed and deflocculated). It is likely that the proportion of sediment retained by the PASS sampler would be greater with untreated natural sediment, because there would be an increased settling rate of finer particles (fine silts and clays) as they would agglomerate into flocs with organic matter (Droppo & Ongley, 1992). The retention of a representative sediment sample mass (a minimum of approximately 80% mass of the source sediment sampled, for concentrations representative of typical storm flows) for the two flow rates suggests the PASS sampler could be effectively applied in a variety of monitoring situations. For example, the higher flow rate (27 ml min^{-1}) could be used to ensure sufficient sample mass for multiple analyses is collected during a short sampling event (e.g., a few hours in an ephemeral stream), whereas the slower flow rate (4 ml min^{-1}) would allow for extended deployments over days or weeks, which could be useful for comparing the TWA suspended sediment concentration of multiple sites within a catchment.

The particle size distribution (the 10th, 50th, and 90th percentiles) of sediment retained in the PASS sampler at both flow rates was significantly different compared with the source solution ($p < 0.001$ for all three percentiles; Figure 2). However, the percent difference of the median particle size (d_{50}) of the source and PASS sampler sediment was notable for the 27 ml min^{-1} (30 ± 2%) and very small for the 4 ml min^{-1} (8 ± 0.5%). Table 1 compares the particle size distributions for the various samples collected at each flow rate.

At a flow rate of 27 ml min^{-1}, the PASS and Phillips samplers retained approximately 79 ± 6% and 85 ± 4% of sediment sampled, respectively. It is likely that the sediment retention of both methods would increase with natural sediment, especially as the treated sediment used in the laboratory test was highly dispersed very fine clay and silt (<35 µm; Phillips et al., 2000; Smith & Owens, 2014). The Phillips sampler retained slightly more source sediment at the 27 ml min^{-1} flow rate, than the PASS sampler did. This is because the Phillips sampler has more than double the volume of the PASS, and therefore, the particles have more time to settle in the main body of the Phillips sampler compared with the PASS sampler. The PASS sampler volume could be increased to improve sediment retention; however, the volume of the current PASS design was intentionally kept at a manageable size for field deployment. Sediment retention could also be improved by the addition of settling plates within the sampler main body or by applying a timer that controls the pump, thus limiting the sampling time to events and not during base flows (Nunny, 1985).

At 242.1 ml min^{-1}, which is the equivalent of ~0.6 m s^{-1} ambient stream velocity, the Phillips sampler retained approximately 50% of the sediment sampled. This agrees with previous studies that show the sampler displays poor sediment retention at elevated flows (>0.5 m s^{-1}; Perks et al., 2017; Perks et al., 2014; Phillips et al., 2000). This is also reflected in the significantly higher median particle size (d_{50}) of the higher flow rates tested using the Phillips sampler and the almost similar median particle size of the effluent leaving the Phillips sampler to the source sediment at the 242.1 ml min^{-1} flow rate. Table 1 compares the sediment mass retained and lost by the Phillips and PASS samplers, at different flow rates.

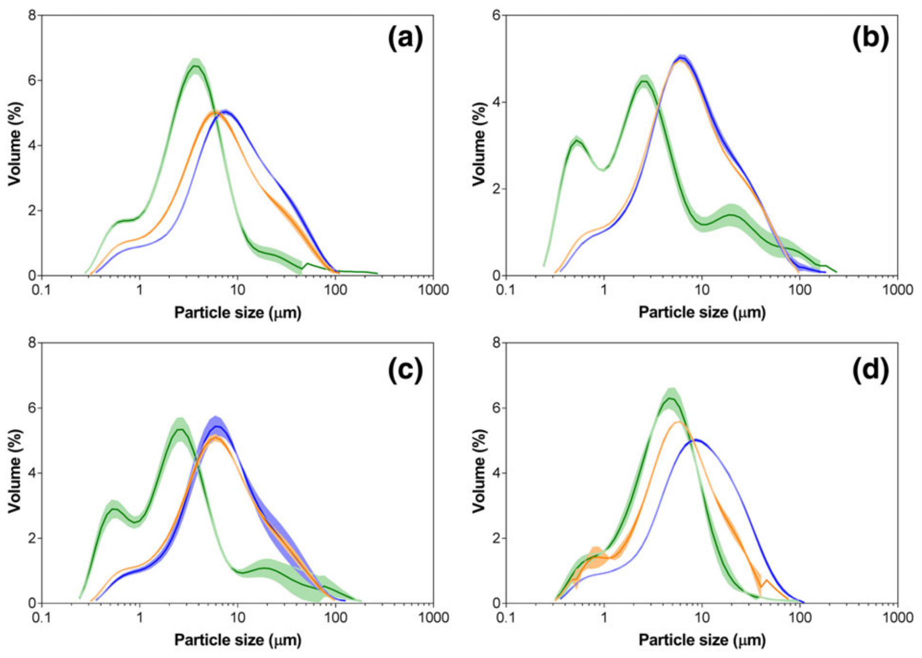

FIGURE 2 Comparison of particle size distribution for source sediment (orange line), sediment retained by sampler (blue line), and effluent sediment (green line) from laboratory tests of (a) PASS at 27 ml min^{-1}, (b) PASS at 4 ml min^{-1}, (c) Phillips at 27 ml min^{-1}, and (d) Phillips at 240.1 ml min^{-1}. Standard deviation is shown as shading around each distribution

TABLE 1 Sample mass retention and particle size distribution of sediment collected by the PASS and Phillips samplers compared with a source sediment

Sampler		PASS		Phillips	
Flow rate (ml min^{-1})		27	4	27	240
Sediment retained (%)		79 (±6)	91 (±2)	87 (±4)	52 (±1)
Source (µm)	d_{10}	1.47 (±0.03)	1.5 (±0.02)	1.45 (±0.02)	1.3 (±0.01)
	d_{50}	6.79 (±0.16)	6.98 (±0.07)	6.67 (±0.16)	5.81 (±0.01)
	d_{90}	30.30 (±1.86)	31.5 (±0.45)	28.8 (±1.55)	19.2 (±0.07)
Sampler (µm)	d_{10}	1.99 (±0.01)	1.74 (±0.03)	1.75 (±0.09)	1.87 (±0.02)
	d_{50}	8.99 (±0.11)	7.52 (±0.13)	7.19 (±0.53)	9.12 (±0.11)
	d_{90}	36.40 (±1.09)	33.20 (±2.16)	28.9 (±3.78)	30.9 (±0.75)
Effluent (µm)	d_{10}	0.90 (±0.02)	0.53 (±0.01)	0.56 (±0.03)	1.07 (±0.01)
	d_{50}	3.60 (±0.08)	2.65 (±0.04)	2.60 (±0.22)	4.43 (±0.01)
	d_{90}	10.90 (±1.09)	3.05 (±3.05)	12.40 (±12.40)	11.6 (±0.04)
Sampler significantly different to source?		Yes ($p < 0.0001$)	Yes ($p < 0.0001$)	Yes ($p < 0.0239$)	Yes ($p < 0.0001$)

Note. The d_{10}, d_{50}, and d_{90} represent the 10th, 50th, and 90th percentiles of the particle size distribution (µm). PASS: pumped active suspended sediment.

The particle size distribution (the 10th, 50th, and 90th percentiles) of the sediment retained by the Phillips sampler for both flow rates (27 and 242.1 ml min^{-1}) was significantly different from the source solution ($p < 0.001$; Table 1). The particle size distribution of the sediment retained by the PASS was also significantly different to the source sediment, at both flow rates (4 and 27 ml min^{-1}). However, the percent difference of the median particle size of the source and PASS sampler sediment was less when compared with the Phillips sampler. The difference of source mass to the sampled mass, as a percentage, for the PASS sampler, at the 4 and 27 ml min^{-1} flow rates, was 7% and 30%, whereas the percent difference for the Phillips sampler was greater, at 8% and 45% for the 27 and 242.1 ml min^{-1} flow rates, respectively (Figure 2). It appears the controlled constant low flow rate of the PASS sampler allows for a greater settling effect compared with the Philips under higher flows, despite using half the volume for sedimentation within the sampler. This suggests the PASS could retain a more representative sediment particle size sample than the Phillips sampler, especially during high flow events when the majority of sediment is transported in fluvial environments (D. E. Walling & Collins, 2016).

3.2 | Comparison of PASS and discrete sampling under field conditions

The TWA suspended sediment concentration of the samples collected using the PASS and discrete sampling techniques agreed well, differing by only 4% and 6% for the two high flow events monitored. The two high flow events had peak flow rates of approximately 0.2 (14-hr event) and 1.2 m s^{-1} (53-hr event). These flow rates translate to approximately equal and double, respectively, the velocity of the flow rates used (27 and 242.1 ml min^{-1}) to evaluate the Phillips sampler. Discrete nonisokinetic sampling (i.e., grab sampling) was appropriate for the 14-hr event because the flow rates were too slow for effective sample collection using an isokinetic sampling technique (<0.3 m s^{-1}). On the other hand, the high flow rates of the 53-hr event likely affected nonisokinetic discrete sampling efficiency. However, the majority of the sediment suspended during the event was <63 µm in size (discussed in Section 3.3), and therefore, the effect of nonisokinetic sampling should be negligible (Ongley, Bartram, & Ballance, 1996). Figure 3 shows the hydrographs of the two high flow events, individual discrete sample concentrations, and the TWA suspended sediment concentration for samples collected using the PASS and discrete sampling techniques.

Based on the comparison of the hydrograph, the concentration of the discrete samples collected, and the high frequency of sample collection during the two high flow events, the discrete sample TWA suspended sediment concentration is likely to accurately represent the actual TWA suspended sediment concentration for each of two monitoring periods. Therefore, the agreement between TWA suspended sediment concentrations measured by the PASS and discrete sampling approaches validates the PASS sampling method as a

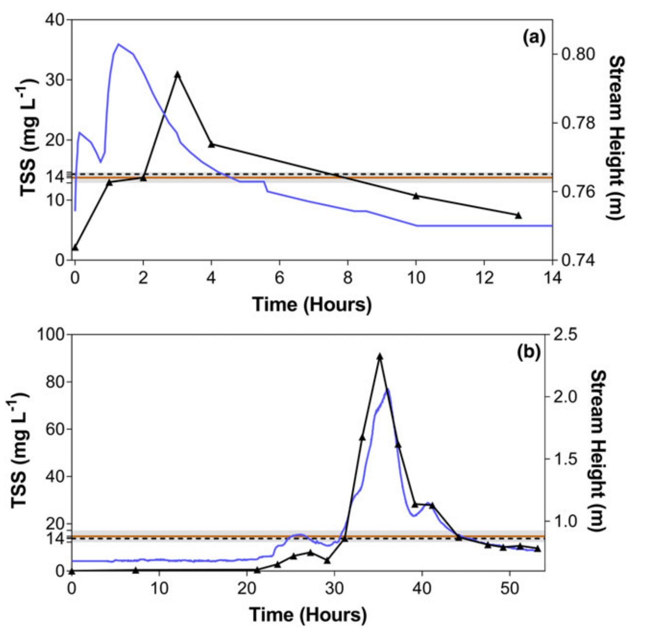

FIGURE 3 Stream Height (solid blue line) and discrete sample TSS concentrations (triangles with black line) during a (a) 14 and (b) 53 hr high flow event at Loders Creek, Gold Coast, Queensland, Australia. Black dashed and solid brown lines represent time-weighted average PASS sampler respectively and TSS concentrations of the discrete samples. PASS sampler standard deviation is shown as light grey shading around black dashed line

way to measure representative TWA suspended sediment concentration, with only 4% (±1) and 6% (±2.4) difference between the two techniques for the 14 and 53 hr high flow events, respectively. It is also likely that the PASS sample will be more representative of the actual TWA suspended sediment concentration in situations where the concentration varies substantially on timescales shorter than that between discrete samples. This is because the PASS continuously samples throughout the event whereas the discrete samples are intermittently collected. It should be noted that for most environmental monitoring programmes, storm events, such as those monitored in this study, would commonly only be sampled at one point in time or not at all during a routine monitoring schedule. In contrast, the application of PASS samplers could provide TWA suspended sediment concentrations for both events with only a small increase in required resources.

The purpose of comparing the discrete and PASS sampling techniques was to evaluate the accuracy of the PASS sampler for measuring TWA suspended sediment concentrations. We should note that the current configuration of the PASS sampler is not suitable for the estimation of sediment loads due to the time-integrated nature of the measurement. This means that the technique would not account for the variable discharge over the hydrograph of an event, thus resulting in the same weighting for suspended sediment concentrations at different discharges and, ultimately, an underestimation of the true sediment load.

3.3 | Comparison of PASS and Phillips samplers under field conditions

Comparison of particle size distributions of the samples collected using the Phillips and PASS samplers showed that both methods collected sediment samples of similar particle size distribution (Figure 4). The median particle size (d_{50}) for PASS and Phillips samplers for the two high flow events were very similar and only differed by 14% and 4% for the 14 and 53-hr high flow events, respectively. (Table 2). This supports the assumption, made in Section 3.2, that both samplers would display improved retention of natural (i.e., not chemically dispersed) sediment. Note that suspended sediment concentrations of samples collected by the Phillips and PASS samplers were not compared because the flow dependent design of the Phillips sampler precludes the determination of an accurate TWA suspended sediment concentration, as the volume of water sampled is unknown (Russell et al., 2000; Smith & Owens, 2014).

There was a high level of variation associated with the sediment mass collected by the Phillips samplers (relative standard deviation of 31% and 54% for 14 and 53 hr high flow events, respectively), compared with the relatively low variation of the sediment mass collected by the PASS (relative standard deviation of 6% and 17% for 14 and 53 hr high flow events, respectively). The variation in sediment mass collected by the Phillips samplers was most likely the result of debris observed at the front of the samplers upon removal after both events, which would differentially impact the flow of water through the individual samplers. This issue has been observed in other studies using the Phillips sampler (Evans et al., 2006; Perks et al., 2017; Perks et al., 2014), as the sampler must be orientated with the direction of water flow in order to function, which permits accumulation of debris around the sample intake port. In contrast, the PASS sampler can be oriented so the sample intake is cross-flow oriented (as opposed to facing it) because it actively samples the solution, thus minimising the effect of debris capture at the sampler intake. The residual unsettled sediment in the PASS and Phillips samples, after 5 days of settling at 4 °C, accounted for only 0.12% (±0.05) of the total sample collected and did not contain enough mass for particle size analysis.

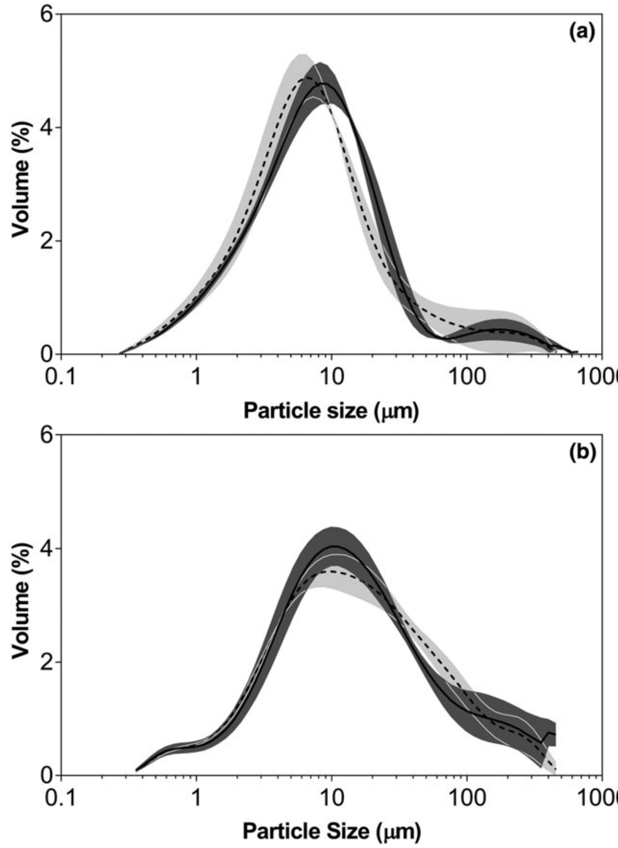

FIGURE 4 Comparison of particle size distribution of sediment collected by PASS (solid black line and Phillips (dashed black line) samplers, for the (a) 14- and (b) 53-hr high flow events. PASS and Phillips standard deviation shown by dark and light grey shading, respectively

TABLE 2 Particle size distribution of sediment collected using PASS and Phillips samplers

Sampler	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)
14 hr high flow event			
PASS	1.6 (±0.08)	7.3 (±0.53)	36.2 (±6.62)
Phillips	1.5 (±0.21)	6.4 (±1.20)	38.3 (±23.72)
p value	0.9486	0.0462	0.0200
53 hr high flow event			
PASS	2.8 (±0.35)	13.9 (±2.70)	108.2 (±32.00)
Phillips	2.6 (±0.14)	14.4 (±0.84)	98.4 (±13.80)
p value	0.1845	0.0871	0.7184

Note. The d_{10}, d_{50}, and d_{90} represent the 10th, 50th (median), and 90th percentiles of the size distribution, respectively. PASS: pumped active suspended sediment.

The particle size distribution (the 10th, 50th, and 90th percentiles) of the samples collected by the PASS and Phillips samplers were marginally significantly different for the 14-hr event and not significantly different for 53-hr event (Table 2). Based on the laboratory comparisons, it was expected that the Phillips sampler would lose a significant portion of finer sediment particles under higher flow conditions (> 0.3 m s^{-1}) and thus have a different particle size distribution compared with the PASS sampler. However, the laboratory tests were done with chemically dispersed sediment, which prevents the agglomeration and settling processes that occur in natural systems, thus representing a worst-case scenario for sediment loss. Previous studies have shown that the Phillips sampler can collect a statistically representative sample for analysis of particle size distribution in natural systems, even when flows are elevated (Perks et al., 2017; Perks et al., 2014; Schindler Wildhaber, Michel, Burkhardt-Holm, Bänninger, & Alewell, 2012; Smith & Owens, 2014; D. Walling, 2005). Therefore, it is likely that the average particle size distribution of the sample collected by the PASS and Phillips samplers are representative of the particle size distribution of suspended sediment in Loders Creek during the two sampled events. It should be noted that the Phillips sampler could lose a significant amount of sediment mass (possibly up to 50%) at higher flows (greater than 0.6 m s^{-1}), which is not uncommon in most fluvial environments (Droppo & Ongley, 1992; Horowitz et al., 2015; Janes et al., 2016; Ongley et al., 1996; Vercruysse, Grabowski, & Rickson, 2017). If the sediment is equally removed from the sampler, this may not adversely affect the particle size distribution of the sample, as demonstrated in Section 3.1; however, it will bias the sample mass collected, thus making the Phillips sampler unsuitable for measuring suspended sediment concentrations.

4 | CONCLUSION

An affordable and representative sampling method for the in situ measurement of TWA suspended sediment concentration has been evaluated. The PASS sampler effectively collects fine suspended sediment (<63 μm) that is representative of both TWA concentration and particle size distribution, in both laboratory and field settings. The sampler is, therefore, well-suited for collecting samples that are representative of suspended sediment concentrations and particle size distributions, over a defined period, in dynamic waterbodies. Further research is needed to assess if this is also true for coarser suspended sediment (medium to coarse sands). The PASS sampler does not collect as much sediment mass as the Phillips sampler, especially at higher flows, because of its fixed lower sampling rate. However, replicate samplers can be deployed with low error, thus allowing for sample material to be composited if more sample mass is needed.

The current design of the PASS sampler is not suitable for the determination of sediment loads. However, the PASS sampler is well-suited for studies that require temporally representative measurements of suspended sediment concentration. For example, the PASS sampler could be used for monitoring suspended sediment concentration for regulatory purposes, ecological suspended sediment impact studies, or as a network of suspended sediment monitoring locations over a wide spatial distribution as part of a preliminary assessment of suspended sediment concentration trends within a catchment. In addition, the independent flow rate of the PASS sampler eliminates the potential error associated with flow-dependent sampling, such as the sampler inlet being compromised by blockage, upstream turbulence, or the loss of fine sediment at high flow rates. This also means the PASS sampler can be applied in a wide range of tidally influenced or low-flow aquatic environments not currently suitable for flow-dependent sampling (e.g., wetlands, reservoirs, and coastal waters).

ACKNOWLEDGMENTS

The authors acknowledge the Southern Cross University Environmental Analysis Laboratory and Gold Coast City Council for their support and advice. We also thank the editor (Des E. Walling) and reviewers (Robert Nunny and John R. Gray), of this manuscript, for their comments and in-depth discussions, which improved the manuscript and gave the authors plenty to think about.

ORCID

Nicholas J.C. Doriean https://orcid.org/0000-0001-9150-8579

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Doriean NJC, Teasdale PR, Welsh DT, Brooks AP, Bennett WW. Evaluation of a simple, inexpensive, in situ sampler for measuring time-weighted average concentrations of suspended sediment in rivers and streams. *Hydrological Processes*. 2019;33:678–686. https://doi.org/10.1002/hyp.13353

4 Suspended sediment monitoring in alluvial gullies: a laboratory and field evaluation of available measurement techniques

Submitted to Hydrological Processes

This chapter consists of a co-authored paper submitted to a peer reviewed scientific journal (Hydrological Processes). This manuscript has been written in the style stipulated by Hydrological Processes.

My contribution to the published paper involved:

Initial concept and experimental design.

Collection and analysis of data.

Preparation of manuscript.

[redacted]

Nicholas J. C. Doriean

[redacted]

Corresponding author of published paper: William W. Bennett

[redacted]

Supervisor: William W. Bennett

Suspended sediment monitoring in alluvial gullies: a laboratory and field evaluation of available measurement techniques

Nicholas J.C. Doriean,[1] Andrew P. Brooks,[2] Peter R. Teasdale,[3,4]

David T. Welsh,[1] and William W. Bennett [1,]*

[1] Environmental Futures Research Institute, School of Environment and Science, Griffith University Gold Coast campus, Queensland 4215, Australia

[2.] Griffith Centre for Coastal Management, Griffith University Gold Coast campus, Queensland 4215, Australia

[3] Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, South Australia 5095, Australia.

[4] Future Industries Institute, University of South Australia, South Australia 5095, Australia.

*Corresponding Author: w.bennett@griffith.edu.au

Running Head: EVALUATION OF SUSPENDED SEDIMENT MONITORING IN ALLUVIAL GULLIES

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

Keywords: suspended sediment, particle size, soil erosion, *in situ*, ephemeral

Abstract

Gully erosion is a significant source of fine suspended sediment and associated nutrient pollution to freshwater and marine waterways. Researchers, government agencies, and monitoring groups are currently using monitoring methods designed for streams and rivers (e.g., autosamplers, rising stage samplers, and turbidity loggers) to evaluate suspended sediment in gullies. This is potentially problematic because gullies have unique hydrological and operational challenges that differ to those of streams and rivers. Here we present a laboratory and field-based assessment of the performance of common suspended sediment monitoring techniques applied to gullies. We also evaluate a recently-described method; the pumped active suspended sediment (PASS) sampler, which has been modified for monitoring suspended sediment in gully systems. Discrete autosampling provided data at high temporal resolution, but had considerable uncertainty associated with the poor collection efficiency (25 ± 10%) of heavier sediment particles (i.e., sand). Rising stage sampling, while robust and cost-effective, suffered from large amounts of condensation under field conditions (25-35% of sampler volume), thereby diluting sample concentrations and introducing additional measurement uncertainty. The turbidity logger exhibited low uncertainty (< 10%) when calibrated with suspended sediment concentration data from physically collected samples, however, this calibration approach needs to be performed on a site-specific basis to overcome the error associated with the impact of different particle size distributions on the turbidity measurement. The modified PASS sampler proved to be a reliable and representative measurement method for gully sediment water quality, however, the time-integrated nature of the method limits its temporal resolution compared to the other monitoring methods. We recommend monitoring suspended sediment in alluvial gully systems using a combination of complementary techniques (e.g., PASS and RS samplers) to account for the limitations associated with individual methods.

1 Introduction

Gully erosion is globally recognised as a significant source of soil loss and can directly influence the water quality of downstream aquatic ecosystems (Vercruysse et al., 2017; Walling, 2006; Walling et al., 2016). The impact to water quality from gully erosion can vary depending on the particle size distribution and sediment yield. For example, small gullies that form in recently tilled agricultural land can affect local waterways (Capra et al., 2002), whereas larger landscape-scale gullies can impact the water quality of connected waterways for hundreds of kilometres downstream (e.g., >40% of the sediment polluting the Great Barrier Reef, in the coastal waters of Northern Australia, is generated by gully erosion that occurs hundreds of kilometres upstream) (Brooks et al., 2013; Olley et al., 2013; Wilkinson et al., 2015).

Gullies are often formed by water flowing over land at a sufficient velocity to incise the soil and form a deep exposed gap, typically in areas with poor soil cohesion (Casalí et al., 2009). Over time the area of gullies expands due to active erosion caused by repeated flow events associated with intense rainfall (Poesen et al., 2003). Gully erosion is a natural process, however, the rate of erosion can drastically increase as a consequence of anthropogenic land use change (e.g., installation of roads and other infrastructure or through agricultural activities, such as, land clearing and livestock grazing) (Nyssen et al., 2002; Wilkinson et al., 2018).

To date, suspended sediment monitoring in gullies has been conducted using methods designed for rivers and streams (e.g., automated discrete samplers (autosamplers), rising stage samplers (RS samplers), and turbidity loggers) (Baker et al., 2016; Bartley et al., 2017; Caitcheon et al., 2012; Nistor et al., 2005). However, gully systems present a unique set of hydrological and operational challenges for which these various sampling and measurement methods have not been thoroughly evaluated. The method considered to be the most accurate for measuring suspended sediment, flow-proportional manual sampling (Horowitz et al., 2008; Perks, 2014), is often infeasible or unsafe to conduct in gully systems due to the unpredictability of rainfall events, the remoteness of many gully landscapes, and the instability of gully channels and banks.

Currently, the operational challenges associated with measuring water quality in gullies are overcome using autonomous sampling or surrogate measurement techniques (autosamplers, RS samplers, and turbidity loggers) and remote sensing methods (time lapse cameras or light detection and ranging (LiDAR) techniques) (Casalí et al., 2009; Castillo et al., 2012). These methods are established monitoring techniques with well understood capabilities and limitations (Table 1). Many of these methods, however, are too expensive to implement over the large spatial network of actively eroding gullies within a catchment (e.g., autosamplers and turbidity loggers), and others provide incomplete information when deployed in isolation (e.g., RS samplers and time-lapse cameras). To address this gap, our study includes the recently developed Pumped Active Suspended Sediment (PASS) sampler; an automated, time-integrated, and *in situ* sampling device, as a low-cost approach that could be used to monitor gully erosion over large spatial scales (Doriean et al., 2019; Nunny 1985; Phillips et al., 2000). As this work is primarily focussed on approaches that measure water quality associated with suspended sediment (i.e., suspended sediment concentration and particle size distribution) remote sensing techniques (i.e., LiDAR) that are used to estimate soil loss using landscape scale volumetric analysis will not be included in this evaluation.

Here we aim to systematically evaluate and compare the capabilities and limitations of a variety of suspended sediment monitoring methods (i.e., autosampler, RS sampler, turbidity logger, and PASS sampler) when applied to gully systems. The methods are compared under controlled laboratory conditions and in the field to assess the relative ability of each method to provide accurate measurements of suspended sediment concentration and particle size distribution.

Table 1. Characteristics of suspended sediment monitoring approaches evaluated in this study.

Sampler Type	*Approximate Cost (AUD)*	*Installation and operation*	*Principal of operation*	*Sampling capacity*	*Advantages*	*Limitations*
Automatic Sampler	$5,000-$30,000	Complex installation and regular maintenance.	Actively collects discrete samples by pumping	1-24 discrete samples (typically 1-3 flow events)	Multiple samples collected over a limited number of flow events. Can be triggered by multiple parameters (stream height, flow, or time).	Provides quality data for short flow events only. Non-continuous, as well as potential incomplete sampling of an entire flow event, can cause bias. Requires power and regular maintenance. Non-isokinetic and potential under-sampling of sand if pump elevated above sample intake.
Turbidity Logger	$2,500-$10,000	Simple installation and low maintenance.	Records turbidity to memory at defined intervals (e.g., every 5 minutes).	>10,000 measurements over weeks or months (unlimited events)	High-resolution data over multiple flow events (limited by battery life).	Data requires site-specific calibration to be converted to SSC. No particle size information. No additional analysis possible as no sample is collected.
Rising Stage Sampler	$90-$600*	Complex installation and frequent maintenance.	Passively collects discrete samples during a single event as the water stage rises	3-12 discrete samples (single flow event)	Multiple samples collected over a limited number of flow events, on the rising hydrograph only. No power required.	No data for falling stage. Non-continuous sampling and lack of sustained or falling stage samples can cause bias toward initial flow concentrations. Requires frequent collection and replacement. Non-isokinetic.
PASS Sampler	$500-$1500	Simple installation and low maintenance.	Continuously collects sample at defined pump rate during flow event (triggered by float switch)	1-3 time-integrated samples (unlimited flow events)	Time-integrated samples collected over one or multiple flow events (limited by battery-life). Samples can be used for multiple analyses due to large sample volume.	Characterisation of hydrograph or individual events not possible. Non-isokinetic.

* = Price for six samplers, SSC = SSC, AUD = Australian dollars as of June 2019. References: (Edwards et al., 1999; Fowler et al., 2009; Gray et al., 2009; Horowitz et al., 2015; HQS, 2018; JMG, 2018; Perks, 2014)

2 Methods

2.1 Modification of the PASS sampler to operate in ephemeral waterways.

The PASS sampler was originally designed for use in perennial waterways (e.g., small permanently flowing streams and rivers) (Figure 1) (Doriean et al., 2019). However, we propose that reconfiguration of the sampler to operate in ephemerally flowing systems (e.g., gullies) will provide an affordable alternative or complimentary monitoring method to those currently used for the measurement of suspended sediment concentration and particle size in ephemerally flowing systems, such as gullies.

The following modifications have been made to allow the use of the PASS sampler in gully systems (Figure 1):

- The peristaltic pump has been placed before the settling column, rather than after it, to allow the sampler to be deployed dry. In its original design, the sampler needed to be filled with ambient water before deployment to ensure the peristaltic pump could generate enough vacuum to collect a sample.
- A small coarse-sediment trap (or initial settling column) has been added at the intake of the pump to ensure larger particles (e.g., silt and sand) do not settle within the sampling tubing or damage the pump.
- The main settling column outlet has been re-configured to include a vertical 4 mm inside diameter polypropylene tube with a 180 degree down-turn at the outlet to ensure water or debris cannot enter the sampler through the outlet (Figure 1).
- A float switch has been added and placed at the same height as the sampler intake to ensure the pump only operates when water is flowing in the gully. The float switch requires the application of a timer (e.g., an hour meter or datalogger) linked to the PASS circuitry, or alternatively in tandem with a water level logger at the location of the sampler, to determine the sampling period and thereby the volume of water sampled.

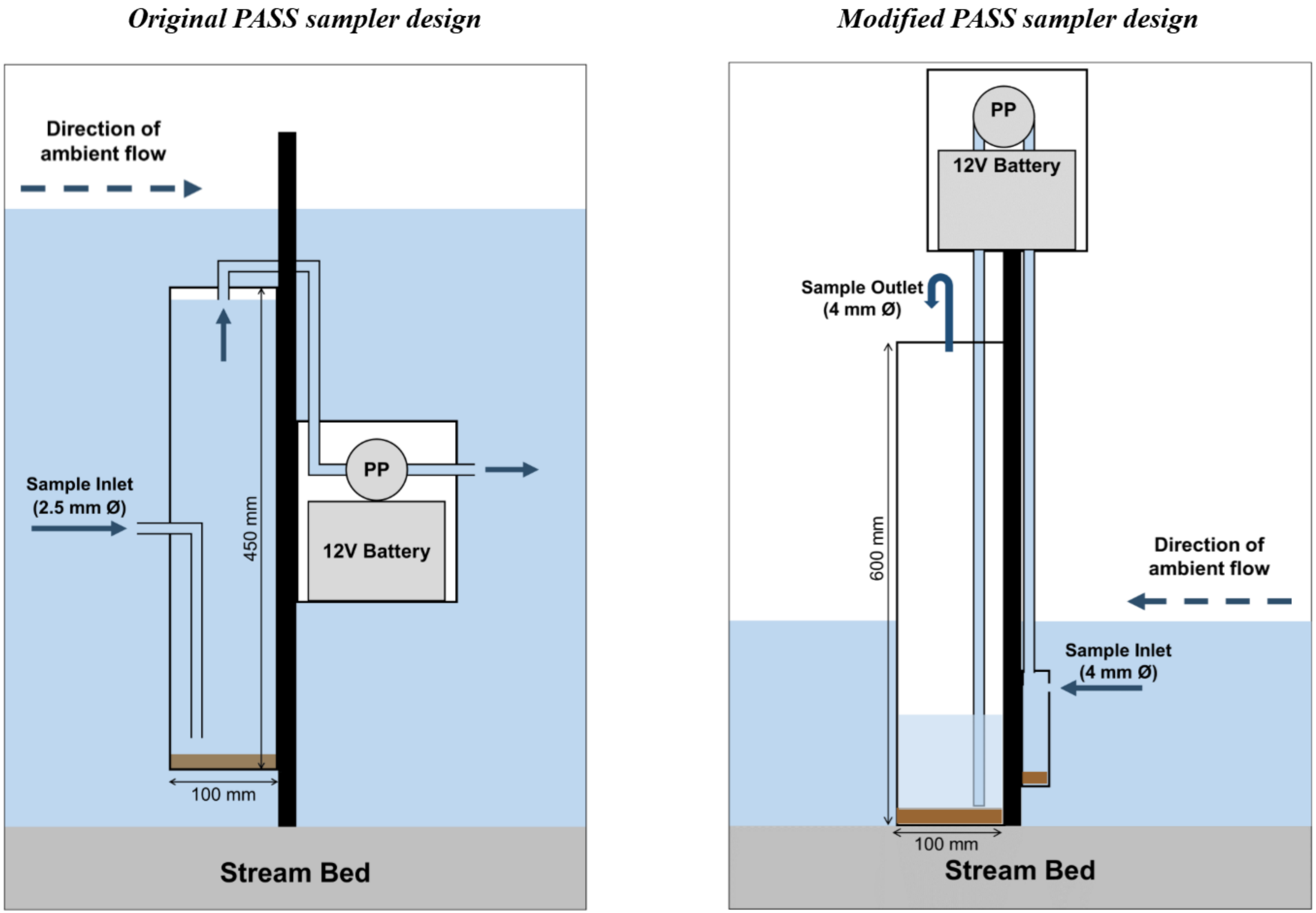

Figure 1. Diagrams of original and modified PASS sampler designs (Doriean et al., 2019). PP = peristaltic pump Ø = inside diameter. Note, the modified PASS sampler sediment trap is placed slightly off centre with the inlet facing downstream on an angle.

2.2 Laboratory evaluation of gully monitoring methods

Water quality conditions typical of a gully flow event, based on previous observations at relevant field sites, were simulated in a laboratory setting to evaluate the modifications made to the PASS sampler design and to compare its performance with the other established methods A falling suspended sediment concentration trend (high (~10,500 mg L^{-1}) to low (4,500 mg L^{-1})) over a 6-hour period (typical of flow events in the active gully used for the field evaluation of this study, determined by preliminary field study data) was imitated using sediment sourced from a gully at the field study site (median particle size of 29 µm). An agitation vessel, similar in design to a churn splitter (20 L cylindrical polypropylene container with four baffles (vertical strips of aluminium, 0.5 cm thick and 3 cm wide, placed perpendicular to the side wall, from the bottom to the top, of the vessel) (Ward et al., 1990)) was used to create a turbulent flow of water during the experiment (Figure 2).

A triplicate set of PASS sampler intakes were placed approximately 0.15 m above the bottom of the vessel. Sample inlets for discrete sample collection, identical to the outlet of a churn splitter (Ward et al., 1990), (6 mm ID polypropylene tube tapped through agitation vessel wall) and the automatic sampler (Sigma® 900) inlet were placed at the same level as the PASS inlets to collect discrete samples. The discrete automatic sampler was elevated (2 m) above its intake point to simulate the configuration that would typically be used in the field. A turbidity logger (Observator, NEP495) was placed at the same level as the sampler inlets and programmed to record a turbidity measurement every ten-minutes.

The RS sampler did not fit inside the agitation vessel, thus, a substitute dataset using the discrete manual sample data (collected from the isokinetic outlet) was generated to simulate the RS sampler data and allow comparison with the other techniques. Laboratory test samples collected using the discrete collection method and an RS sampler were compared and found to be similar in suspended sediment concentration and particle size distribution (< 2% ± 1% for both), which provided confidence to rely on the discrete sample dataset to simulate RS sample data. Flow event data gathered during a preliminary study, from the gullies monitored at the field-test site show that there is little hysteresis between suspended sediment concentration and water level. Thus, the RS sample data was constructed based on time after initial flow, estimating the peak stage to occur relatively early during the simulated event (i.e., the peak water height of the simulated event occurred 75-minutes into the 6-hour event).

To simulate the flow event, dry gully soil was weighed, suspended in a small volume of rain water (collected from the laboratory roof) to aid dispersion, and then diluted in rain water to a predetermined suspended sediment concentration with a final volume of 15 L. The sediment was kept in suspension using an overhead stirrer (OS40-S paddle stirrer) operating at 500 rpm. The concentration was changed by exchanging the water and sediment solution in the agitation vessel at 30-minute intervals. Triplicate PASS samplers continuously sampled water from the agitation vessel during the simulated flow event and repeat discrete samples (three samples per method) were collected from the same vessel using flow-proportional discrete sampling, simulated RS sampling and discrete autosampling methods every 30 minutes (15-minutes after each change in concentration).

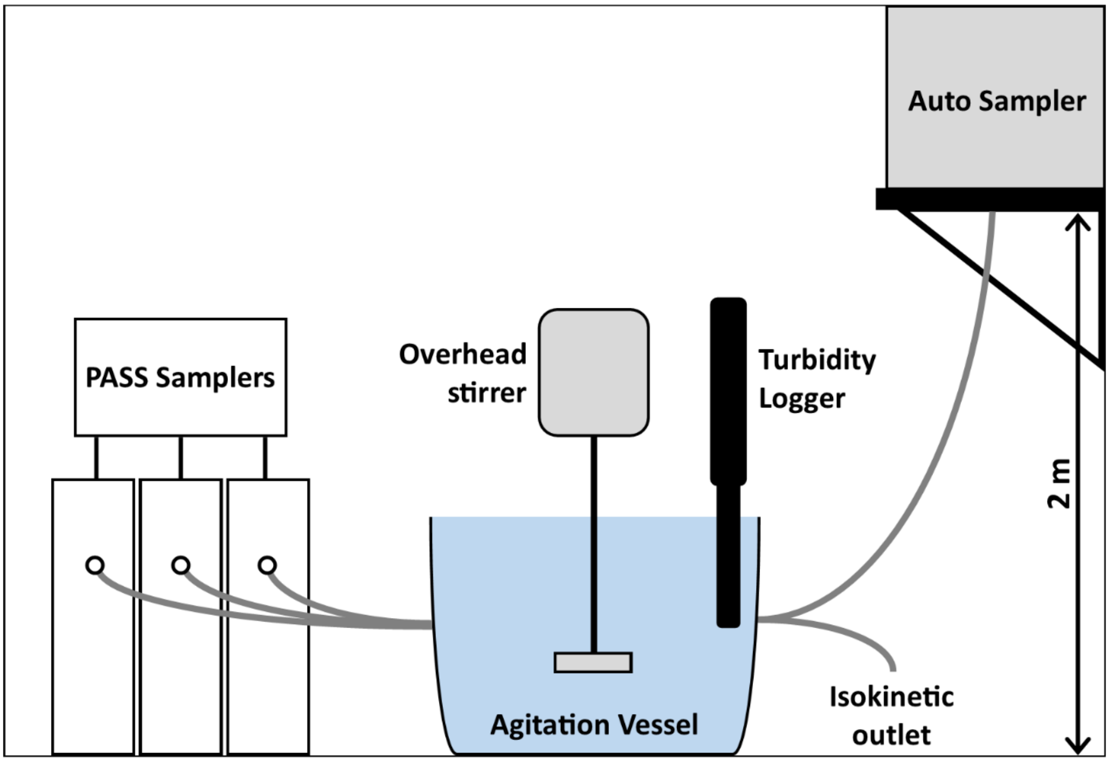

Figure 2. Diagram of the laboratory test used to imitate the suspended sediment dynamics of a gully flow event for the evaluation of each monitoring method. Note that the intakes/measurement point for the methods were all adjacent to one another at the same level in the agitation vessel.

2.3 Field evaluation of gully monitoring methods

The gullies monitored in this study were located at Crocodile Station in North Queensland (15°40'08.4"S, 144°35'38.4"E), Australia, and drain directly into the Laura River, which is connected to the coastal waters of the northern Great Barrier Reef via the Normanby River (Olley et al., 2013) (SI-1). The gullies are identified as alluvial gullies because they are located in alluvial soils of the Laura River floodplain (Brooks et al., 2013). Two gullies were studied to evaluate the accuracy and limitations of the monitoring techniques for measuring suspended sediment dynamics of gullies at different stages of erosion: an actively eroding gully (gully-1) with high suspended sediment output consisting of fine sediment (<63 µm) and some suspended sand (63-2000 µm); and a gully remediated in 2016 (gully-2) with relatively low suspended sediment output dominated by fine sediment (<63 µm) (SI-2). The suspended sediment particle size data used to describe the suspended sediment characteristics of the test gullies was gathered in a pilot study conducted at the study site.

The evaluated monitoring techniques consisted of a Sigma® 900 autosampler, a modified PASS sampler, a RS sampler array (six stages), and an Observator® NEP495 turbidity logger (measurement range 40-4000 nephelometric turbidity units (NTU)). Instruments were deployed in close proximity to each other in a straight section of channel approximately 50 m and 110 m downstream from the head of gully 1 and 2 respectively. The autosampler was placed on the bank beside the channel (elevated approximately 2 m above its intake) with the intake positioned in the middle of the channel cross section, 0.2 m above the channel bed with the inlet facing downstream (SI-3). A float switch, placed at the intake, was used to initiate and halt sampling. A PASS sampler was also placed at the midpoint of the channel affixed to a steel fencing post, driven into the channel bed; the intake and float switch were placed approximately 0.2 m above the channel bed. RS samplers were placed in a line along the channel centre at various heights above the channel bed, ranging from 0.2 to 0.45 m at 0.05 m intervals. The turbidity logger was placed alongside the autosampler inlet. A level logger (In-situ® R100) was placed at the midpoint of the channel directly on top of the bed, fixed to the steel support for the rising stage samplers. A barometric pressure logger (In-situ® baroTROLL) was placed nearby above maximum flood elevation, to allow accurate calibration of the level logger. A rain gauge (Hydrological Services tipping bucket rain gauges - 0.2 mm/tip with Hobo data logger) was also placed within the catchment area of the gullies.

Once activated, the autosampler collected a sample of approximately 800 mL every ten minutes, whilst the PASS sampler continuously sampled until the ambient water level dropped below the float switch. The turbidity logger was programmed to record a measurement every 10-minutes whilst deployed. The RS samplers collected a sample when the water level covered the intake and caused a pressure difference in the sampler, resulting in rapid filling of the sampler (Braatz, 1961). Manual flow-proportional samples were collected using a DH-48 sampler using the equal discharge method when flow velocity and depth were sufficient (>0.3 m sec^{-1} and >0.17 m, respectively), or taken directly from the stream with a sample bottle when flow velocity and depth was too low for accurate use of the DH-48 sampler (Edwards et al., 1999).

2.4 Sample analysis and statistics

Samples collected from the laboratory and field evaluations were analysed for suspended sediment concentration using ASTM standard method D 3977-97 and particle size distribution using laser diffraction spectroscopy (Malvern Mastersizer 3000, Malvern Instruments). Discrete samples from the autosampler were analysed as received, whilst the PASS samples (composites of main settling column and intake sediment trap), were placed in cold storage (4°C) for five days to settle, after which they were decanted to 1 L and analysed. The supernatant was filtered through a pre-weighed glass fibre filter (Whatman GF/F (0.7 µm)), to account for the mass of any sediment that may have remained in suspension. The time-weighted average (non-continuous) suspended sediment concentration was determined by averaging the concentration of multiple discrete samples, weighted by the time span between two sequential samples. The PASS sampler continuously samples whilst in operation, thus, the time weighted average suspended sediment concentration is calculated by weighting the total mass of suspended sediment collected by time as a function of volume (Doriean et al., 2019). Turbidity measurements were calibrated using the discrete samples from the autosampler. A linear regression between turbidity and suspended sediment concentration was used to convert NTU measurements into suspended sediment concentration, when appropriate (Rasmussen et al., 2009). Statistical analysis was conducted using GraphPad-Prism®. The sample data did not share similar standard deviations, thus, the unpaired nonparametric Mann-Whitney t-test method was used to compare differences between methods ($p = 0.05$).

2.5 Data quality and uncertainty

The uncertainty of each measurement method must be considered when evaluating their relative performance. The uncertainty assigned to a particular technique was determined based on laboratory evaluations conducted during this study and the scientific literature. If the difference in suspended sediment concentration between two sampling methods was equal to or less than the cumulative error associated with those methods, the individual results were not considered significantly different (Horowitz 2017). For example, manual sampling uncertainty is typically ~10% of the sample suspended sediment concentration (Sauer et al., 1992), whereas, the PASS sampler was previously demonstrated to exhibit ~6 to 17% uncertainty (Doriean et al., 2019). Cumulatively this suggests a sample concentration difference range in the order of 16 to 27%. Thus, suspended sediment concentrations of samples collected by these methods that differed within this uncertainty range were not likely to be statistically different (Horowitz, 2017).

3 Results and Discussion

3.1 Comparison of laboratory evaluation of gully suspended sediment monitoring methods

The laboratory evaluation of the various monitoring methods (flow-proportional discrete manual sampling, simulated RS sampler, PASS sampler, autosampler, and turbidity logger) demonstrated the capabilities and limitations of the methods to provide representative measurements of suspended sediment concentration and particle size distribution (Table 2, Figure 3, SI-4) as discussed in relevant sections below. The scientific literature considers discrete manual, isokinetic depth and width integrated, sampling to be the most representative field sample collection method (Horowitz et al., 2008; Perks, 2014; Ward et al., 1990). For this reason, we argue that assessment of sampler performance under laboratory conditions should be made by comparison to the discrete manual sampling results. The flow-proportional discrete manual samples collected during the laboratory evaluation are comparable to what would be collected using isokinetic manual sampling techniques in the field (Ward et al., 1990).

3.1.1 Autosampler

The time-weighted average suspended sediment concentration of the samples collected using the autosampler underestimated the manual discrete sample time-weighted average suspended sediment concentration by 38% and was also lower than the other tested methods (Table 2). The coarser sediment fraction (100-2000 µm) was also underrepresented in the samples collected by the autosampler (Figure 3, Table 2). This is due to increased head pressure and slower sampling velocity as a result of the elevation difference between the autosampler and its sample intake. Thus, heavier particles (i.e., sand) were under-represented in the samples collected with the autosampler (Bent et al., 2003; Clark et al., 2009; Fowler et al., 2009). These samples also had different suspended sediment concentrations and particle size distribution to comparable samples collected by the other methods (Figure 3). The finer fraction of sediment (the 10^{th} percentile (d_{10}) of the particle size distribution) within the samples, collected using the autosampler, appears to be similar to the discrete sample sediment d_{10}, however, the two datasets were significantly different (Table 2). Additionally, the median sediment particle size (d_{50}) and 90^{th} percentile (d_{90}) of samples collected using the autosampler were generally close to half or less of those sediments collected by the other methods (Table 2). These data indicate that unless an autosampler can be configured so that the level of its intake is close to that of the sampling unit there will likely be under-representation of larger suspended sediment particles (>100 µm) and therefore also the suspended sediment concentration in the collected samples. This limitation suggests that suspended sediment data collected using an autosampler from a gully with high channel banks should be corrected using comparable data from a more representative method (e.g., manual sampling).

3.1.2 Rising stage sampler

The time weighted-average suspended sediment concentration derived from RS sampler data was biased to a higher sediment concentration (32%) compared to the time-weighted average suspended sediment concentration of the manually collected samples (Table 2). This bias was expected as samples were not collected after the simulated peak stage (i.e., 75 mins). The particle size distribution was not significantly different to the discrete manual sample data, as previously discussed in the methods, and it was also similar to the PASS sample data (Table 2, Figure 3).

The RS sampler provides representative individual sample data, however, the often rapid sampling rate due to gullies having a fast rising stage and lack of falling stage data will likely result in an overestimation of suspended sediment concentration and a potentially unrepresentative PSD for a flow event (García-Comendador et al., 2017; Shellberg et al., 2013). However, we note that this laboratory simulation represents only one type of hydrograph that may occur in gully systems, so the suitability of the RS sampling approach should be considered on a case-by-case basis using available data on the relationship of suspended sediment concentration and flow at a particular field site.

3.1.3 PASS sampler

The time-weighted average suspended sediment concentration of the samples collected using both discrete and PASS sampling methods differed by only 9% ± 5% (Table 2). The suspended sediment concentration of the sample water expelled (i.e., water not retained) by the PASS sampler was 150 mg/L, which is equivalent to the sampler retaining 98.5 ± 1% of the total sediment sampled. The modifications made to the PASS sampler, therefore, have not hindered its ability to collect a representative sample of time-weighted average suspended sediment concentration and particle size distribution.

The particle size distribution statistics (i.e., d_{10}, d_{50}, *and* d_{90}) of the suspended sediment collected using the PASS and discrete sampling methods reveal generally good agreement between the two methods (Table 2). The distribution of fine particles < 10 µm were almost identical, whereas distributions of larger (heavier) particles differed with increasing size (Figure 3). This difference is likely due to the heterogeneity in sand particles in suspension within the agitation vessel during the test. The continuous collection of sediment by the PASS sampler should more accurately incorporate this heterogeneity into the final measurement compared to discrete sampling, which likely explains the difference in the coarser sediment particle size fractions collected by the PASS and discrete sampling methods (Figure 3).

Overall, our data suggests that the PASS sampler is capable of collecting a time-integrated sediment sample that is comparable in suspended sediment concentration and particle size distribution to that collected by isokinetic manual sampling approaches, under controlled laboratory conditions.

3.1.4 Turbidity Logger

Turbidity measurements and discrete sample suspended sediment concentrations had a strong linear relationship (R^2 = 0.97), indicating that a predictive relationship between turbidity and suspended sediment could be used to estimate SSC from turbidity data (SI-5). Simulated RS sampler sample suspended sediment concentrations also had a strong linear relationship with turbidity (R^2 = 0.94), however, this was only for three paired measurements, which is not sufficient to derive a predictive relationship between turbidity and suspended sediment concentration (Rasmussen et al., 2009). Suspended sediment concentrations of the samples collected with the autosampler showed a more variable relationship with turbidity measurements (R^2 = 0.87) (SI-5). The time-weighted average suspended sediment concentration derived from turbidity data corrected with manually collected discrete samples compared well to the PASS (within 11%) and RS samples (within 26%) (SI-4). These results suggest the turbidity logger may be a good surrogate for the other monitoring methods provided a significant relationship between suspended sediment concentration and turbidity can be obtained under field conditions.

Table 2. Time weighted average suspended sediment concentration and particle size distribution of samples collected using different monitoring methods, exposed to conditions imitating a flow event in a gully, under laboratory conditions.

Sampler type		***Discrete***	***PASS***	***RSS***	***Autosampler***
TWA SSC (mg L^{-1})		7149 (± 1501)*	6476 (± 349)	9456 (± 1986)*	4447 (± 934)*
Average particle size (µm)	d_{10}	2.3 (± 0.23)	2.54 (± 0.06)	2.11 (± 0.04)	2.08 (± 0.18)
	d_{50}	17.1 (± 2.26)	21.6 (± 1.34)	15.19 (± 0.61)	12.9 (± 1.35)
	d_{90}	170 (± 23.4)	210 (± 15.2)	167.22 (± 22.65)	76 (± 10.4)
Different to discrete samples?	d_{10}	na	No ($p > 0.05$)	Yes ($p = 0.002$)	Yes ($p < 0.0001$)
	d_{50}	na	Yes ($p = 0.002$)	Yes ($p = 0.008$)	Yes ($p < 0.0001$)
	d_{90}	na	Yes ($p = 0.001$)	No ($p > 0.05$)	Yes ($p < 0.0001$)

na = not applicable, TWA SSC = time weighted average SSC. RSS = rising stage sampler, * = error calculated using fractional uncertainty to account for propagated error associated with the average of triplicate samples collected through time.

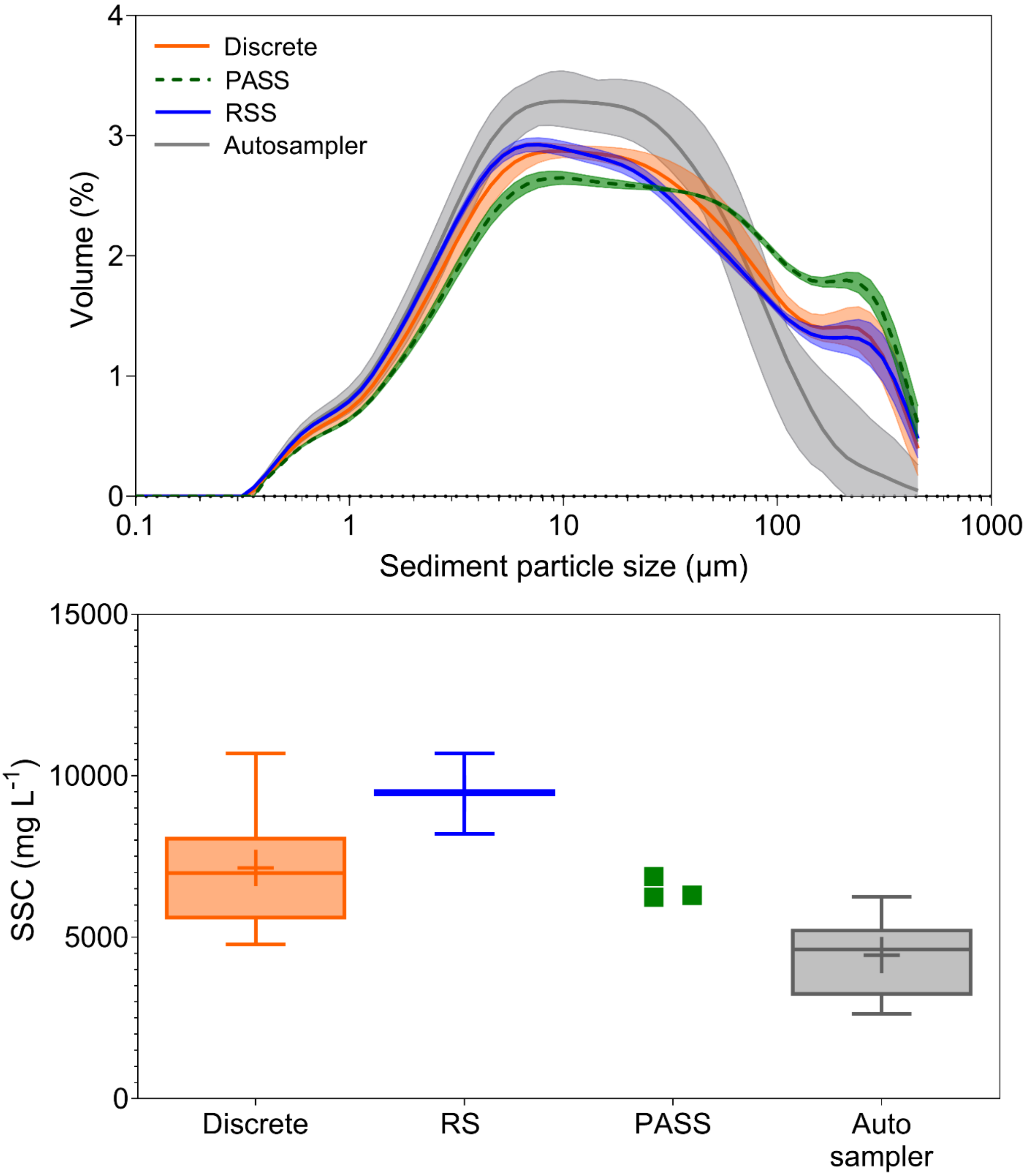

Figure 3. Average sediment particle size distribution (top) and suspended sediment concentrations (bottom) of samples collected using flow-proportional discrete manual sampling (orange), autosampler (grey), PASS sampler (green), and simulated rising stage (RS) sampler (blue) in a simulated flow event. Shading around particle size lines represents the error (standard deviation for PASS samples and aggregated standard deviation of all repeat samples for autosampler, discrete, and simulated RS samples). Suspended sediment concentrations are shown as box plots representing the minimum, maximum, 25th and 75th percentiles, median (horizontal line) and mean (cross). The PASS sampler suspended sediment concentrations represent time-weighted average suspended sediment concentrations and thus boxplots are not appropriate to display their variability and individual sample values are shown.

3.2 Field evaluation of gully monitoring methods

The two gullies at the field site were investigated over two wet seasons (2017/2018 and 2018/2019). During this time several flow events of different intensities were monitored (SI-6). Due to the remote locations of gullies used in this study, samples were often only able to be retrieved after multiple flow events had occurred, rather than after individual flow events. As such, there were only a limited number of single flow events that could be used to directly compare the performance of the various monitoring methods.

3.2.1 Autosampler

The autosampler collected samples in gully-2 with suspended sediment concentrations and particle size distributions that were similar to the other methods. The lack of suspended sand in gully-2 (commonly less than 2% by sample volume) meant that samples were representative despite the sampling unit being elevated (>1.5 m) relative to the intake (Table 3 and Figure 4). In contrast, samples collected using the autosampler from gully-1 had similar characteristics to those observed in the laboratory test, where suspended sediment concentration and particle size distribution were different to the PASS and RS samples when a relatively large amount of suspended sand was present (>20%) (Table 3). For example, during a short and intense flow event during the Jan-18 to Feb-18 sampling period in gully-1, samples collected by the autosampler underestimated the time-weighted average suspended sediment concentration by ~30% compared to the PASS sampler (Table 3, SI-6). Conversely, flow events that had relatively lower proportions of suspended sand (<10%) compared well to PASS sampler and RS sampler estimates. These differences in sample suspended sediment concentration and particle size distribution are consistent with observations from the laboratory test where the autosampler was unable to collect representative samples of the coarser sediment fractions due to the vertical displacement between the sampler position and its inlet. Additionally, the autosampler had several operational issues (e.g., insect infestation, sample intake blockages, and programming malfunctions) that limited the number of samples it collected in these specific field settings.

3.2.2 Rising Stage Sampler

The remote location of the study site meant the RS sampler arrays (i.e., six samplers) were only collected three times during the study period. This highlights the challenge of gaining sufficient samples for more than a small number of flow events from a gully using this method compared to the autosampler and PASS sampler, which can sample multiple flow events per deployment.

Based on the results of the laboratory evaluation, samples collected using the RS sampler were expected to be more representative of actual suspended sediment concentrations compared to samples collected by the autosampler. This was valid for most samples, however, under the field conditions prevailing at the study site some of the RS samplers were observed to accumulate large quantities of water (between 25-35% of the 1 L sampler volume) due to condensation. This phenomenon was unpredictable and resulted in suspended sediment samples being diluted by unknown amounts of water, thus potentially introducing significant error to the calculated SSC. Condensation in RS samplers has been noted in previous studies (Edwards et al., 1999), however, these comparatively large accumulations of condensate are likely caused by the high ambient daytime air temperatures and relative humidity, followed by cooler night time temperatures (a change of ~18°C), at the study site. This is likely to be an issue at many sites located in tropical regions and should be considered when designing monitoring programs in such places.

Unfortunately, upon return to a remote site following a flow event, there is no way of knowing which, if any, or to what degree individual samples collected by the RS samplers were affected by condensation. Considering this, it is best to interpret the RS sample suspended sediment concentration data with approximately 25-30% uncertainty. The RS samples had suspended sediment concentrations and particle size distributions in the range of the autosampler and PASS sampler samples (Table 3, Figure 4), although it is possible some of the suspended sediment concentrations could be outside of that range if condensation is considered. RS samples demonstrated the variability in particle size distribution under different water depth conditions well. For example, during a flow event in gully-1, the particle size distribution shifted between being dominated by finer and coarser particle as the water level increased (e.g., sample d_{50} and d_{90} ranged between 6.24 to 11.8 and 59.9 to 116, respectively) (SI-7). This ability to obtain information on suspended sediment particle size dynamics is a strength of the RS sampler approach.

Overall, suspended sediment concentration (provided the sampler is not compromised by condensation) and sediment particle size data of the RS samples compared well with the PASS sampler in both gully types. The development of a falling stage sampler has been recently reported, although no assessment of its limitations or capabilities has been done to date (DPI, 2017). Such a sampler could address a major limitation of using RS samplers for monitoring sediment transport processes in gullies.

3.2.3 PASS sampler

The particle size distribution of the samples collected from gully-2 by the autosampler, RS sampler, and PASS sampler were all very similar for all flow events (Table 3 and Figure 4). The average particle size distribution of the samples collected by the autosampler and PASS sampler were often within the uncertainty of their respective particle size distribution statistics (d_{10}, d_{50}, d_{90}) (Table 3). This data confirms the observations of the laboratory test in that the PASS sampler is collecting a sample comparable to the other methods for both time-weighted average suspended sediment concentration and particle size distribution of fine suspended sediment (< 63 µm).

The PASS sampler, RS sampler, and autosampler data did not agree as well for samples collected from gully-1, where the higher percentage of suspended sand present during flows resulted in more variable suspended sediment concentrations and particle size distributions (Table 3, Figure 4). Despite this, the range of time-weighted average suspended sediment concentrations of PASS samples compared relatively well with the other methods for flow events with less suspended sand (e.g., flow events sampled between November 2017 and January 2018) (Table 3). The particle size distribution of coarser sediment (i.e., the d_{90}) measured for the PASS samples were typically more than double those measured on the RS and autosampler samples, which indicates that the latter methods likely under-represented the coarser suspended sediment fraction in gully-1. The time-weighted average design of the PASS sampler means it cannot provide information on suspended sediment dynamics during a flow event. However, the PASS sampler is well-suited for investigating long-term trends in suspended sediment concentration and particle size distribution (e.g., several wet seasons), and for assessing the effectiveness of gully remediation works. Comparison of the laboratory and field data of the PASS sampler to the autosampler and RS sampler shows the method provides the most representative time-integrated suspended sediment data of the three methods and because the PASS sampler data was most consistent with manually collected samples.

3.2.4 Turbidity Logger

The turbidity logger can provide a high frequency of suspended sediment concentration measurements over extended time periods (e.g., months), provided there are sufficient comparable physical samples collected to ensure accurate calibration of the method (Rasmussen et al., 2009). There were some instances, at gully-2, where turbidity measurements could have been corrected to suspended sediment concentration measurements, using samples collected by the autosampler ($R^2 > 0.83$ (SI-8)). However, this characteristic was not reflected in the measurements collected from gully-1, where the relationship between the autosampler sample suspended sediment concentrations and the turbidity logger measurements was poor (R^2=0.17 (SI-8)).

The lack of a relationship between turbidity and SSC at gully-1 was likely due to the higher proportion of sand at this site. The turbidity measurement method is based on the detection of light intensity, originally emitted from the instrument, refracted from a particle back to the instrument detector. A study by Rasmussen et al. (2009) found the presence of fine to very coarse sand (125-2000 µm) can often a negatively bias turbidity measurements because the larger particles do not reflect light in a manner that is consistent with that used to calibrate the instrument (Rasmussen et al., 2009). This measurement characteristic often leads to an underestimation of the turbidity-suspended sediment concentration relationship (Bent et al., 2003; Clark et al., 2009; Fowler et al., 2009).

Without site-specific calibration, turbidity measurements are unlikely to be suitable for even semi-quantitative investigations of suspended sediment dynamics in gully systems. This is evidenced by the lack of significant difference between the turbidity measurements of the loggers located in the two studied gullies (SI-9), despite very different suspended sediment concentration ranges and PSDs (Table 3, Figure 4). For example, the mean turbidity of gully-1 (1250 (± 1173) NTU) and gully-2 (1501 (± 994) NTU), for the 2017/2018 wet season, were not significantly different, yet the SSCs measured by the other methods differed by ~4 to 7-fold between these gullies (Table 3). This emphasises the importance of collecting representative suspended sediment concentration samples in-order to calibrate the turbidity measurement to a surrogate suspended sediment concentration. Turbidity measurements alone do not provide useful information and thus should only be relied upon as a complimentary addition to other monitoring methods (e.g., RS or PASS samplers).

Table 3. Time-weighted average suspended sediment concentrations and average particle size distributions of samples collected using different suspended sediment sampling methods from Gullies 1 and 2 during the 2017/2018 wet season. Note, some sampling periods had multiple flow events (SI-6).

		Gully-1			*Gully-2*		
Sampling period		Nov-17 to Jan-18	23-Jan-18	Jan-18 to Feb-18	Nov-17 to Jan-18	Jan-18 to Feb-18	Feb-18 to May-18
PASS sampler							
TWA SSC (mg L^{-1})		8,037	5,948	14,125	2,000	1,295	2,044
PSD (µm)	***d_{10}***	1.69	1.81	2.21	1.47	1.59	1.29
	d_{50}	9.09	12.3	16.2	6.03	6.81	5.32
	d_{90}	159	243	305	33	34.9	28.8
Autosampler							
TWA SSC (mg L^{-1})		6,030	5,364	9,976	1,916	1,106	1,232
PSD (µm)	***d_{10}***	1.53 (± 0.11)	2.54 (± 0.167)	1.8 (± 0.144)	1.35 (± 0.17)	1.24 (± 0.27)	0.917 (± 0.22)
	d_{50}	7.07 (± 0.774)	10.1 (± 0.951)	9.28 (± 1.09)	5.57 (± 0.76)	5.35 (± 1.10)	4.14 (± 0.79)
	d_{90}	65.2 (± 15.6)	88.5 (± 15.3)	115 (± 34.5)	25.2 (± 7.34)	22.6 (± 10.50)	15.9 (± 6.64)
RS sampler							
TWA SSC (mg L^{-1})		8,873	8,647	nd	2,172	nd	1,117
PSD (µm)	***d_{10}***	1.56 (± 0.111)	1.62 (± 0.172)	nd	1.49 (± 0.087)	nd	1.4 (± 0.056)
	d_{50}	7.62 (± 0.766)	8.45 (± 2.02)	nd	6.52 (± 0.465)	nd	5.99 (± 0.301)
	d_{90}	71.6 (± 18.3)	90.5 (± 37.5)	nd	33.6 (3.88)	nd	34.9 (± 13.3)

nd = no data

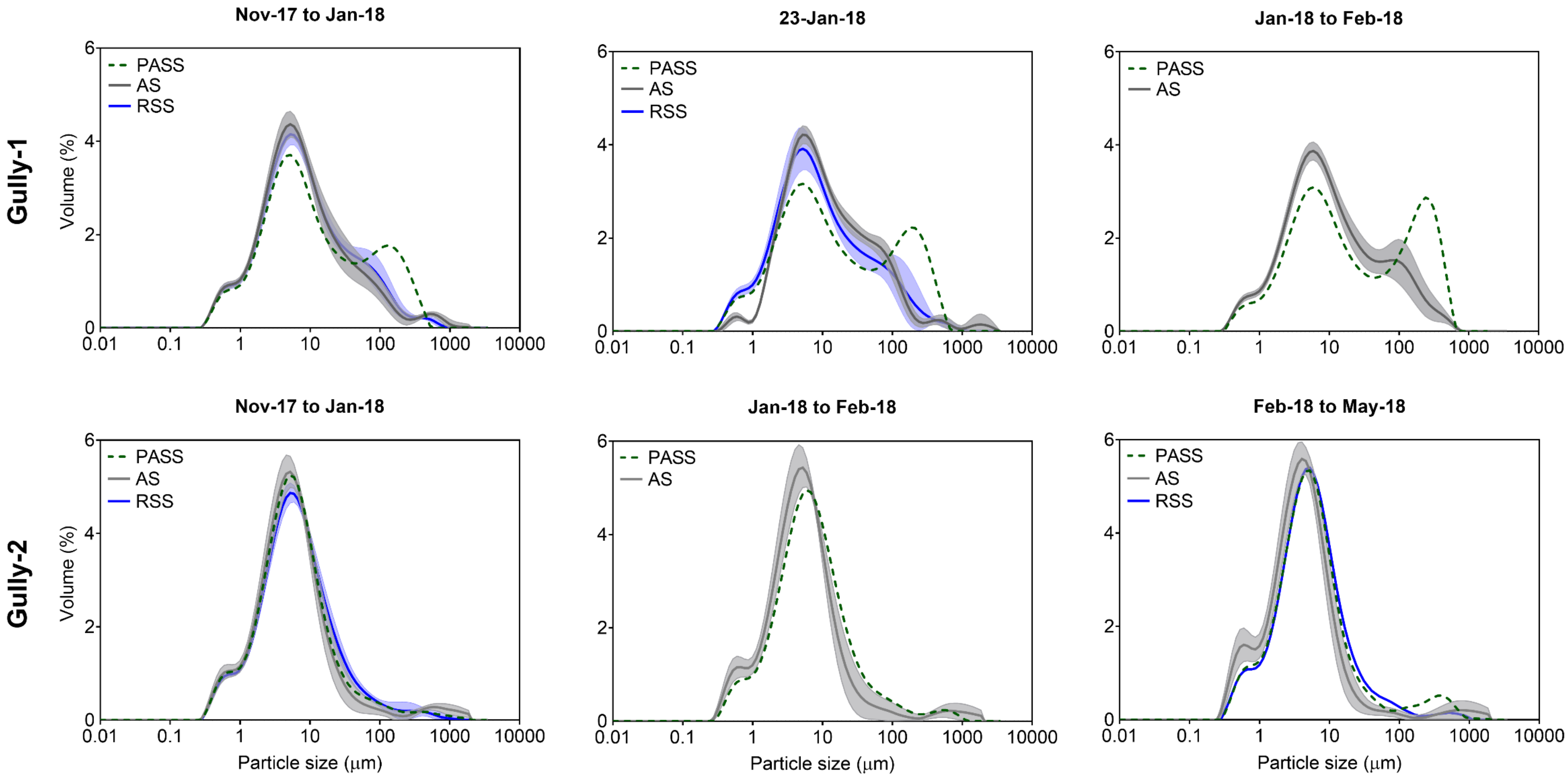

Figure 4. Average particle size distribution of samples collected from control and remediated gullies using autosamplers (grey), RS samplers (blue) and PASS samplers (green dashed). Shading indicates the error (standard deviation) for each technique. PASS data does not have a standard deviation because only one sample was collected per sample period. RS samples only represent the first flow event for each sampling period.

3.2.5 Comparison to manual sampling

The collection of manual samples from gullies is often difficult due to the remote location of the sites, safety concerns, and the unpredictability of flow events. However, samples were able to be collected from a single flow event in gully-1. Seven samples were manually collected during this event using a DH-48 sampler, and one time-integrated sample was collected over the same period by a PASS sampler deployed in the gully. There was little difference between average particle size distributions (Table 4, Figure 5) and the time-weighted average suspended sediment concentrations of the manually collected samples (6067 mg L^{-1}) and PASS sample (6082 mg L^{-1}), respectively. While these data are preliminary, it further supports the ability of the PASS sampler to collect representative samples of time-weighted average suspended sediment concentration and particle size distribution in challenging field settings.

Table 4. Time weighted average suspended sediment concentration and particle size distribution of samples collected using manual and PASS sampling methods from gully-1, during a single flow event on 6-Feb-2019.

PASS sampler	***TWA SSC (mg L^{-1})***	***PSD (µm)***		
		d_{10}	***d_{50}***	***d_{90}***
	6,067	1.62	8.01	68.9
Manual sampling	***TWA SSC (mg L^{-1})***	***PSD (µm)***		
		d_{10}	***d_{50}***	***d_{90}***
	6082	1.59 (± 0.101)	8.01 (± 0.706)	89 (± 26.5)
Difference between PASS and Manual samples	0.3%	1%	0%	23%

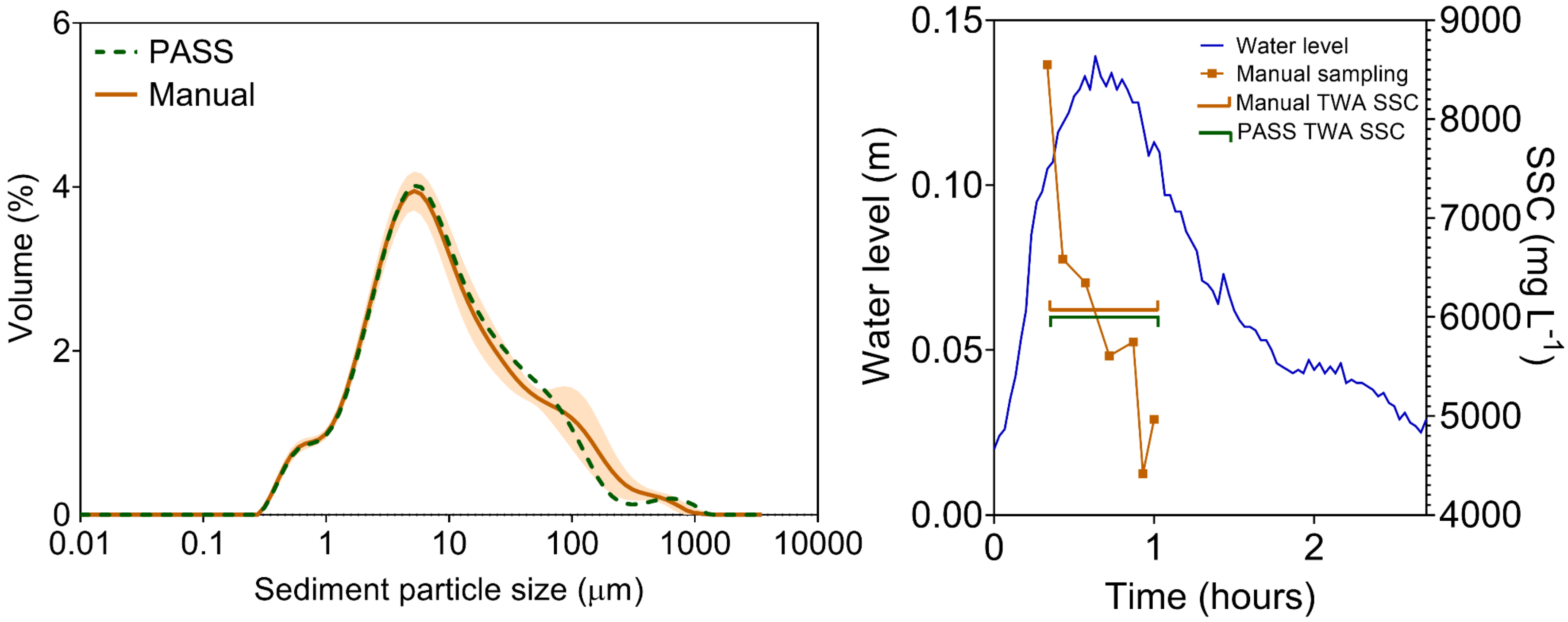

Figure 5. Suspended sediment concentrations and particle size distributions of samples collected during a single flow event on 6-Feb-2019. The average particle size distribution of manual samples (brown) and PASS sample (green dashed). Shading indicates the error (standard deviation) for the manual samples. Note the PASS only collected one sample. Hydrograph shows the water level (blue) and PASS (green) and manual (brown) sample time-weighted suspended sediment concentration, manual sample individual suspended sediment concentrations (brown squares). Note, the intake height of the PASS sampler was closer to the channel bed (~0.1 m) during this flow event due to sand aggradation in the channel during a previous flow event.

4 Conclusion

This study shows that no individual suspended sediment monitoring method is suitable for providing the necessary data to understand sediment transport dynamics in a flowing gully. Rather, the application of a combination of complimentary methods is necessary to reliably provide representative data from these challenging aquatic environments. For example, autosamplers provide multiple samples over a flow event but fail to sample coarser particles accurately; the calibration of samples collected by autosamplers with the time-integrated data from a PASS sampler, which does sample coarser particles relatively accurately, would result in a more reliable dataset than the use of either method alone. Other configurations could be used to improve the spatial scale of monitoring effort, for example, low cost methods (i.e., PASS and RS samplers) could be deployed at various locations throughout a network of gullies, whereas multiple methods (i.e., PASS and RS samplers, turbidity logger, and an autosampler) would be deployed at the gully network outlet.

The modified PASS sampler performed well in both laboratory and field trials. The modification of the PASS sampler to operate in gullies is a good example of how existing techniques can be customised to operate in the harsh environments typical of gully systems. We aim to further modify the PASS sampler by interfacing a flow meter and pump controller so that its sample rate can be matched to stream velocity, thus allowing the collection of a flow proportional (i.e., isokinetic) sample. Further comparisons using the PASS sampler and other methods in different gullies with varied suspended sediment dynamics are required to confirm its validity as an automated sampling method for gully systems.

5 Acknowledgments

The authors acknowledge the traditional owners of the country this study was conducted on. We thank the Laura Ranger group for their support throughout the field monitoring component of this study, we would not have half the information we do now without their help. We also thank William Higham and Michael Goddard for the opportunity to collaborate with them on the site. Much gratitude to John Spencer for his technical expertise and for the long hours of fieldwork and data processing. Thanks also to the assistance of Emily Looke.

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5 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

Manuscript prepared to be submitted to Hydrology and Earth System Sciences.

This chapter consists of a co-authored paper submitted to a peer reviewed scientific journal (Hydrology and Earth System Sciences). This manuscript has been written in the style stipulated by Hydrology and Earth System Sciences.

My contribution to the published paper involved:

Initial concept and experimental design.

Collection and analysis of data.

Preparation of manuscript.

[redacted]

Nicholas J. C. Doriean

[redacted]

Corresponding author of published paper: Andrew P. Brooks

[redacted]

Supervisor: William W. Bennett

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

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

[1] Environmental Futures Research Institute, School of Environment and Science, Griffith University Gold Coast campus, Queensland 4215, Australia

[2.] Griffith Centre for Coastal Management, Griffith University Gold Coast campus, Queensland 4215, Australia

[3] Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, South Australia 5095, Australia.

[4] Future Industries Institute, University of South Australia, South Australia 5095, Australia.

[5] Department of Environment and Science, Queensland Government, 4102 Brisbane, Australia

*Corresponding Author: andrew.brooks@griffith.edu.au

Abstract

Gully erosion is a dominant source (~40%) of fine suspended sediment pollution to the Great Barrier Reef. Mitigating this source of erosion will have a lasting positive impact on the water quality of downstream 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 into a catchment draining to the Great Barrier Reef. A novel suspended sediment monitoring network, comprised of a suite of new and established 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. Suspended sediment concentrations were >80% lower at the remediated site compared to the control site, indicating the remediation works were successful in stabilising the erosion within the gully. Dissolved and particulate nutrient concentrations were also significantly lower at the remediated site, consistent with the decreased sediment export. The novel combination of suspended sediment measurements from both the gully channel and the overland flow in the surrounding catchment suggests that sediment and nutrients at the remediated site are likely sourced from erosion processes occurring within the catchment (at relatively low concentrations), in contrast to the control site where gully erosion is the primary source of suspended sediment and associated nutrients. This study demonstrates the potential landscape-scale remediation has 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

Water quality in the Great Barrier Reef (GBR) is negatively impacted by fluvially sourced pollutants; primarily suspended sediment and dissolved and particulate nutrients (Bainbridge et al., 2018; Bartley et al., 2014; Brodie et al., 2012; Fabricius 2005). Land use change, such as, mining, agriculture (particularly grazing) 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 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 (Furuichi et al., 2016; Wilkinson et al., 2018). 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).

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 hr^{-1}) that can rapidly erode tonnes of soil from an actively eroding gully in a single storm (Brooks et al., 2015; BOM, 2019). 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 output to the GBR (Brooks et al., 2013; Brooks et al., 2019). Alluvial gullies are located on the floodplains or terraces of river systems and consist of mostly fine (<63 μm) dispersive sediments. 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).

Gully remediation efforts in GBR catchments have typically 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 geotextile fabric check dams (Bartley et al., 2017; Wilkinson et al., 2015; Wilkinson et al., 2013; Wilkinson et al., 2018). However, these strategies are not well-suited for stabilising the much larger alluvial gullies that are present in many GBR catchments. Recent research suggests alluvial gullies require the intervention of intensive landscape scale remedial efforts in-order to stem further erosion and reduce sediment export (Brooks et al., 2016; Brooks et al., 2018; Carey et al., 2015). 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, 2018).

Here we aim to conduct a preliminary evaluation of the effectiveness of landscape-scale remediation in reducing suspended sediment and nutrient (nitrogen and phosphorus) flow event concentrations associated with a large alluvial gully system in a GBR catchment. We applied a novel gully water-quality monitoring approach that utilises a suite of new and established autonomous suspended sediment sampling methods suitable for use in ephemerally flowing systems in remote locations (Doriean et al., 2019b). This new approach enables accurate measurement of both suspended sediment and nutrient concentrations, while meeting the financial and operational requirements of a monitoring program situated in a remote location.

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 occurs during the wet season (Brooks et al., 2014a). The study site topography is relatively flat 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 around 0.6 ha, with a catchment area of 13.7 ha. The active secondary incision of the control gully is around 0.2 ha while the gully catchment area is 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, tunnel erosion, head scarp mass-failure, and gully sidewall erosion within the incised part of the gully). Erosion rates derived from repeat airborne LiDAR between 2009 and 2015, when normalised for gully catchment area, suggest the control gully has slightly higher specific yield (77 t/ha) compared with the combined loads from the three active lobes of the treatment gully (45 t/ha). This suggests the two gully systems would have had similarly high suspended sediment concentrations when under flow. 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).

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).

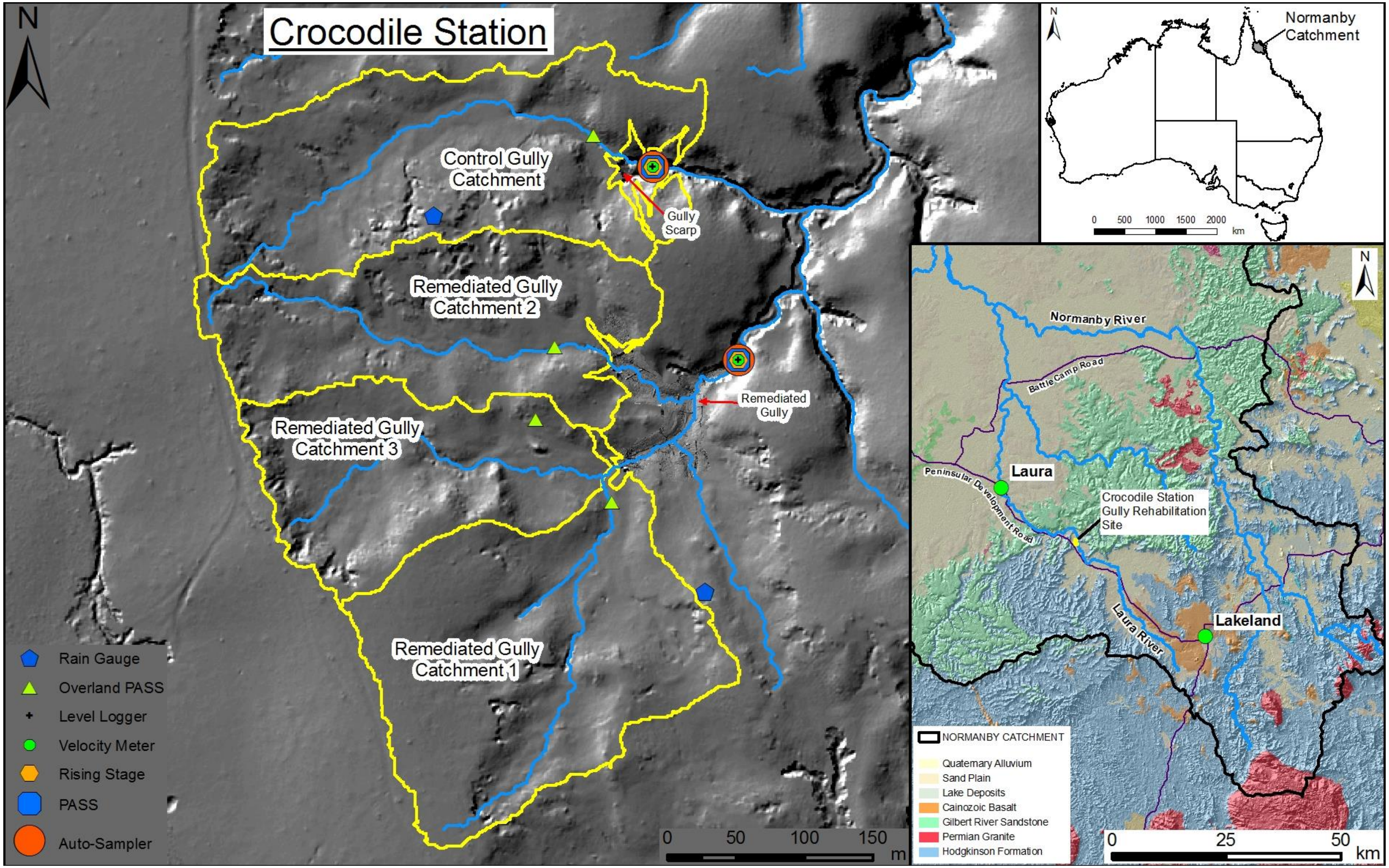

Figure 1. Topographic map of the study site, including surface geology and gully locations. Source: (Geoscience., 2019).

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 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 stock were excluded from the gully and its surrounding catchment. No remedial efforts were applied to the control gully, except for the exclusion of stock (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, there are many variables that need to be considered before implementing a monitoring plan to evaluate the 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 water quality condition (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 suspended sediment concentration (SSC) and particle size distribution (PSD). Entire flow events should 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., 2019b).

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 the 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 the PASS sampler to operate in gullies (Doriean et al., 2019b) 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: pumped active suspended sediment (PASS) samplers designed for gully deployments (Doriean et al., 2019b); rising stage (RS) samplers (Edwards et al., 1999); autosamplers (Edwards et al., 1999); and turbidity loggers (Gray et al., 2009 and Doriean et al., 2019b). Several monitoring methods were used in this study to provide multiple lines of evidence to determine the effectiveness of the remediation activities at reducing suspended sediment 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 (2019). 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 (Doriean et al., 2019b).

The TWA SSC and PSD of overland flow (i.e., catchment runoff) into the gullies was measured from samples collected using PASS samplers, configured to operate in ephemeral waterways (Doriean et al., 2019b). 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 were collected from the face and walls of the gullies using a hand trowel and auger. 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). Note, the soil samples primary purpose of the soil sampling was for the design of the gully remediation plan. The candidate used this data with the permission of those who collected the samples (the co-authors of this manuscript) for the purposes of the candidates PhD research.

2.5 Sample analysis and statistics

Samples collected 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). Samples were screened using a 2mm sieve prior to analysis to remove any debris or detritus. Sediment used for particle size analysis was not chemically treated and was kept in suspension using mechanical (i.e., a baffled container with an impellor stirrer) or ultrasonic dispersion methods (Doriean et al., 2019b). Nutrient analyses was conducted on a select group of samples. The samples were analysed for total and dissolved organic carbon, (APHA et 2005) and total and dissolved nitrogen and phosphorus (4500-Norg

D and 4500-P B). Dissolved nutrient species (ammonium, oxidised nitrogen, and phosphate) were also analysed (segmented flow analysis methods: 4500-NH3, 4500-NO3, and 4500-P) (Garzon-Garcia, Bunn, et al., 2018; Garzon-Garcia et al., 2015). Due the very difficult field conditions for sample retrieval it was only possible to collect nutrient samples from the autosampler 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 processed within the 48-hour timeframe. Consequently, the percentage of sand was likely underestimated in the samples, collected by the autosampler, analysed for nutrients (Doriean et al., 2019b).

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 ($p = 0.05$). 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 used during this study determined the approximate uncertainty associated with each method (Table 1) (Doriean et al., 2019b). These uncertainties were accounted for when interpreting data from the various methods.

Table 1. Uncertainties associated with suspended sediment monitoring methods used in alluvial gullies. Source: (Doriean et al., 2019b).

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

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). The flooding 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 events types (i.e., intensity, length, time of year; SI-3) to meet the objectives of the study.

3.1 Rainfall and major hydrological events

Rainfall totals at the study site for 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=0.59; 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 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 and available erodible soil, suggested the gullies likely had similar suspended sediment dynamics. The 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). This suggests the dominant source of suspended sediment in the remediated gully has been altered. 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 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., 2019b). 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 for comparing 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., 2019b), and monitored the most flow events for 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 short periods of time (Doriean et al., 2019a). However, comparable SSC data collected by manual flow proportional sampling, autosamplers, and RS sampler methods, which have high temporal resolution, correspond well with the SSC range of the PASS samples from both gullies (Doriean et al., 2019b) (Table 2).

The median TWA SSC of PASS samples collected from the control gully (7123 mg L^{-1}) was five times higher than the median SSC of samples collected from the remediated gully (1429 mg L^{-1}) (Table 3). This suggests there was significantly more sediment export from erosion in the control gully than in the remediated gully. Comparison of remediated and control gully SSC by sediment particle size class indicates the remedial works have significantly reduced the concentration of suspended sand (96%), silt (76%), and clay (73%) (Figure 2). Bulk densities of the different sediment size fractions were very similar (~0.1 g/mL 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. Continued monitoring of the remediated gully, for several more wet seasons, will be needed to determine the persistence of the sediment reductions associated with the gully remediation works.

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

Sampling location	***Remediated Gully***				***Control Gully***			
Sampling method	***AS***	***FP***	***RSS***	***PASS****	***AS***	***FP***	***RSS***	***PASS****
Number of values	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? (p-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.

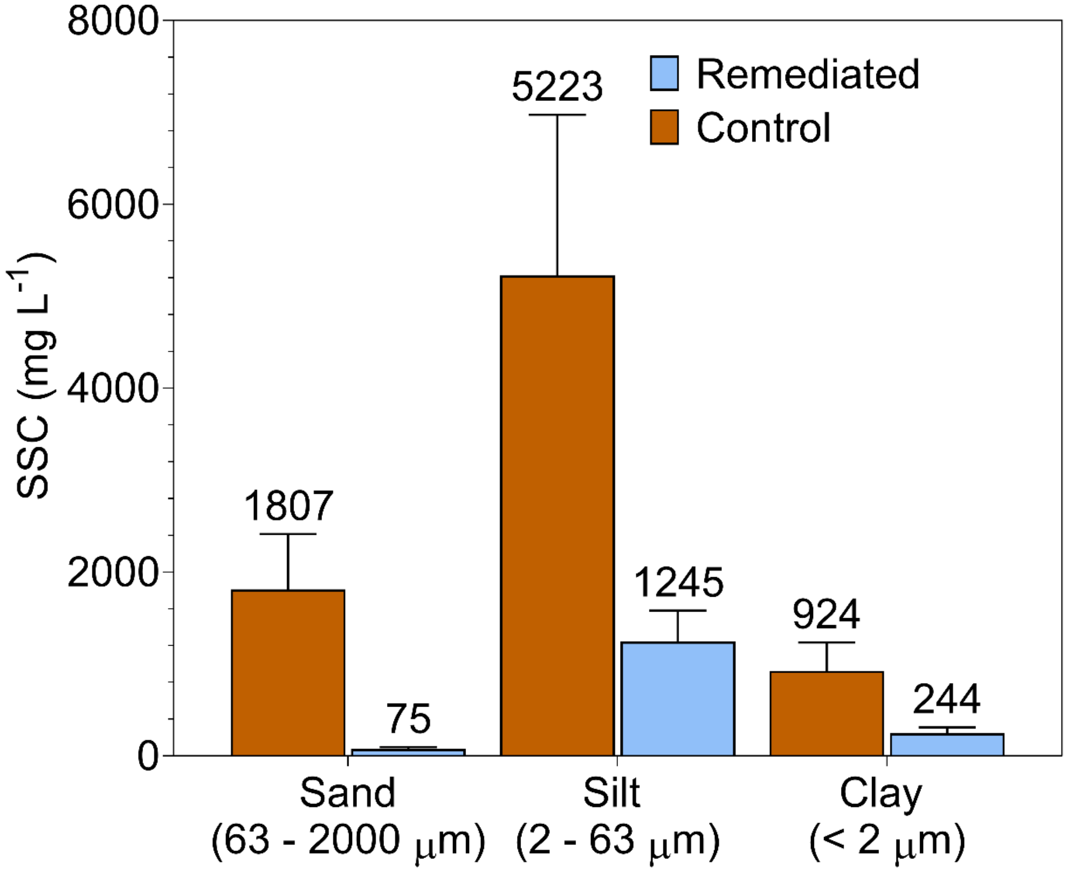

Figure 2. Median SSC by sediment size class for PASS samples collected from the control (brown) and remediated (blue) gullies during the 2017/2018 and 2018/2019 wet seasons. Error bars represent sample standard deviation. Autosampler and RS sampler SSC by PSD are included in SI-7.

3.2.2 Relationship between SSC and flow

There is currently insufficient water discharge data to accurately estimate a sediment load for 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 almost always infeasible. 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 can be very dangerous due to the risk of rapid water level rise (e.g., the control and remediated gullies can often encounter water level changes of 0.5 m in under 5 minutes). 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.

Preliminary water velocity measurements collected to date indicate there is a strong relationship between water level and velocity. Using water level as a proxy for velocity, it appears there is little hysteresis between SSC and water velocity in the control gully. However, SSC trends in the remediated gully appear to be linked to water level, likely as a function of velocity (Figure 3) (SI-3).

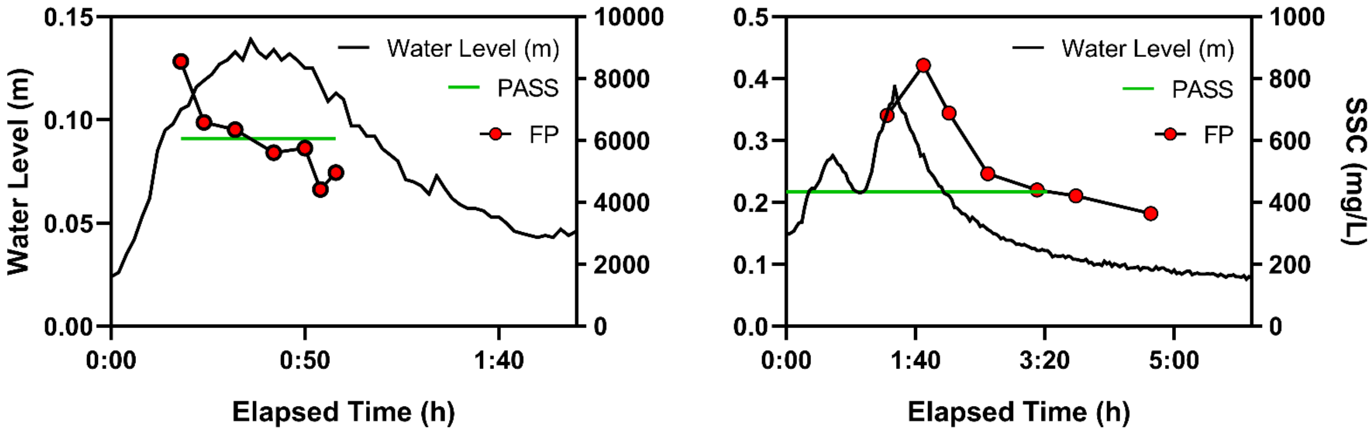

Figure 3. Relationship between SSC and stream height for single flow events in the control (left panel, flow event B) and remediated (right panel, flow event F) gullies, that occurred during the 2018/2019 wet season (SI-3). Water level (black line), PASS TWA SSC (green line), and flow proportional (FP) 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 4). 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 the previous flow event contributing 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). This process has 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 4). The SSC trend in the gully is no longer symptomatic of an actively eroding system, rather, it is more similar to that of a stream (Doriean *et al.* 2019a). This suggests gully erosion is no longer the dominant sediment source and the gully may now be a conduit for suspended sediment sources from erosion processes occurring in the catchments.

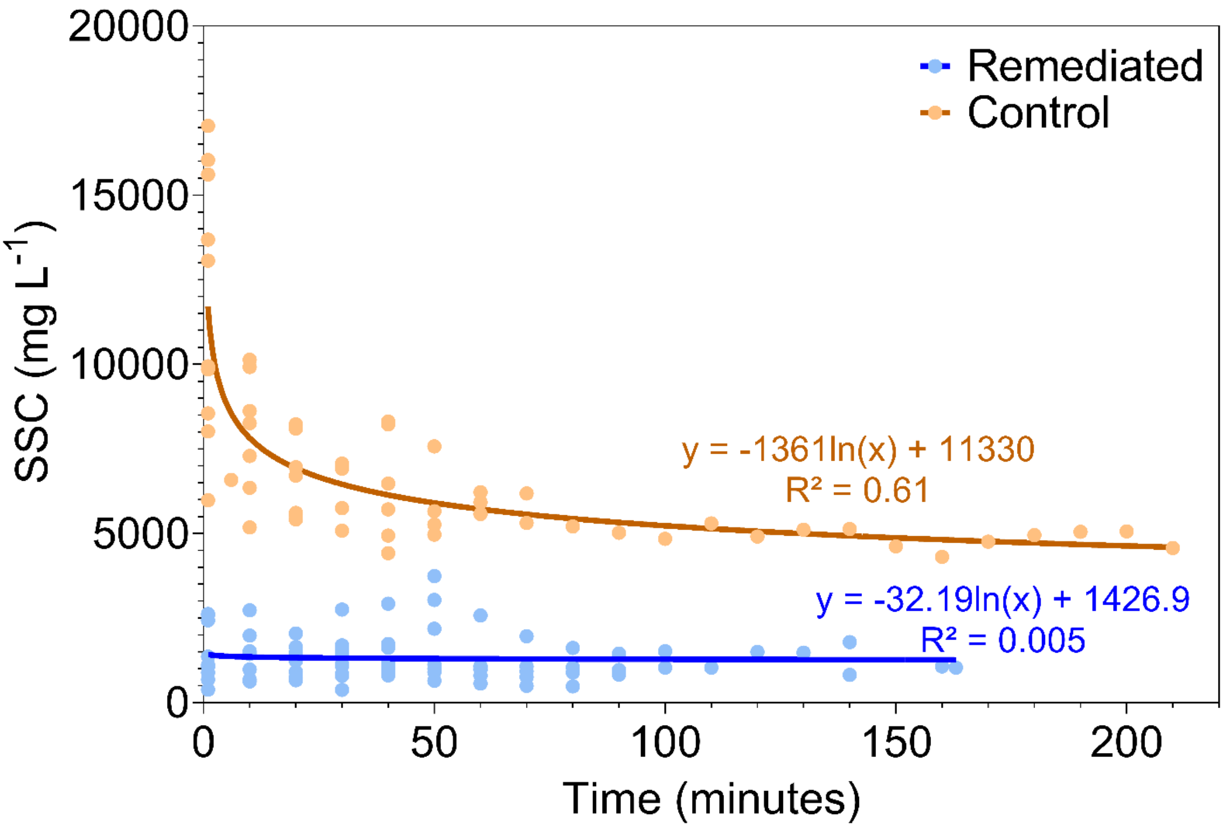

Figure 4. Relationship between time after initiation of flow and SSC of samples collected from the control (brown) and remediated (blue) gullies using autosamplers and RS samplers during the 2017/2018 and 2018/2019 wet seasons. Trend lines represent logarithmic regression models.

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 5). For both gullies, ~45% of readily erodible soil from the gully was comprised of sand, with the remainder being silt (~35%) and clay (~20%). 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 and mixed with sediment transported from the catchment (Figure 6). This change in PSD is expected because the sediment particles will distribute throughout the water column based on their physical and chemical characteristics (e.g., shape, size, mass, affinity to flocculate into composite particles) (Vercruysse et al., 2017; Walling et al., 2016). Hence, the 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 in the control gully channel bed support 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 in the remediated gully samples (Figure 7). There was no visual evidence of bedload sediment being transported in the remediated gully outlet channel, with heavier sediment particles visibly trapped behind check dams (SI-9). Comparison of suspended sediment PSD characteristics (10th (d_{10}), 50th (d_{50}), and 90th (d_{90}) percentiles) of PASS samples collected from the control and remediated gullies show that the suspended sediment from the remediated gully (d_{50} of 5.84 µm) was significantly finer than the control gully (d_{50} of 10.8 µm) (Table 3).

The suspended sediment average PSD characteristics of the control gully outlet and catchment were significantly different (Table 3). This indicates the contribution of suspended sediment from gully erosion (d_{50} 10.8 µm) is greater than the suspended sediment contribution of the catchment (d_{50} 4.29 µm) in the control gully. In contrast, there were no significant differences between the PSD characteristics of suspended sediment samples collected from the outlet of the remediated gully (d_{50} of 5.84 µm) and samples collected from catchments 2 (d_{50} of 5.52 µm) and 3 (d_{50} of 5.06 µm) of the three catchment areas draining into the gully (Table 3) (Figure 8). This suggests there is a notable contribution of sediment entering both gullies from their respective catchments. The lack of similarity in suspended sediment PSD characteristics between the remediated and control gullies, 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 catchments.

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 were 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
Significantly different?	***p-value***			
Control gully to Remediated gully	Yes 0.003	Yes 0.028	Yes 0.027	Yes 0.021
Control catchment to Control gully	Yes 0.014	Yes 0.043	Yes 0.036	Yes 0.015
Remediated gully to Control catchment	No 0.962	Yes 0.049	No 0.057	No 0.825
Remediated catchment 1 to Remediated gully	Yes 0.012	No 0.065	Yes 0.018	No 0.226
Remediated catchment 2 to Remediated gully	No 0.229	No 0.380	No 0.613	No 0.700
Remediated catchment 3 to Remediated gully	No 0.470	No 0.760	No 0.278	No 0.299

TWA SSC of catchment samples is represented as a range due the small of number of PASS samples collected (n=2). This is an acceptable number for a T-test. Please note, each catchment PASS sample TWA SSC represents the average SSC of several flow events.

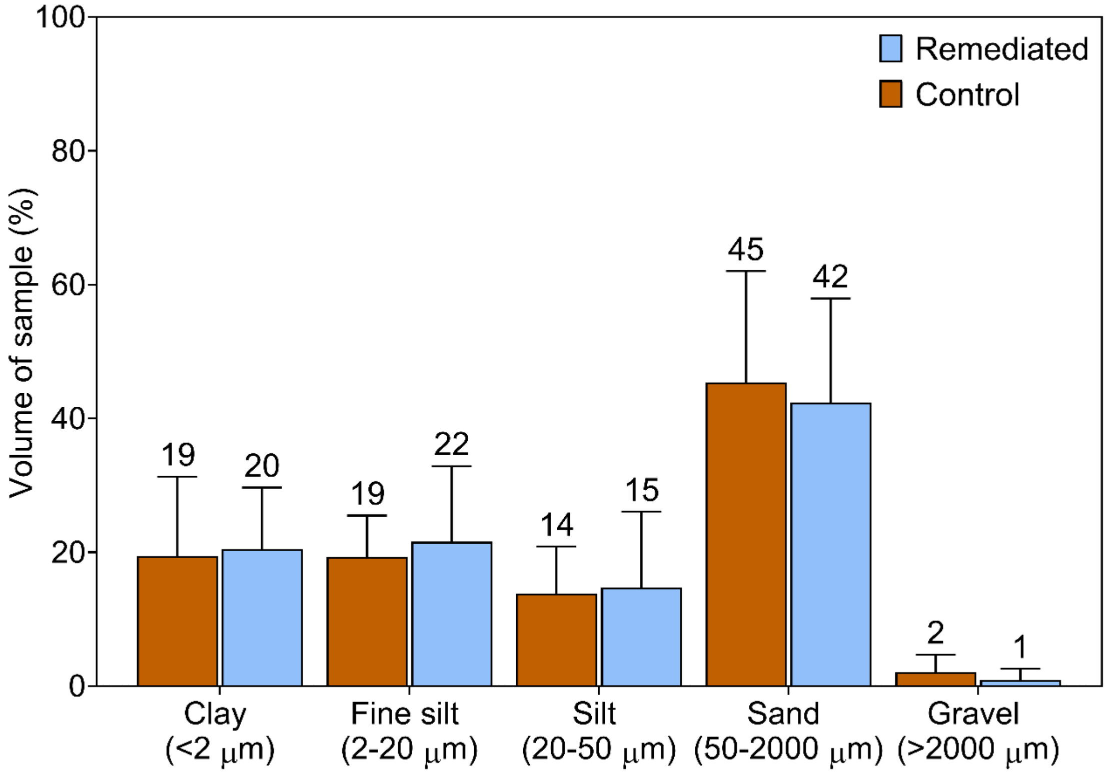

Figure 5. Average PSDs, by size class, of soil collected from the control (brown) and remediated (blue) gullies, prior to remedial works. Error bars represent the standard deviation of each class. Control n=4 and remediated n=14.

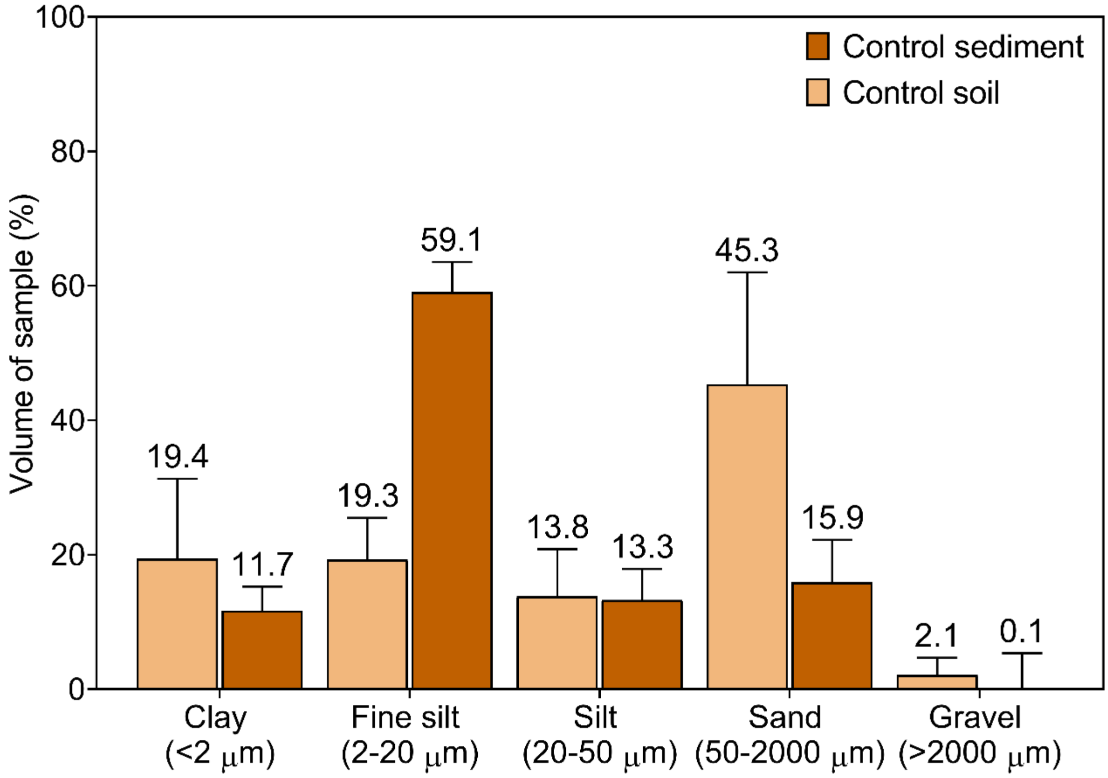

Figure 6. Control gully soil (brown, n=4) and control gully suspended sediment (light brown, n=6) PSD by size class. Error bars represent error as standard deviation for the soil and sediment PSDs respectively.

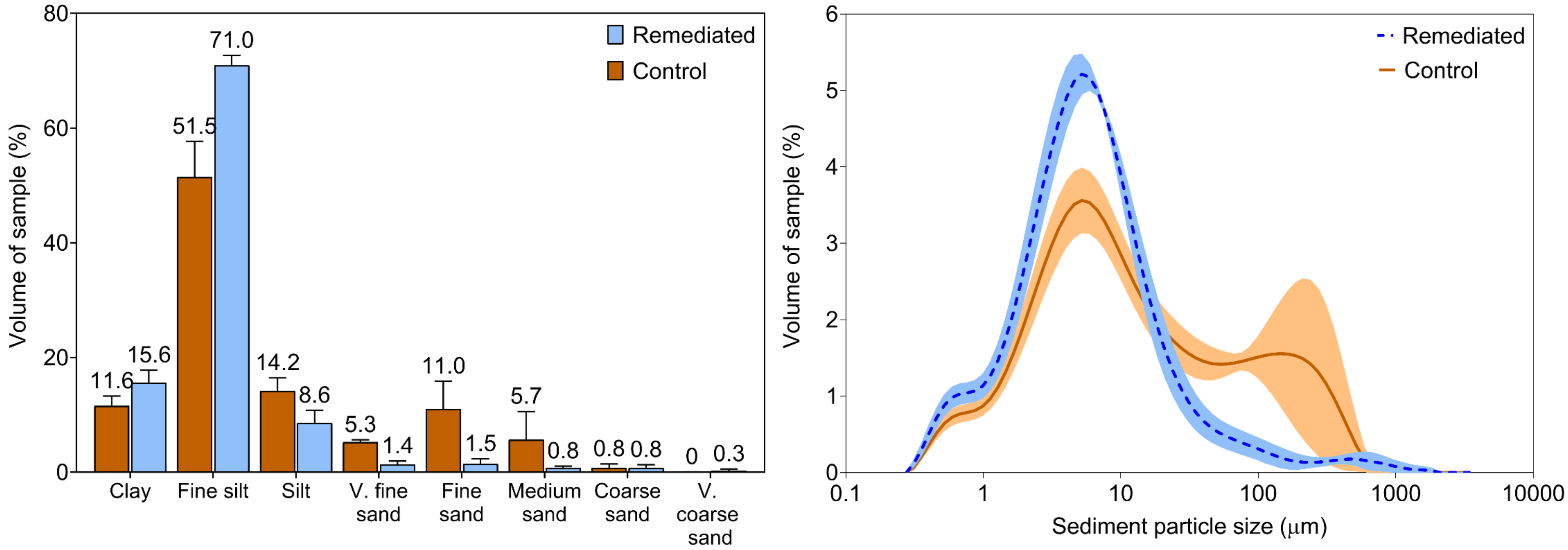

Figure 7. Average suspended sediment PSD by sediment size class (left panel) and plotted by frequency (right panel) for PASS samples collected from the control (brown) and remediated (blue) gullies during the 2018/2019 and 2018/2019 wet seasons. Error bars (left panel) and shading (right panel) indicate 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.

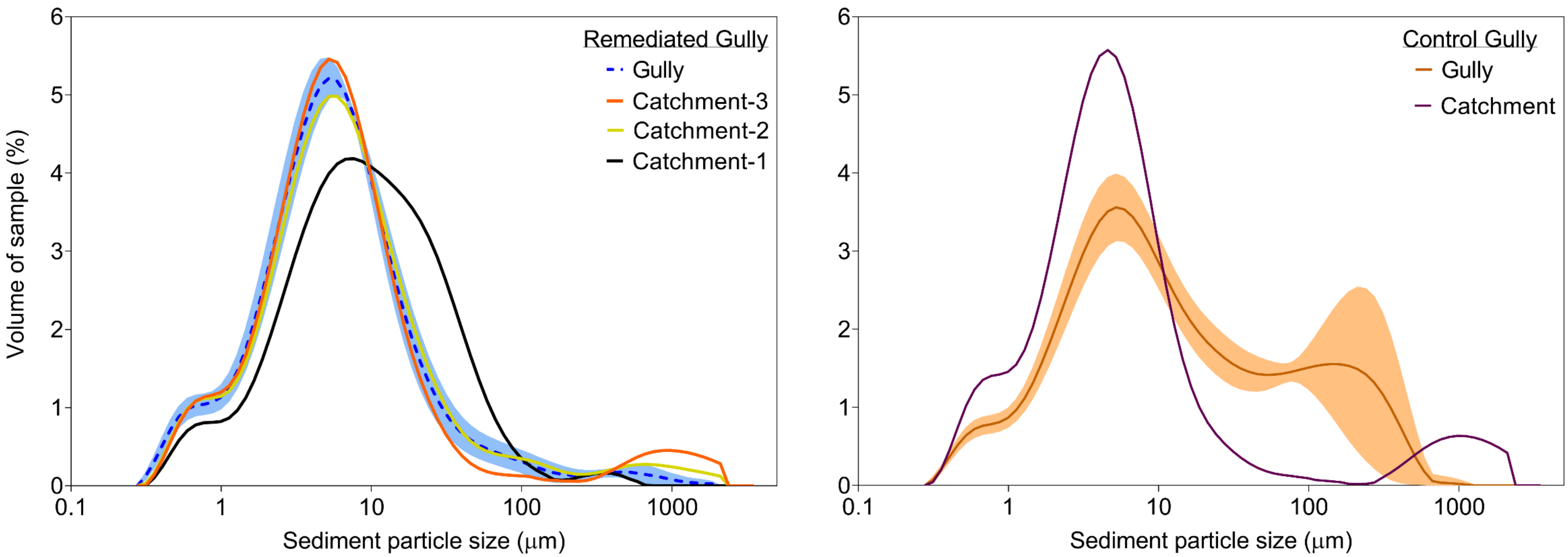

Figure 8. Average PSDs of PASS samples collected from the remediated gully (blue) and catchments (orange, yellow, and black) and control gully (brown) and catchment (purple) suspended sediment PSD frequency plots, during the 2018/2019 wet season. Shading around gully PSDs represents error as standard 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 retrieved from the remote sampling site within a time frame (i.e., refrigerated samples filtered and frozen within 24 hours of collection) that allowed for analysis of dissolved and particulate nutrients. The hydrographs and SSC trends of these events indicate they are representative of the flow events observed in the two gullies (SI-3). 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 9). 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 9).

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 the chemical speciation (Garzon-Garcia et al., 2016; Garzon-Garcia et al., 2015; Lloyd et al., 2019). We do not currently have enough information to investigate the effects these processes have on dissolved nutrient trends occurring in the gullies and their catchments, so our interpretation of this data will be limited. However, particulate nutrients and carbon are more stable, taking days or weeks to undergo changes due to biogeochemical processes (Garzon-Garcia, Lewis, et al., 2018). Thus, 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 concentration in the remediated gully (Figure 10; SI-10). The strong positive relationship between SSC and nutrient concentrations in the control gully supports the hypothesis that erosion processes of the gully are acting as the dominant source of suspended sediment and particulate nutrients. In contrast, the poor relationship between SSC and nutrient concentration 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. 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 (Figure 7) (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. However, our PSD data is consistent with a dominant catchment source of suspended sediment associated particulate nutrient sources in the remediated gully. Whereas, the significant relationships between SSC and particulate nutrients in the control gully demonstrate that eroding subsoil was 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.

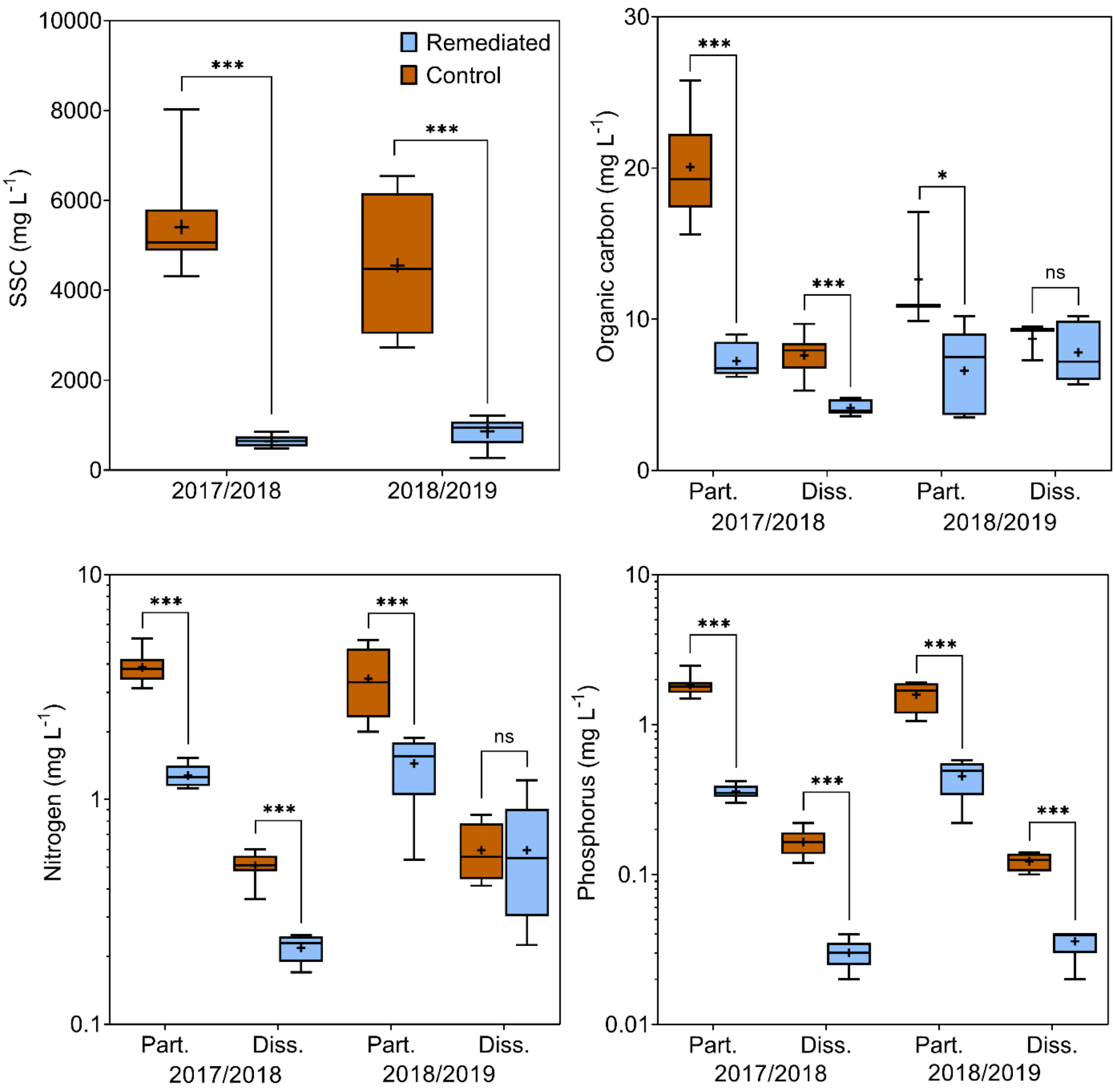

Figure 9. SSC and nutrient concentrations of samples collected during flow events in the 2017/2018 and 2018/2019 wet seasons. Note, the 2017/2018 data represents a single flow event and the 2018/2019 data represent multiple flow events. Box plots represent the minimum, maximum, 25th and 75th percentiles, 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).

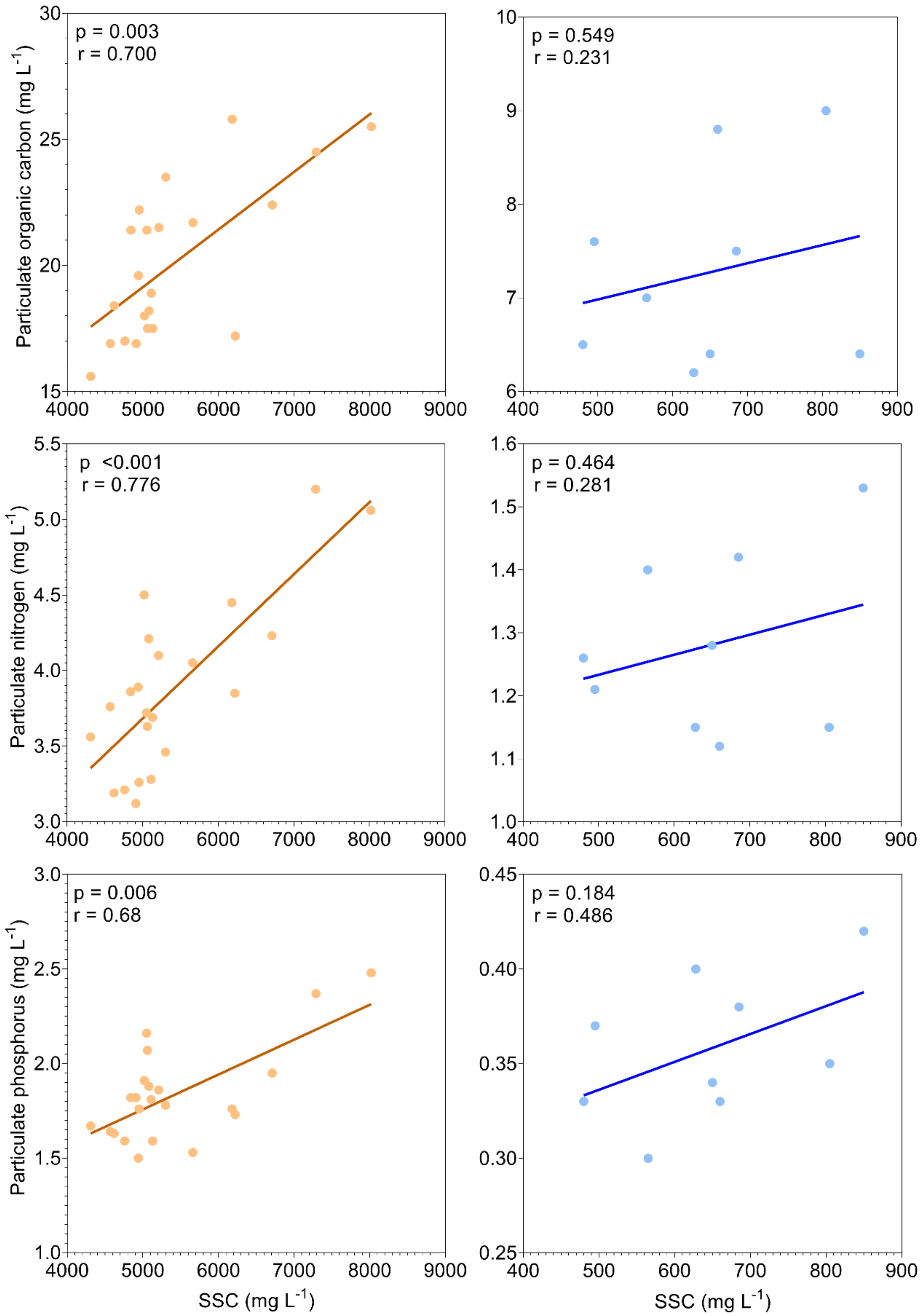

Figure 10. Relationships between SSC, and POC and nutrient concentrations in the control (brown) and remediated gully (blue) from single flow events on the same day during 2017/2018 wet season.

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 activities to ensure their effectiveness is appropriately measured. 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 in regard to in-stream suspended sediment heterogeneity; 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 not be a feasible approach with the other 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 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 is accompanied by the added benefit of significant reductions in nutrients (nitrogen and phosphorus) and carbon concentrations flowing through the gully. To further understand the effects of these reductions on bioavailable nutrient export, future studies should investigate the speciation of particulate and dissolved nutrients in remediated and active alluvial gully systems. This study has demonstrated the advantages of using multiple suspended sediment monitoring methods in a configuration that ensures one method is complimentary to the limitations of another. Future water quality studies, particularly in different alluvial gully types, should implement similar monitoring networks to determine if the findings of this study are applicable to the wide range of alluvial gullies in the catchments of the GBR. The intensive remediation of alluvial gullies, as described in this study, represents a promising opportunity to significantly reduce the contribution of sediment and associated nutrient flowing from gullies to the GBR. However, more information is needed, particularly sediment load estimates, and the assessment of remediation longevity (i.e., decadal timescale monitoring data) should be conducted.

5 Acknowledgments

The authors acknowledge the traditional owners of the country this study was conducted on. We thank the Laura Ranger group for their support throughout the field monitoring component of this study. We also thank William Higham and Michael Goddard, from Cape York Natural Resource Management, for giving us the opportunity to collaborate with them on the site at Crocodile Station.

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6 Conclusion

This thesis presents a series of research chapters focused on improving suspended sediment monitoring of aquatic environments in challenging and remote conditions. This study included the development of a new suspended sediment sampling method (the PASS sampler) designed to semi-autonomously collect representative samples from small streams and rivers. This was followed by a detailed evaluation and comparison of the performance against established suspended sediment monitoring methods with a PASS sampler modified for deployment in remote ephemerally flowing waterways, and the application of a suite of these monitoring tools to investigate the suspended sediment dynamics of actively eroding and remediated gully systems.

Chapter 3 describes the development of a novel method for measuring suspended sediment. The PASS sampler is an affordable automated method that collects a time-integrated sample via the continuous collection of water when the device is in operation. This study demonstrated that the PASS sampler works effectively and collected samples that were representative of the TWA SSC and PSD of suspended sediment in a perennial urban stream under challenging sampling conditions (i.e., short and intense flow periods). Due to its low cost, robust design and capability for long deployments (i.e., days to weeks) the PASS sampler could be deployed in high numbers throughout a catchment (e.g., samplers located at individual streams and along a river) to provide a representative measure of suspended sediment dynamics on a landscape scale.

Chapter 4 describes the successful optimisation of the PASS sampler to be used in ephemerally flowing systems as well as a laboratory and field evaluation of the PASS sampler and established suspended sediment monitoring methods for operation in alluvial gullies. The laboratory and field evaluation validated the application of the PASS sampler in an alluvial gully. The data also showed that no individual method could provide all necessary information to define the suspended sediment dynamics of a flowing gully. Rather, the application of multiple methods used in a configuration complimentary to their limitations provided the most representative data in these challenging environments. The knowledge gathered in this chapter allowed for the design and implementation of a comprehensive monitoring network to evaluate gully erosion mitigation effectiveness (Chapter 5).

Chapter 5 describes the application of the newly developed PASS sampler designed for sampling ephemeral aquatic systems, in combination with a suite of complimentary suspended sediment monitoring methods, to provide a preliminary evaluation of the impact of landscape-scale remediation on suspended sediment and nutrient transport in an alluvial gully network located in a catchment of the Great Barrier Reef. A comparison between a remediated and control gully showed there was a significant reduction in suspended sediment concentration across all particle size classes (i.e., clay, silt, and sand) in samples collected from the remediated gully. Additionally, suspended sediment-associated bioavailable nutrients (i.e., particulate nutrients) were also significantly reduced. Some of the key data of this investigation was found through the innovative approaches to monitoring suspended sediment. For example, the application of the PASS samplers to collect suspended sediment from runoff from the catchment entering the head of both gullies provided crucial data that indicated the catchment had become the dominant source of sediment post remediation. This study demonstrated the benefits of using multiple monitoring techniques applied in customised configurations to ensure the most representative data is collected.

This thesis focused on expanding our understanding of remote alluvial gullies and our ability to monitor their water quality. However, much broader implications have arisen from this work. The lack of data collected from significant sources of suspended sediment (i.e., remote and unpredictable systems) limits our ability to understand and manage aquatic environments. This study provides insight into the limitations of our current monitoring methods and also gives direction for where effort should be placed in future monitoring. The mitigation of gully erosion will make a lasting improvement to the water quality of downstream systems. The data collected in Chapter 5 demonstrates that landscape scale intensive gully remediation is effective at reducing sediment and particulate nutrient concentrations. Further evaluation of this remediation method in different gully systems is required to validate these findings. As our ability to monitor the hydrological dynamics of gully erosion expands, we will be better prepared to manage these systems. It is likely that gully erosion control measures will be implemented in greater numbers in-order to improve downstream catchment water quality and the research described in this thesis provides components for establishing a foundation for how the success of these mitigation actions will be measured and assessed.

7 Future Research

Several areas of future research were identified from this study:

1. Collection of samples for the analysis of suspended sediment-associated nutrients and contaminants is the next logical step in the optimisation of the PASS method. Testing needs to determine if it is possible to collect a representative time-integrated sample of sediment-associated compounds without preservation, and define its limitations. Modification of the sampler design may also be necessary. For example, the use of the PASS sampler for the collection of nutrient samples may require the main body of the sampler to be refrigerated in order to reduce microbial alteration of analytes, whereas the collection of metal samples may require pre-treatment of the sampler or the use of inert materials to limit contamination.
2. This study has demonstrated the use of the PASS sampler in remote and unpredictable fluvial environments (i.e., streams and gullies). However, there is potential to evaluate the practicality of using the PASS sampler in other remote systems. For example, the sampler could be modified to operate in tidal systems linked to a water level sensor to sample on particular tides or it could be deployed in deep marine waters to evaluate the movement and settling of suspended sediment in coastal zones.
3. The results of chapters 4 and 5 highlighted how little we know of how soil eroded from gullies transforms into suspended sediment and the instream processes that occur as the suspended sediment and associated compounds are transported through a catchment. The application of the monitoring method configurations used in this study could be applied to gather information on these processes. For example, data collected from a grid of PASS and RS samplers located above a gully head and in high density at the base of an actively eroding head scarp could provide information on the transition and mixing of eroding soils and suspended sediments. Furthermore, the application of high temporal resolution methods (e.g., autosamplers or surrogate monitoring devices) paired with velocity measurements could assess how sediment dynamics and loads change at different locations in a gully system.
4. The results of chapter 5 showed there is a need for an affordable method to estimate suspended sediment loads from remote waterways. This method would also need to be able to operate independently for several months whilst providing an accurate measure of sediment discharge. The modification of the PASS sampler to collect flow-proportional samples using a water velocity sensor coupled to a pump speed controller

could address this gap in monitoring capability, whilst remaining relatively affordable compared to established methods.

8 Appendix

Appendix 1. Griffith University Higher Doctorates by Publication Policy

Higher Doctorates by Publication Policy

Doctor of Letters (DLitt) | Doctor of Science (DSc)
Doctor of Philosophy by Prior Publication (PhD Prior Pub)

Approving authority	Academic Committee
Approval date	16 July 2015 (5/2015 meeting)
Advisor	Dean | Griffith Graduate Research School | ggrs-dean@griffith.edu.au | (07) 373 57290
Next scheduled review	2020
Document URL	http://policies.griffith.edu.au/pdf/ Higher Doctorates by Publication Policy.pdf
TRIM document	2019/0000032
Description	This policy covers higher doctorates that are awarded by the University in recognition of substantial scholarly achievements especially through published works.

Related documents

Intellectual Property Policy
Higher Degree Research Policy
Student Academic Misconduct Policy
Academic Misconduct Policy - Higher Degree Research Candidates
The Responsible Conduct of Research
Fees and Charges Policy
Student Administration Policy
Conflict of Interest Policy
Statement Regarding Integrity of Student Admissions, Scholarships and Prizes, Processes and Decision Making at the University
Higher Degrees Research Website

1. SCOPE

1.1 This policy prescribes the requirements for the award of Higher Doctorate qualifications, including the Doctor of Letters (DLitt), Doctor of Science (DSc), and Doctor of Philosophy by Prior Publication (PhD Prior Pub). Higher Doctorates are not Higher Degree Research (HDR) programs and are therefore not reported to Government as an HDR completion. Refer to the *Higher Degree Research Policy* for conditions for the award of HDR programs, including the Doctor of Philosophy (PhD).

Elaboration of this policy is available on the Higher Degree Research Website. Where there is an inconsistency between the policy and the website, the policy applies.

1.2 DLitt, DSc

The Council may confer the degrees of Doctor of Letters (DLitt) and Doctor of Science (DSc). These prestigious degrees are awarded to eminent doctoral graduates who have made outstanding contributions to their field and who have had a substantial association with the University.

1.3 PhD by Prior Publication

The PhD by Prior Publication arrangement enables the degree of PhD by Prior Publication to be awarded to candidates on the basis of their original scholarly contribution to knowledge in research areas of strategic importance to the University. The purpose of the program is to allow formal recognition of established researchers who do not already hold a doctoral level qualification, who have substantial international standing in their respective fields on the basis of their record of academic publication, and for whom enrolment in the existing PhD program would be inappropriate. Previous association with the University is not required.

2. DEFINITIONS

AQF qualification is a completed University accredited program of learning that leads to formal certification that a graduate has achieved the learning outcomes as described in the AQF.

Discipline refers to a defined branch of study or learning consistent with the field of education classification in the Australian Standard Classification of Education (ASCED). The ASCED includes 12 broad fields of education with each classification further divided into narrow and detailed fields of education. Same discipline qualifications are designed to deepen knowledge, skills and application and different discipline qualifications are designed to broaden knowledge, skills and application through further learning.

Domestic students (candidate) refers to students who are an Australian citizen; or an Australian permanent resident or holder of an Australian Permanent Humanitarian visa; or a New Zealand citizen.

Elements include Schools, Departments, Research Centres, Colleges, Institutes, other budget elements in which students are enrolled, as well as central administration and support units.

Field of study refers to the main focus of work activities and/or a learning program. Refer also to Discipline.

Full-time equivalent (FTE) refers to the duration of candidature expressed as full-time equivalent where a student undertakes part-time study.

Higher Degree by Research (HDR) refers to a Research Masters or Research Doctorate where a:

- Research Masters means a Level 9 qualification as described in the AQF and where a minimum of two-thirds of the program of learning is for research, research training and independent study.
- Research Doctorate means a Level 10 qualification as described in the AQF and where a minimum of two years of the program of learning, and typically two-thirds of the qualification, is research.

Higher Doctorate refers to a doctoral degree that may be awarded by an institution on the basis of an internationally recognised original contribution to knowledge rather than through the process of supervised independent study.

International student (candidate) refers to students who are **not** an Australian citizen; or an Australian permanent resident or holder of an Australian Permanent Humanitarian visa; or a New Zealand citizen.

Learning outcomes are the expression of the set of knowledge, skills and the application of the knowledge and skills a person has acquired and is able to demonstrate as a result of learning.

Research comprises *systematic experimental and theoretical work, application and/or development that results in an increase in the dimensions of knowledge, culminating in a thesis, dissertation, exegesis or equivalent that is formally examined.* The term ***research*** includes original, exploratory, experimental, applied, clinically or work-based and other forms of creative work undertaken systematically to increase knowledge and understanding, deploying a range of research principles and methodologies.

3. THE DEGREE

3.1 DLitt, DSc

The appropriate degree of Doctor may be awarded by the University Council on the recommendation of the Board of Graduate Research Committee for original and substantial contributions of distinguished scholarship adding to the knowledge and understanding of any branch of learning with which the University is concerned.

The award of the degree shall be based on the examination of substantial published work, or a combination of thesis and published works.

3.2 PhD Prior Pub

The degree will be awarded to a candidate who, through published work of which the candidate is either sole author or primary author (that is, responsible for the intellectual content and the majority of writing of the text), has made an original scholarly contribution to knowledge and demonstrated a capacity for independent research as judged by independent experts applying appropriate international standards.

The published work may consist of journal articles, book or book chapters. It may also include original creative work where appropriate to the discipline. Whatever the form, the publication(s) must have been subjected to peer review and be published in high quality outlets of international standard. The number of publications to be presented for the award of the degree will vary based on the nature of the published work and the candidate's research field, and what is required in order for the work to be presented as an integrated theme. Where additional research work is required in order for the work to form an integrated theme, the candidate will normally not be admitted and will be advised to apply for admission to the PhD program.

The published work may be based on or manifested in rigorous experimental, theoretical, creative, empirical and/or design inquiry. The standard for the degree will be the same as that required for the degree of PhD at Griffith University.

The PhD by Prior Publication will not include unpublished work, review articles, newspaper articles, articles in non-refereed professional journals, work that has already been submitted successfully or unsuccessfully for the award of a degree at any university, or works where the applicant's role was that of editor.

The policy and procedures pertaining to the PhD in the *Higher Degree Research Policy* are closely connected to this degree and links are made to the HDR Policy throughout this document.

4. ADMISSION

4.1 Eligibility for Candidature

4.1.1 DLitt, DSc

A candidate for these higher doctorates shall either be a graduate of the University of at least five-years standing, or hold equivalent qualifications in another university or institution recognised for the purpose by the University, and have a substantial association with the University.

4.1.2 PhD Prior Pub

The following criteria need to be satisfied for admission:

- applicants will be established researchers and be of international standing in their respective field on the basis of their ongoing record of academic work, and for whom admission to the PhD program is inappropriate;
- applicants will have a portfolio of high quality publications, published in quality outlets of international standard, which may be presented as an integrated theme;

- applicants will be researchers in areas of strategic importance to the University and be consonant with the academic aims and objectives of the Element to which admission is sought; and
- the Element is able to provide the necessary resources and supervision expertise.

An applicant who has already been awarded a doctoral level qualification will not be admitted to candidature.

An applicant who is pursuing, or who has previously pursued within the previous five years, a program of research under the University's *Higher Degree Research Policy*, or an equivalent rule at another Australian or overseas university, will not be admitted to candidature, except that an experienced researcher may make a case for admission.

4.2 Admission Procedures

4.2.1 DLitt, DSc

A person who proposes to become a candidate for the degree shall first submit to the Board of Graduate Research Committee a list of his/her publications and a curriculum vitae. The applicant should include an indication of how his/her work has developed, the way in which the publications relate to each other to constitute a theme, and the extent to which the publications make an original and substantial contribution to knowledge and understanding. Where joint publications are concerned, the applicant shall make clear his/her own contribution. The applicant should also provide a statement detailing the extent of his/her association with the University. The applicant will not be required to enrol but must pay any prescribed fee.

On receipt of a proposal for candidacy, the Board of Graduate Research Committee shall appoint an ad hoc committee, composed of at least three academic staff members. The ad hoc Committee normally will be convened by the Dean, Griffith Graduate Research School. The ad hoc Committee shall consult with the appropriate Dean (Research)/Director (or the Dean, Griffith Graduate Research School or his/her nominee where the Dean (Research)/Director shall himself/herself be a candidate), and recommend to the Board of Graduate Research Committee whether the applicant should be admitted as a candidate. If admission is recommended, the ad hoc Committee shall also recommend an appropriate composition of the Examination Board, including at least one reserve examiner.

The Board of Graduate Research Committee shall consider the recommendation of the ad hoc committee as to the eligibility of the applicant and shall decide whether they will be admitted as a candidate

4.2.2 PhD Prior Pub

An intending applicant must complete and submit an approved application form (Refer to the application form for all application requirements). Applicants will be required to enrol and pay any charges (refer section 4.3.2).

Deans (Research), after consultation with relevant Head of Element, are responsible for determining that applicants not be admitted as candidates, or recommending to the Dean, Griffith Graduate Research School that applicants be admitted as candidates. The recommendation to the Dean, Griffith Graduate Research School will include advice on the strategic importance of the research and proposed program of study to the University.

The Dean, Griffith Graduate Research School may approve an application for candidature provided that the Element is able to provide the necessary supervision, resources and facilities without compromising its capacity to meet other commitments.

4.3 Admission Offers (PhD by Prior Publication Only)

4.3.1 Following approval of an application for admission an offer letter will be issued that is valid for six months. An offer will automatically lapse if the applicant has not enrolled within six months or sought a deferral to the commencement date.

4.3.2 Admission offers are made for the following types of places:

Domestic Candidate Places

Domestic candidates (refer section 2.0 Definitions) are required to pay tuition fees at the PhD by Prior Publication flat fee rate (PhDPub_Flat) as specified in the *Fees and Charges Policy*. A prescribed fee will apply irrespective of the period of enrolment.

International Candidate Places

International candidates (refer section 2.0 Definitions) are required to pay tuition fees at the PhD by Prior Publication flat fee international rate (PhDPub_Flat_FPOS) as specified in the *Fees and Charges Policy*. A prescribed fee will apply irrespective of the period of enrolment.

4.3.3 Refer to the *Higher Degree Research Policy* for admission appeal procedures.

5. CONDITIONS OF CANDIDATURE (PHD BY PRIOR PUBLICATION ONLY)

5.1 Intellectual Property - PhD Prior Pub

Candidates will have ownership of intellectual property directly related to their research, unless other arrangements have been mutually agreed in advance by the candidate and the University. (Refer to the University's *Intellectual Property Policy*.)

5.2 Standard of Academic Conduct

Candidates are expected to undertake their program in accordance with accepted standards of academic conduct. Any form of academic conduct which is contrary to these standards is academic misconduct, for which the University may penalise a candidate. (Refer to *Student Academic Misconduct Policy* and *Academic Misconduct Policy - Higher Degree Research Candidates*.)

5.3 Supervision

The Dean, Griffith Graduate Research School will, after consultation with the Dean (Research) and Head of Element, appoint normally two staff members to advise a candidate on the preparation of the submission and the substantial exegesis.

5.4 Length of Candidature

The minimum and maximum periods of enrolment will be one trimester and one year respectively whether the candidate is enrolled full-time or part-time. A request to extend the maximum period of candidature may result in candidates incurring additional tuition fees.

5.5 Confirmation of Candidature

Applicants will be admitted to candidature unconditionally, and will not be reviewed for confirmation of candidature.

5.6 Further Conditions of Candidature

The policies and procedures pertaining to the degree of PhD will apply for suspension of candidature, variation to period of candidature, review of progress (as applicable to the degree) and termination of candidature (refer *Higher Degree Research Policy* Section 8).

6. FORM OF SUBMISSION

6.1 DLitt, DSc

The candidate will submit:

- as many copies of the work or works as is required plus one, which are to be the basis of examination;
- such statements as will, in the judgment of the candidate, facilitate evaluation by the examiners; and
- evidence of the candidate's academic qualifications.

A collection of published works which is submitted for examination shall be accompanied by an introductory paper listing:

- in chronological order, the publications being presented for examination; and
- in respect of each publication of which the candidate is a joint author, a designation of the candidate's responsibility and credit for the investigation which led to the published work.
- The candidate shall also indicate any work which has formed the basis of a degree award from any university or other institution.

6.2 PhD Prior Pub

The submission will take the form of a collection of original authored published works (as approved for inclusion in the final submission upon admission to the program), and a substantial exegesis. The exegesis will:

- in chronological order, list the publications being presented for examination;
- indicate the way in which the candidate's work has developed;
- demonstrate the contemporary relevance of each publication;
- make clear the way in which the publications make an original scholarly contribution to knowledge;
- provide a thematic overview which converts the individual publications into an integrated work;
- make clear the candidate's contribution to all jointly authored publications.

7. THE EXAMINATION

7.1 DLitt, DSc

At the time that the Board of Graduate Research Committee approves the recommendation from the ad hoc committee on the admission of a candidate, the Board of Graduate Research Committee will consider the recommendation of the ad hoc committee concerning the appointment of examiners and reserve examiners. The Board of Graduate Research shall appoint an Examination Board of distinguished scholars consisting of a Chairperson and not less than three examiners who shall be external to the University. The Chairperson of the Examination Board will not be an examiner.

The Chairperson of the Examination Board may, at the request of an examiner, require the candidate to answer any questions, either orally or in writing, concerning his/her work.

The Chairperson of the Examination Board shall submit a report to the Board of Graduate Research Committee on the results of the examination which will include the text of the examiners' reports and recommendations.

7.2 PhD Prior Pub

The policies and procedures pertaining to the degree of PhD apply for the submission; appointment of examiners and the examination unless otherwise detailed below (refer *Higher Degree Research Policy* Section 9).

If the principal supervisor/s are unable to advise that, in their opinion, the submission is prima facie worthy of examination, the Dean, Griffith Graduate Research School will offer the candidate the opportunity to withdraw the submission before examination.

The University will provide the examiners with a statement certifying that it is satisfied as to the applicant's claims concerning his/her contribution to any co-authored publications.

The examination will be conducted in accordance with the highest contemporary standards for a doctoral thesis.

A candidate may be required to participate in an oral or written defence of the submission.

As the nature of the submission does not permit revision and re-examination, an examiner will recommend:

- the degree be awarded to the candidate;
- the candidate submit an oral or written defence of the submission;
- the degree should not be awarded to the candidate.

8. AWARD OF THE DEGREE

8.1 DLitt, DSc

After considering the report of the Chairperson of the Examination Board, the Board of Graduate Research Committee may recommend that the appropriate degree be awarded. The Dean, Griffith Graduate Research School approves that the award be granted.[1]

8.2 PhD Prior Pub

The Dean, Griffith Graduate Research School certifies that the candidate has satisfied the requirements for the degree and approves that the award be granted.[2]

A candidate who has been rejected for the award of the degree will be provided with the reasons therefore.

[1] Council 4/2012 resolved to delegate authority to the Dean, Griffith Graduate Research School to approve the granting of higher degree by research awards, and doctorates and higher doctorates by publication awards to candidates who have satisfied the requirements for the award of a degree.

[2] As above

Appendix 2. Supporting Information for Chapter 3

The following appendix is the published Supporting Information for the research article included as

Chapter 3 of this thesis:

Nicholas J.C. Doriean, Peter R. Teasdale, David T. Welsh, Andrew P. Brooks, and William W. Bennett. (2019). Evaluation of a simple, inexpensive, in situ sampler for measuring time-weighted average concentrations of suspended sediment in rivers and streams. Hydrological processes, 2019, 33(5), 678-686

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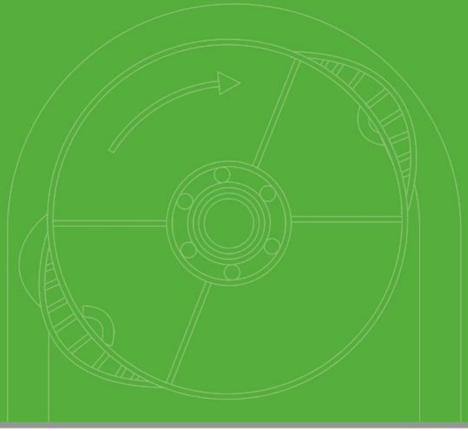

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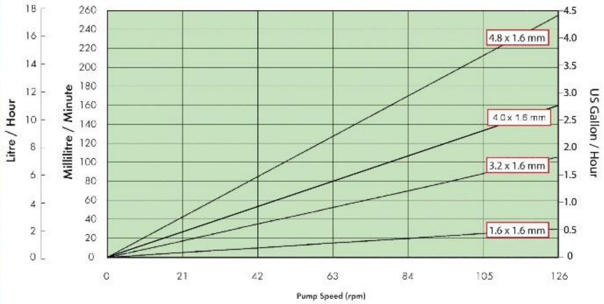
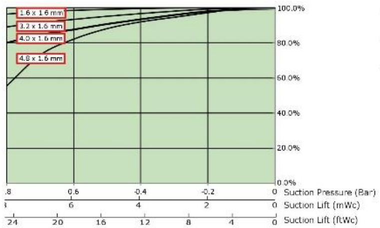
2 roller design for low flow dosing applications and intermittent duty. A low cost option for light duty operation.

- Flow rates up to 260 ml/min (4.1 US GPH)
- D.C. motor provides speed/flow rate variations
- Typically used in:
  Air conditioning
  Refrigeration
  Condensate removal

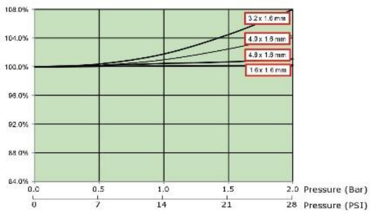
M025 Free Flow Curve



Suction



Discharge



Flow rates with water at 20°C (68°F)

Technical Overview

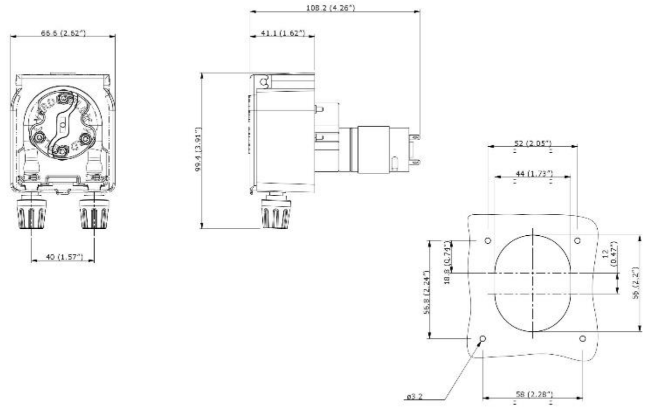
Function	Detail
Pump head	Polycarbonate/ABS blend (blue) with clear-hinged polycarbonate cover
Motor	Permanent magnet with spur gearbox
Rotor	2 roller with rapid tube loading feature
Options	3 roller option
Power Supply	12/24V D.C. 15W
Tube	Verderprene, Silicone, Viton®, Tygon®
Tube Sizes	1.6 x 1.6mm, 3.2 x 1.6mm, 4.0 x 1.6mm, 4.8 x 1.6mm
Weight	0.4 kg (0.9 lb)

Tube Size Options

Tube (ID x WT)	15 RPM	30 RPM	60 RPM	120 RPM
1.6 x 1.6 mm (1/16" x 1/16")	3.6 ml/min 0.2 l/hr 0.05 GPH	7.2 0.4 0.1	14.4 0.8 0.2	28.8 1.7 0.5
3.2 x 1.6 mm (1/8" x 1/16")	12.6 ml/min 0.8 l/hr 0.2 GPH	25.2 1.5 0.4	50.4 3.0 0.8	100.8 6.0 1.6
4.0 x 1.6 mm (5/32" x 1/16")	18.8 ml/min 1.1 l/hr 0.3 GPH	37.5 2.3 0.6	75.0 4.5 1.0	150.0 9.0 2.0
4.8 x 1.6 mm (3/16" x 1/16")	30 ml/min 1.8 l/hr 0.5 GPH	60 3.6 1.0	120 7.2 1.9	240 14.4 3.8

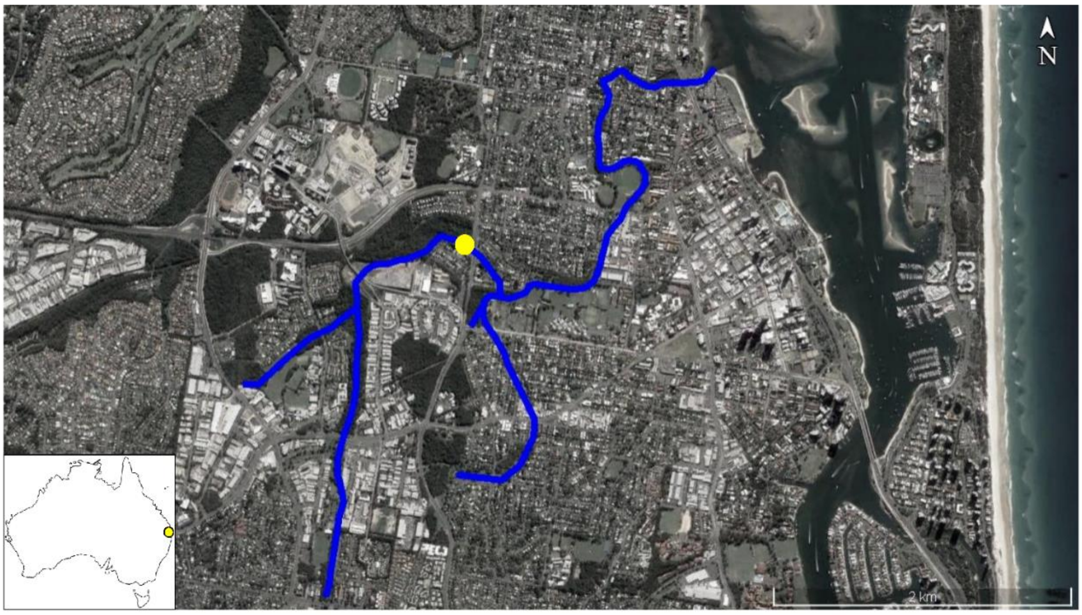
Flow rates for 2 roller option

General Arrangement Drawing and Mounting Positions



All dimensions in millimetres and inches

Appendix 1. SI-1. Data sheet for peristaltic pump component of PASS sampler.



Appendix 1. SI-2. Sampling location (yellow circle) in Loders Creek in the Gold Coast, Queensland, Australia. Note, the scale bar on the bottom right represents 2km.

Appendix 3. Supporting Information for Chapter 4

The following appendix is the Supporting Information for the research article included as Chapter 4 of this thesis:

Suspended sediment monitoring in alluvial gullies: a laboratory and field evaluation of available measurement techniques

Nicholas J.C. Doriean,[1] Andrew P. Brooks,[2] Peter R. Teasdale,[3,4]

David T. Welsh,[1] and William W. Bennett [1,]*

[1] Environmental Futures Research Institute, School of Environment and Science,

Griffith University Gold Coast campus, Queensland 4215, Australia

[2.] Griffith Centre for Coastal Management,

Griffith University Gold Coast campus, Queensland 4215, Australia

[3] Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, South Australia 5095, Australia.

[4] Future Industries Institute, University of South Australia, South Australia 5095, Australia.

*Corresponding Author: w.bennett@griffith.edu.au

Supporting information

SI-1

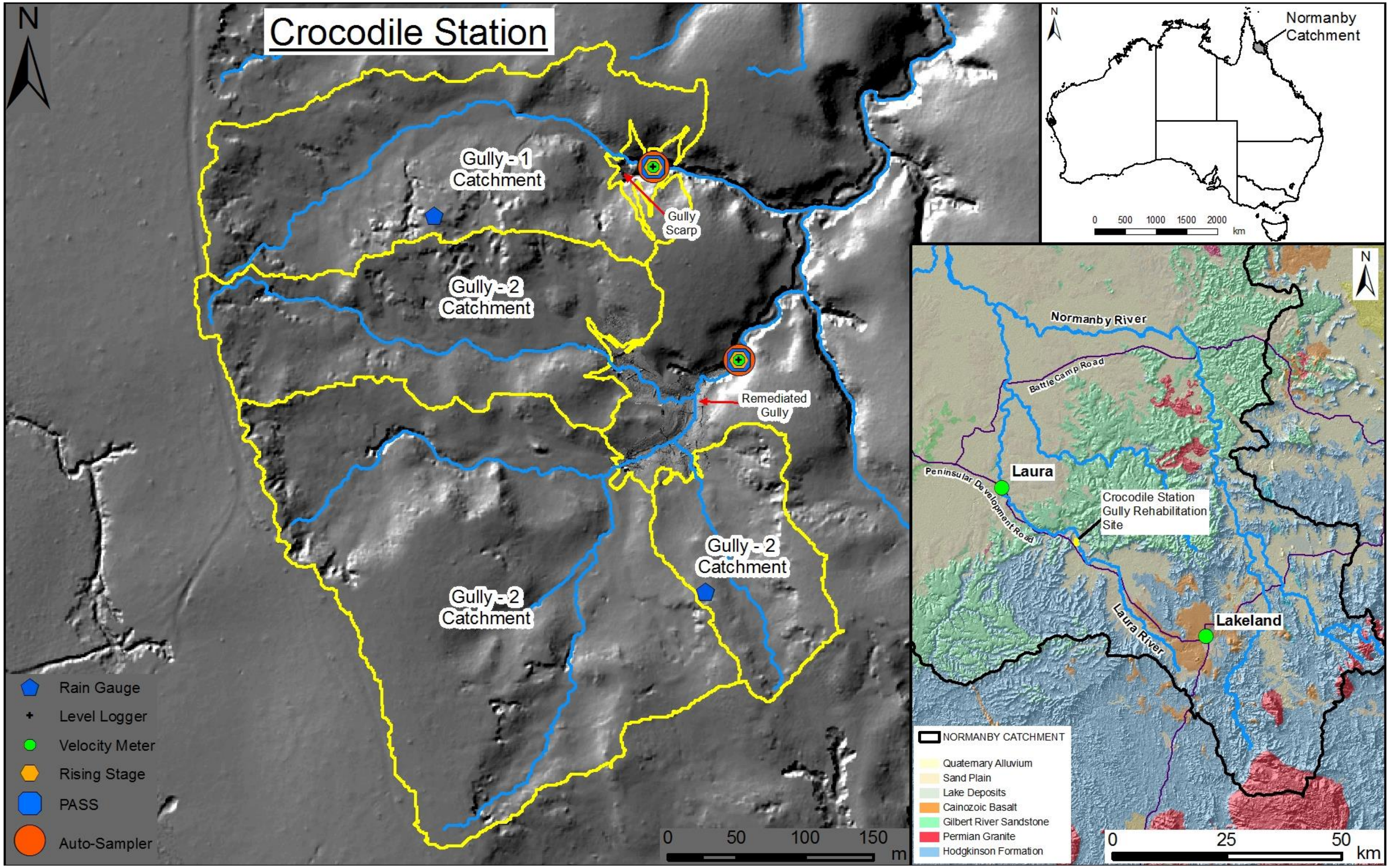


Figure SI-1A. Area map of study site.

SI-2

Figure SI-2A. Actively eroding gully (gully-1), January 2018.

Figure SI-2B. Remediated gully (gully-2), January 2018.

SI-3

Figure SI-3. Example of monitoring equipment in channel of the outlet from gully-1. The direction of flow is from left to right of the figure. AS = autosampler, PASS = PASS sampler, RSS = rising stage sampler, Turb= Turbidity logger, LL = level logger. The blue arrow indicates the elevation difference between the autosampler body and intake.

SI-4

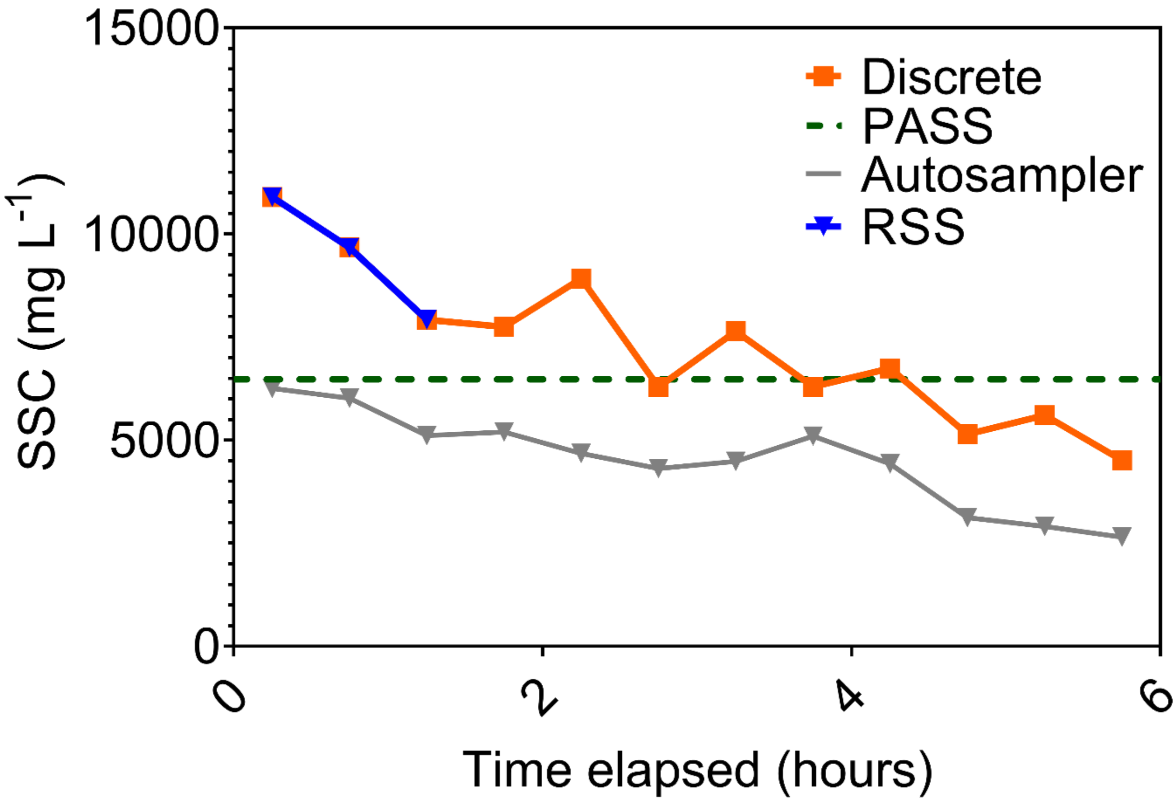


Figure SI-4. Time series of average suspended sediment concentration of samples collected using different sampling methods under laboratory conditions. Note, the PASS sampler data represents the time-weighted average suspended sediment concentration. RSS = Rising stage sampler.

SI-5

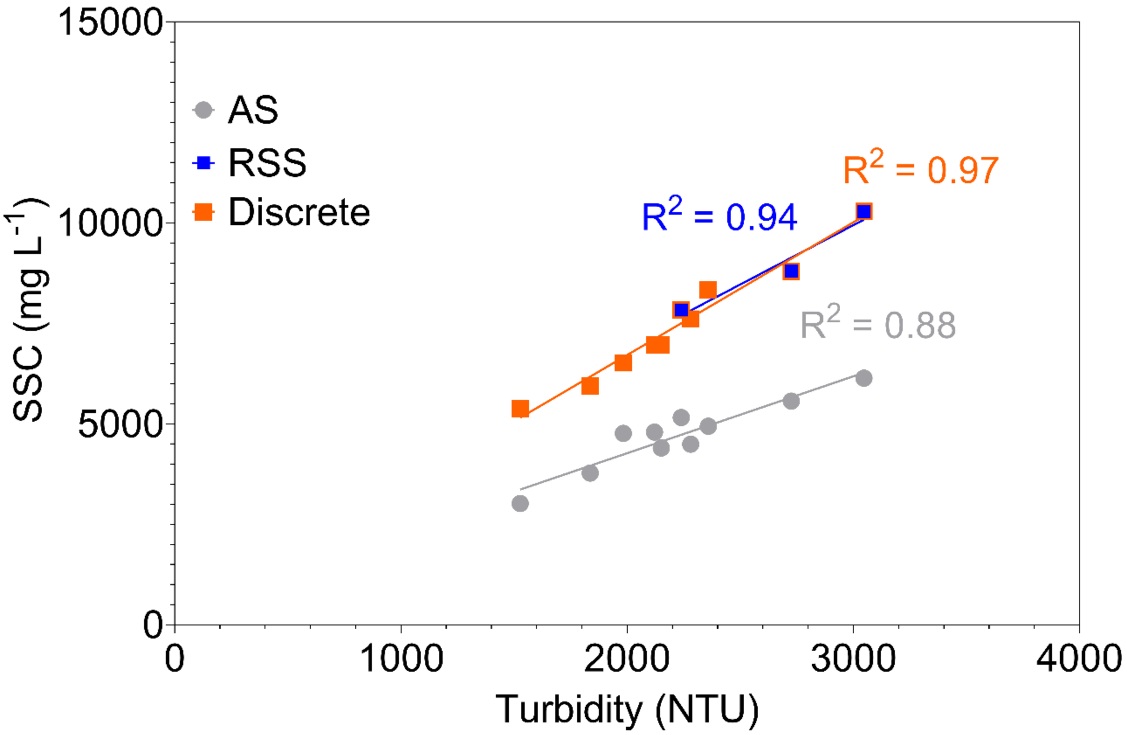


Figure SI-5A. Linear correlation of SSC and turbidity for autosampler (grey), discrete samples (orange), and RS samplers (blue).

SI-6

Table SI-6. Hydrology and rainfall data summary of flow events monitored as part of the field method evaluation of this study. Note, some sample periods had multiple flow events, whereas, others only had one flow event per sampling period.

Sampling period	*Date*	*Max water level (m)*	*Flow Duration (hrs)*	*Total rainfall (mm)*	*Rainfall duration (hrs)*
Gully-1					
Nov-17 to Jan-18	22/11/2017	0.32	1	43.8	2.5
	1/12/2017	0.46	1	46.2	3.5
	4/01/2018	0.26	1.25	61	6.5
	19/01/2018	0.22	1	72	28
Jan-18	23/01/2018	0.57	12	69.6	15.75
Jan-18 to Feb-18	24/01/2018	0.51	1	64.2	3.25
Feb-2019*	6/2/2019	0.14	1.5	30	2.25
Gully-2					
Nov-17 to Jan-18	22/11/2017	0.35	1	43.8	2.5
	1/12/2017	0.38	1.25	46.2	3.5
Jan-18 to Feb-18	24/01/2018	0.52	1.5	64.2	3.25
Feb-18 to May-18	25/03/2018	0.22	1.75	57.6	17

***=** *Intake height of PASS sampler was closer to the channel bed (~0.1 m) during this flow event, due to sand aggradation in the channel.*

SI-7

Table SI-7. PSD statistics of gully-1 samples collected at different heights using RS samplers

RS sampler intake height above channel (m)	***Dx (10) (μm)***	***Dx (50) (μm)***	***Dx (90) (μm)***
Dec -17 Flow event			
0.20	1.59	7.88	59.9
0.25	1.60	7.96	72.6
0.30	1.47	7.05	79.7
0.35	1.42	6.24	60.2
0.40	1.87	11.8	154.0
0.45	1.76	9.74	116.0
Jan-18 Flow event			
0.20	1.38	6.83	40.1
0.25	1.64	8.30	85.5
0.30	1.65	8.32	78.5
0.35	1.65	8.22	85.5
0.40	1.54	7.39	81.2
0.45	1.47	6.65	58.8

SI-8

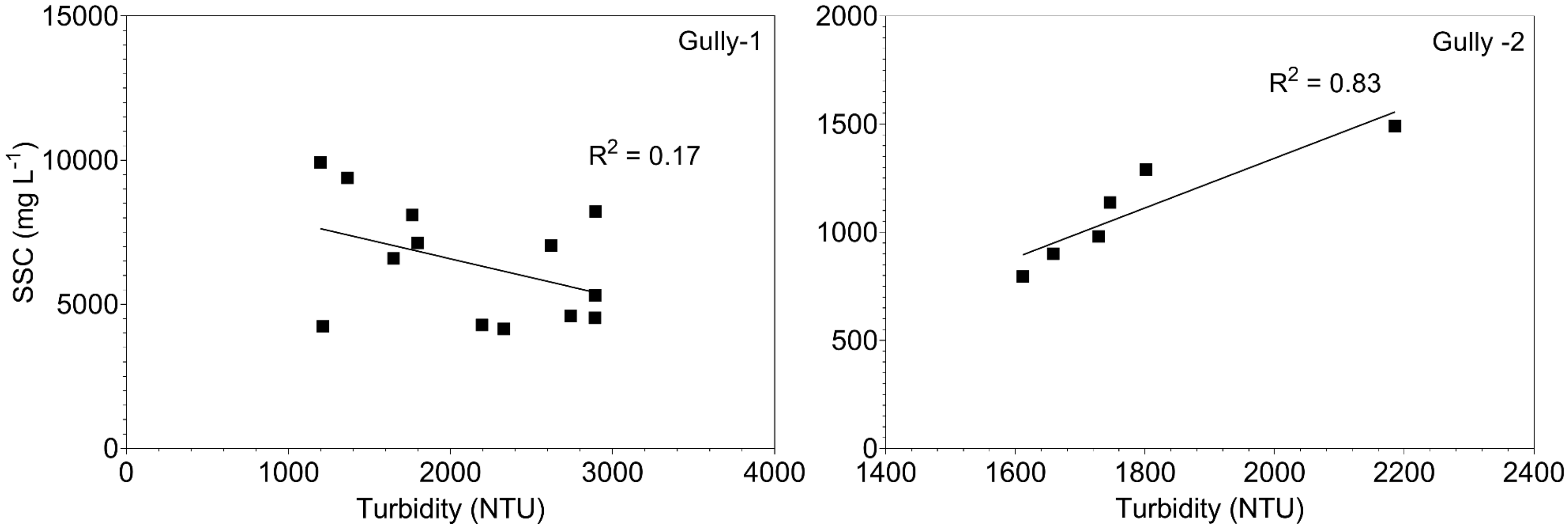


Figure SI-8. Correlation between SSC, collected from an autosampler, and turbidity for gullies 1 and 2.

SI-9

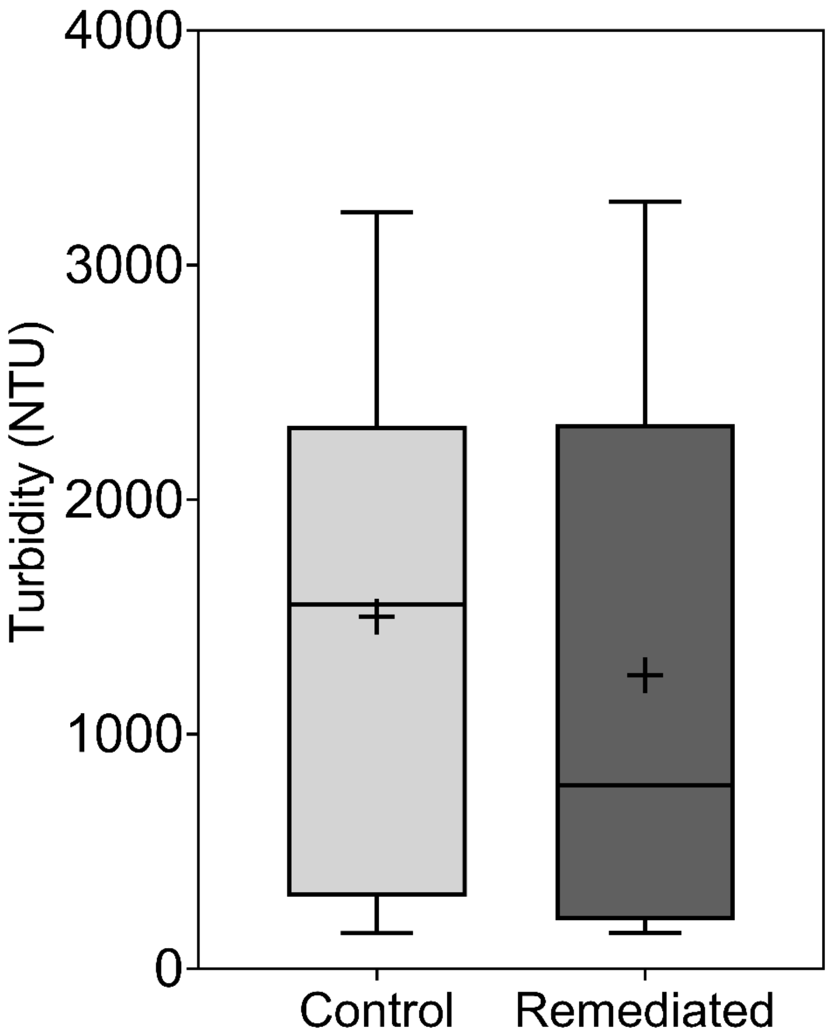


Figure SI-9. Comparison of turbidity measurements made at the control and remediated gullies. Turbidity measurements are shown as box plots representing the minimum, maximum, 25th and 75th percentiles, median (horizontal line) and mean (cross). No significant difference between sample sets ($p > 0.05$)

Appendix 4. Supporting Information for Chapter 5

The following appendix is the Supporting Information for the research article included as Chapter 5 of this thesis:

Alluvial gully remediation reduces export of suspended sediment and associated nutrients to a Great Barrier Reef catchment: evidence from a novel intensive monitoring program

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

[1] Environmental Futures Research Institute, School of Environment and Science, Griffith University Gold Coast campus, Queensland 4215, Australia

[2.] Griffith Centre for Coastal Management, Griffith University Gold Coast campus, Queensland 4215, Australia

[3] Natural and Built Environments Research Centre, School of Natural and Built Environments, University of South Australia, South Australia 5095, Australia.

[4] Future Industries Institute, University of South Australia, South Australia 5095, Australia.

[5] Department of Environment and Science, Queensland Government, 4102 Brisbane, Australia

*Corresponding Author: andrew.brooks@griffith.edu.au

Supporting Information

SI-1

Figure SI-1A. A lobe of the remediated gully, prior to remediation.

Figure SI-1B. Reshaping the remediated gully.

SI-1

Figure S1-C. Finished reshaping of remediated gully.

Figure S1-D. Spreading gypsum over remediated gully.

Figure S1-E. Geotextile fabric laid over former gully head scarp

Figure S1-F. Rock capping remediated gully.

SI-1

Figure SI-1G. Remediated gully completed with check dams 2016.

Figure SI-1H. Remediated gully 2017

SI-1

Figure SI-1I. Control Gully 2018.

SI-2

Figure SI-2 PASS sampler located in catchment drainage channel, upstream of the remediated gully.

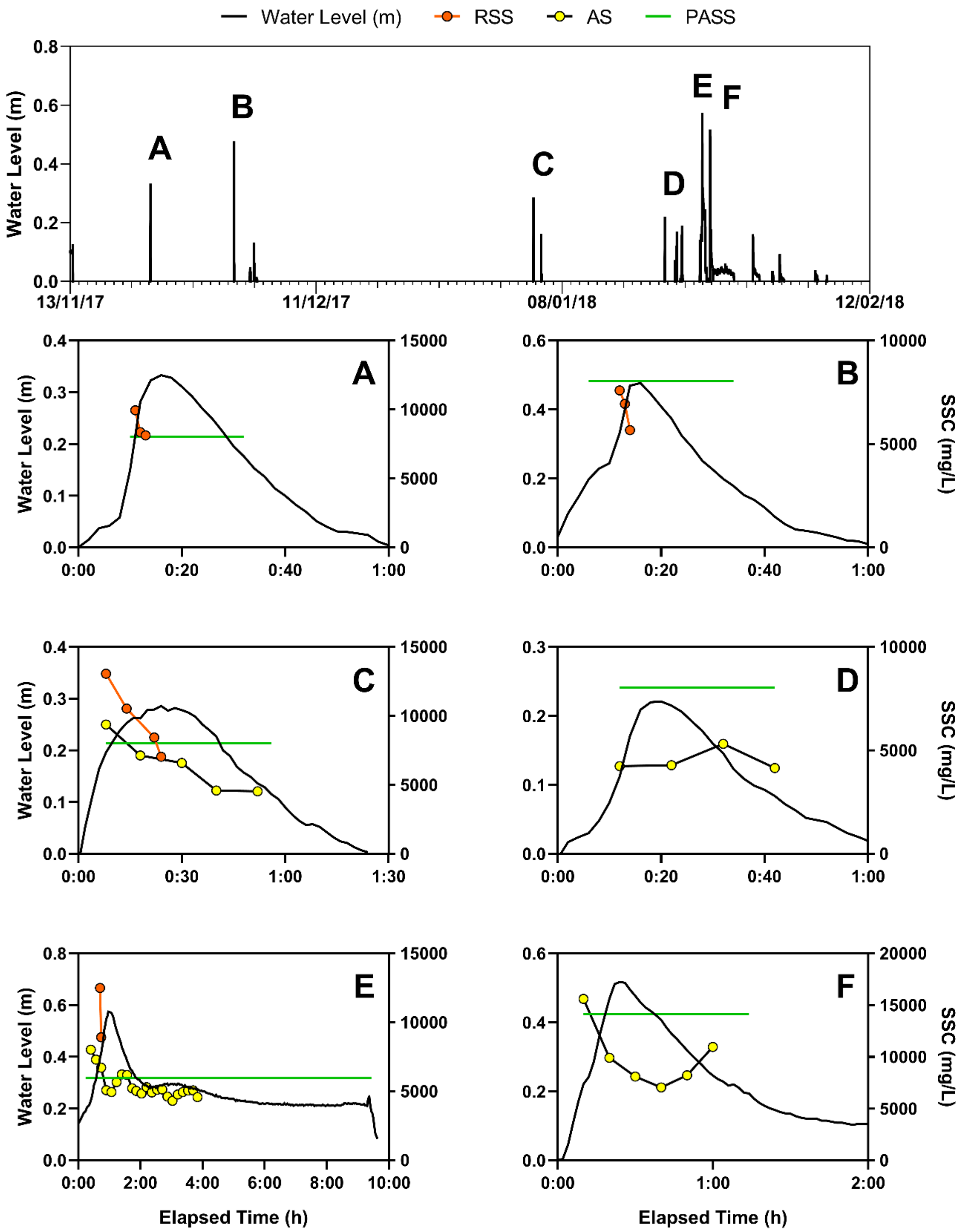


Figure SI-3A Timeline of flow events that occurred in the control gully during the 2017/2018 wet season. The top panel shows the water level for the heights for each flow event over the wet season. The individual panels show the water level (black line) and sample suspended sediment concentration data (orange = RS sampler, green = PASS sampler, yellow = autosampler, and red = flow proportional manual sampling).

SI-3

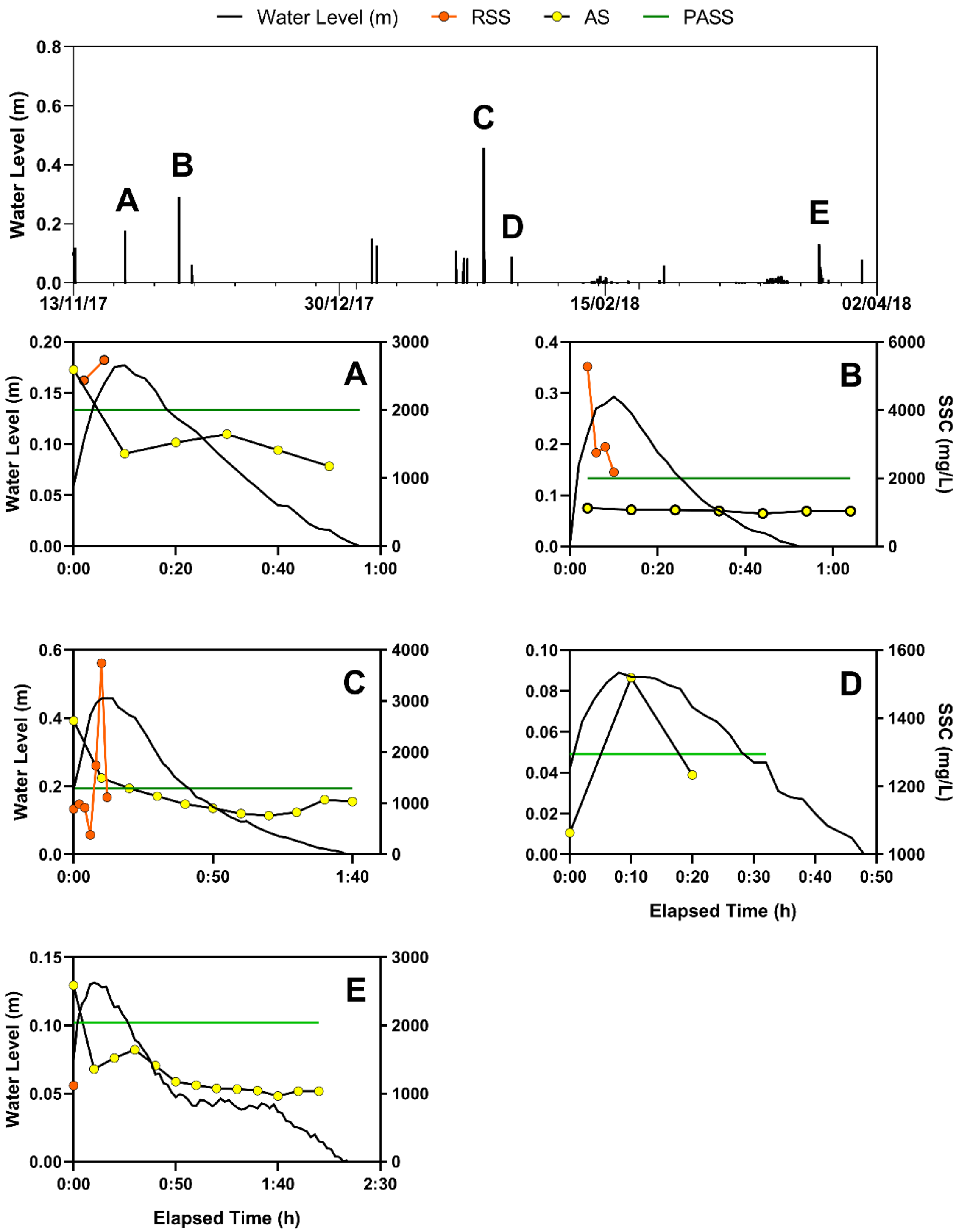


Figure SI-3B Timeline of flow events that occurred in the remediated gully during the 2017/2018 wet season. The top panel shows the water level for the heights for each flow event over the wet season. The individual panels show the water level (black line) and sample suspended sediment concentration data (orange = RS sampler, green = PASS sampler, yellow = autosampler, and red = flow proportional manual sampling).

SI-3

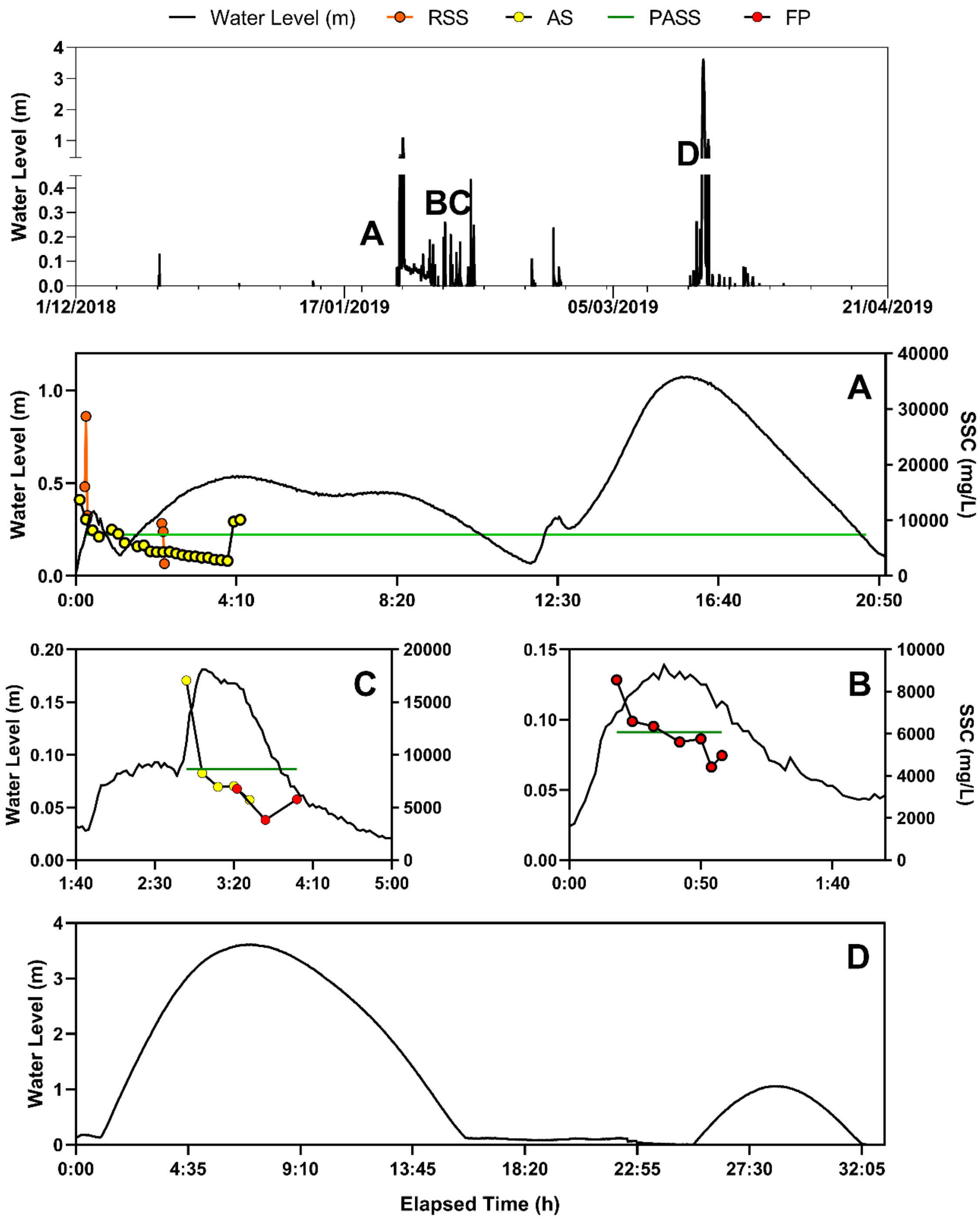


Figure SI-3C Timeline of flow events that occurred in the Control gully during the 2018/2019 wet season. The top panel shows the water level for the heights for each flow event over the wet season. The individual panels show the water level (black line) and sample suspended sediment concentration data (orange = RS sampler, green = PASS sampler, yellow = autosampler, and red = flow proportional manual sampling).

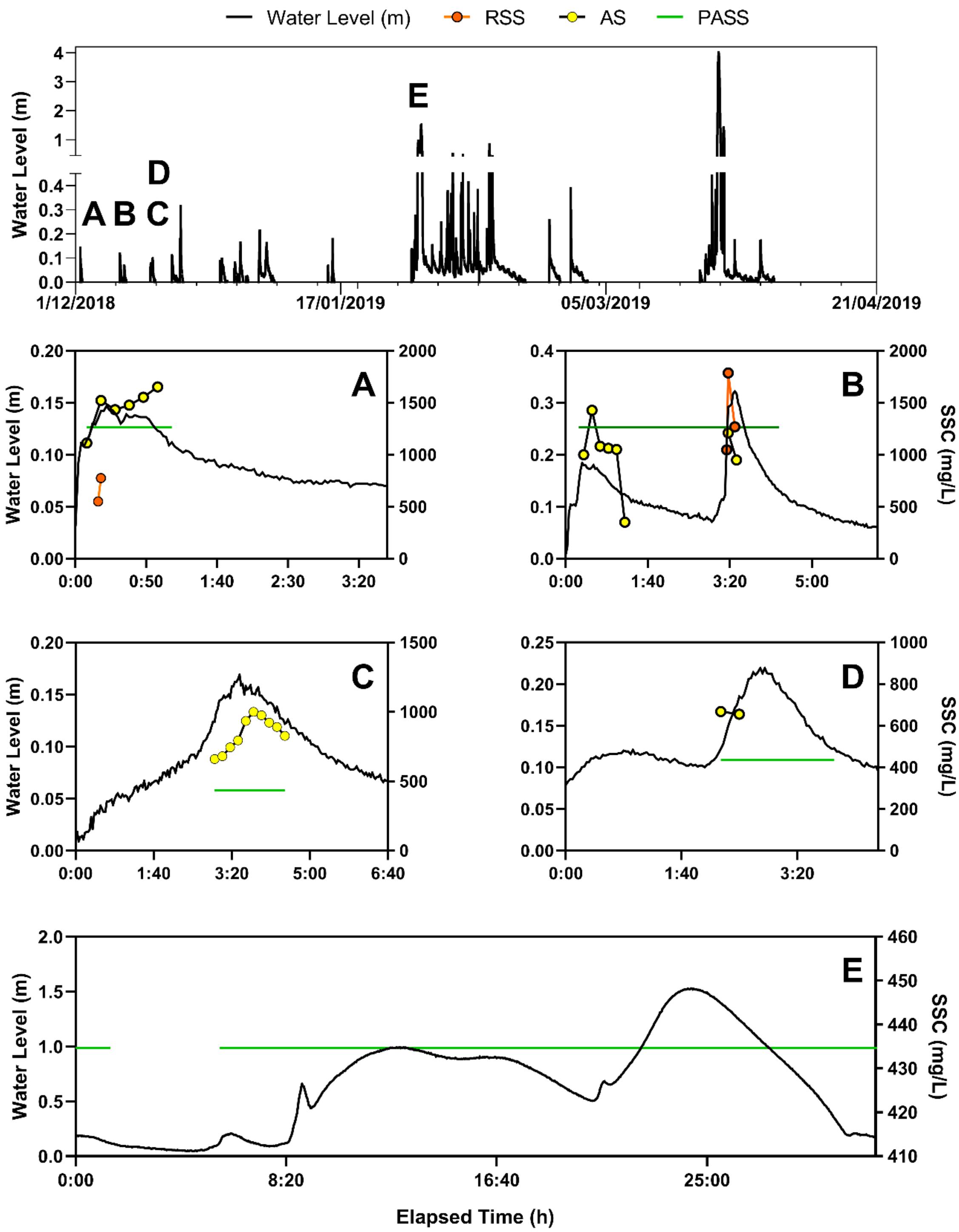


Figure SI-3D Timeline of flow events that occurred in the Remediated gully during the first half of 2018/2019 wet season (i.e., up to January 2019). The top panel shows the water level for the heights for each flow event over the wet season. The individual panels show the water level (black line) and sample suspended sediment concentration data (orange = RS sampler, green = PASS sampler, yellow = autosampler, and red = flow proportional manual sampling).

SI-3

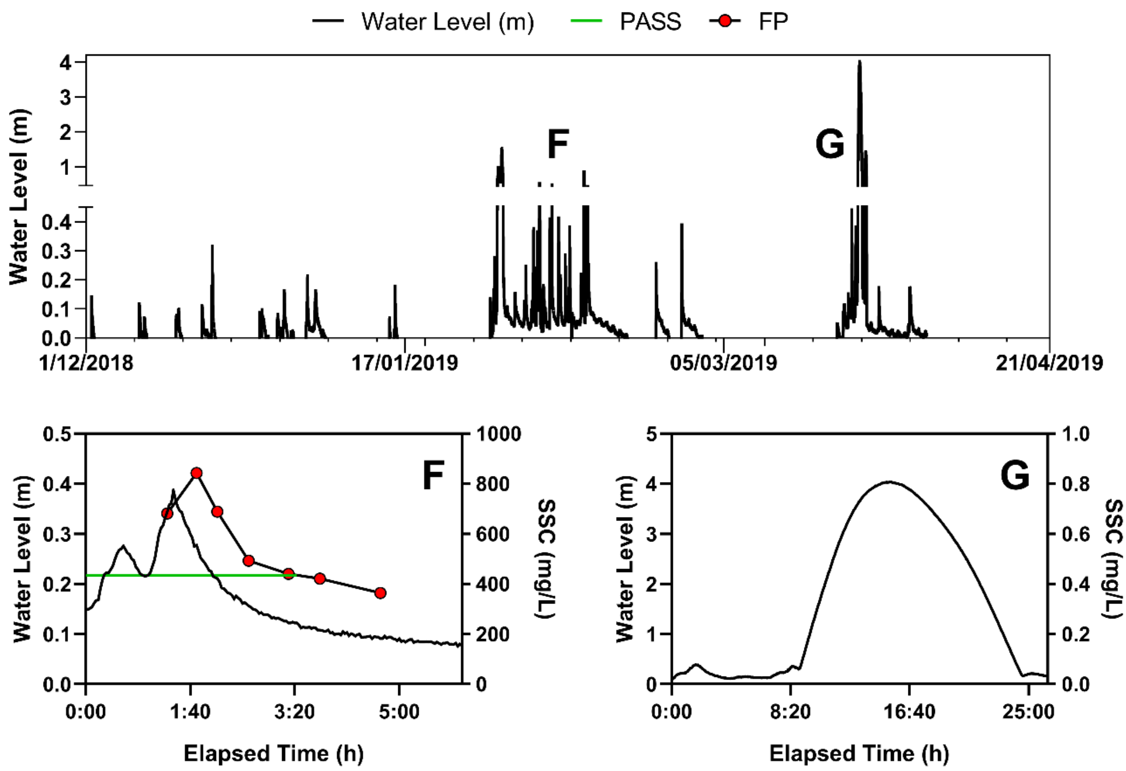


Figure SI-3D Timeline of flow events that occurred in the Remediated gully during the second half of 2018/2019 wet season (i.e., February to April 2019). The top panel shows the water level for the heights for each flow event over the wet season. The individual panels show the water level (black line) and sample suspended sediment concentration data (orange = RS sampler, green = PASS sampler, yellow = autosampler, and red = flow proportional manual sampling).

SI-4

Figure SI-4A. Infrared image of remediated gully flooded during January 2019 backwater event.

SI-4

Figure SI-4B Remediated gully during small flow event on 6 February 2019.

SI-4

Figure SI-4C: Control gully during small flow event on 6 February 2019

SI-5

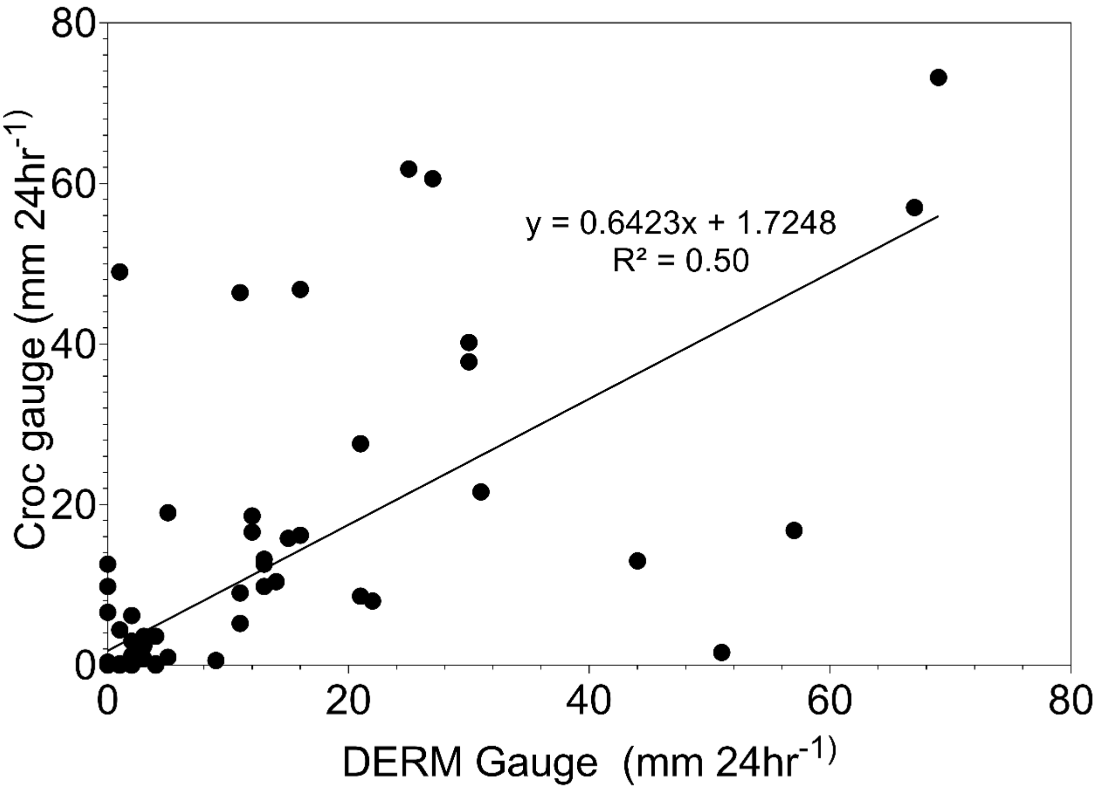


Figure SI-5. Linear correlation between daily total rainfall measured using raingauges located at the study site and the Laura River.

SI-6

Table SI-6. Density of gully sediment

Sample Number	***size class (μm)***	***Density (g/mL)***
1	<63	2.30
2	<63	2.30
3	<63	2.26
4	<63	2.28
5	63-2000	2.43
6	63-2000	2.44
7	63-2000	2.40
Average		2.34
Standard deviation		0.08
RSD		3%

Please note, in-order to have enough sediment mass, density testing was conducted on gully sediment from the control gully and assumed to be comparable to remediated gully sediment, based on soil chemistry and PSD.

SI-7

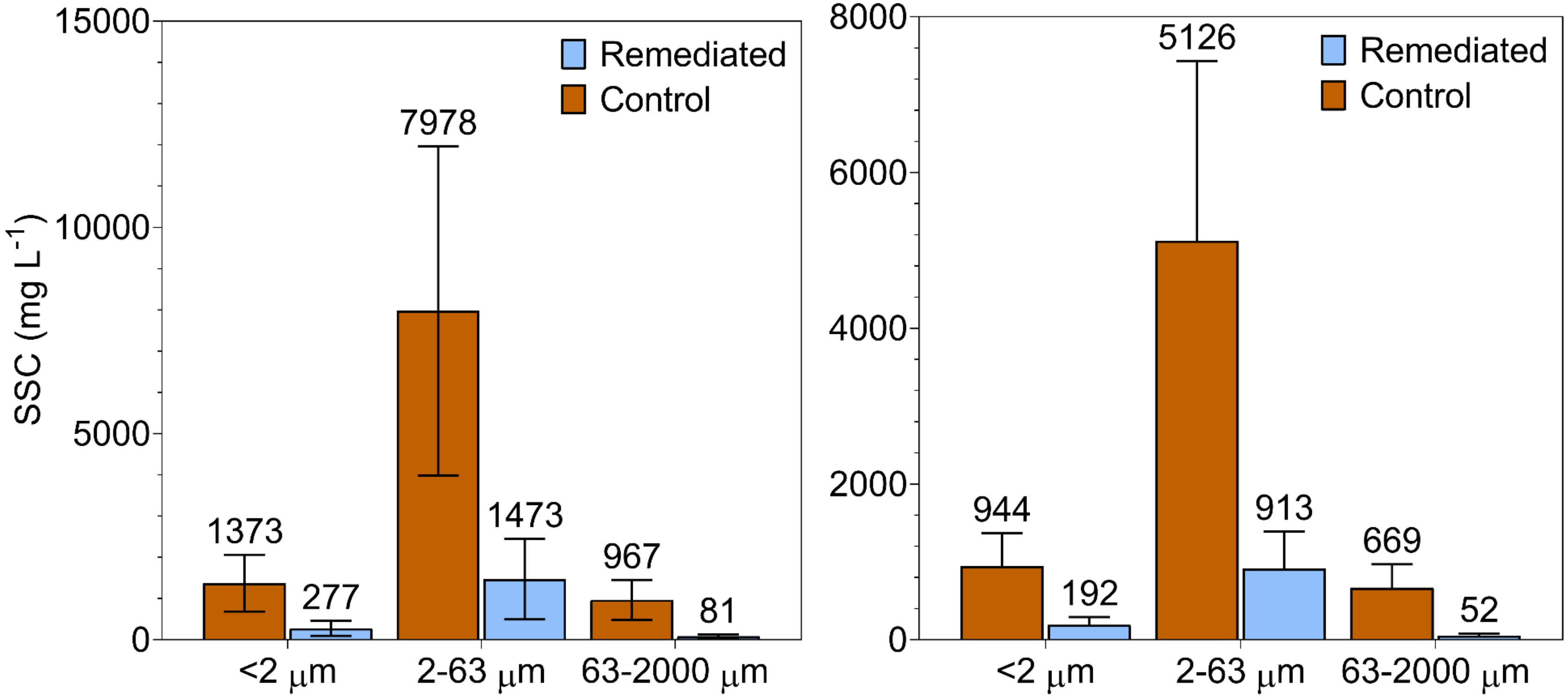


Figure SI-7 SSC by PSD for samples collected using autosamplers (left) and RS samplers (right) from the control (brown) and remediated (blue) gullies during the 2017/2018 and 2018/2019 wet seasons.

SI-8

Table SI-8. Statistical comparison of control and remediated gully soil PSD measurements.

Soil size (μm)	*Significant?*	*p value*	*Mean of Control*	*Mean of Remediated*	*Difference*	*SE of difference*	*t ratio*	*df*
>2000	No	0.219477	2.25	0.9133	1.337	1.048	1.275	17
2000-50	No	0.617292	47.75	43.23	4.523	8.887	0.509	17
50-20	No	0.724715	61.25	57.97	3.283	9.17	0.358	17
2-20	No	0.699885	19.25	21.58	-2.33	5.943	0.3921	17
<2	No	0.830985	19.25	20.43	-1.183	5.46	0.2167	17

SI-9

Figure SI-9A. Looking down stream at the outlet channel from control gully head. Photo taken in on 16/02/2018. Note large deposit of sand making up channel bed.

SI-9

Figure SI-9B. Looking downstream from at remediated gully head outlet channel. Photo taken in on 16/02/2018. Note the lack of sediment in the channel bed.

Figure SI-9C. Looking upstream into remediated gully at same location as Figure SI-9B. Photo taken in on 16/02/2018. Note the check dam has collected coarse sediment and now supports vegetation.

SI-10

Table SI-10A. Pearson's correlation analysis of SSC and nutrient fractions of samples collected from the control gully on 24/01/2018.

Control Gully							
Analytes compared	*r*	*95% confidence interval*	*R squared*	*P (two-tailed)*	*P value summary*	*Significant? (alpha = 0.05)*	*Number of XY Pairs*
SSC vs.Total OC	0.5985	0.2365 to 0.8146	0.3582	0.0033	**	Yes	22
SSC vs.Dissolved OC	-0.2228	-0.5890 to 0.2195	0.04962	0.3191	ns	No	22
SSC vs.POC	0.6951	0.3868 to 0.8636	0.4831	0.0003	***	Yes	22
SSC vs.Total N as N	0.7675	0.5113 to 0.8984	0.589	<0.0001	****	Yes	22
SSC vs.Organic N (dissolved) as N	-0.268	-0.6196 to 0.1732	0.07183	0.2279	ns	No	22
SSC vs.Total nitrogen (dissolved) as N	-0.3307	-0.6603 to 0.1056	0.1094	0.1327	ns	No	22
SSC vs.Total N (suspended) as N	0.7759	0.5266 to 0.9024	0.6021	<0.0001	****	Yes	22
SSC vs.Ammonium N as N	-0.1665	-0.5496 to 0.2743	0.02774	0.4588	ns	No	22
SSC vs.Oxidised nitrogen as N	-0.6403	-0.8399 to -0.2883	0.41	0.0018	**	Yes	21
SSC vs.Total Kjeldahl N as N	0.7708	0.5173 to 0.8999	0.5941	<0.0001	****	Yes	22
SSC vs.Dissolved Kjeldahl N as N	-0.2654	-0.6178 to 0.1759	0.07041	0.2327	ns	No	22
SSC vs.Total P (suspended) as P	0.6758	0.3554 to 0.8541	0.4567	0.0006	***	Yes	22
SSC vs.Organic P (dissolved) as P	-0.1788	-0.5583 to 0.2626	0.03198	0.4259	ns	No	22
SSC vs.Phosphate P as P	-0.4957	-0.7639 to -0.08144	0.2457	0.0223	*	Yes	21
SSC vs.Total Kjeldahl P as P	0.6609	0.3317 to 0.8466	0.4367	0.0008	***	Yes	22
SSC vs.Dissolved Kjeldahl P as P	-0.3086	-0.6462 to 0.1299	0.09525	0.1623	ns	No	22

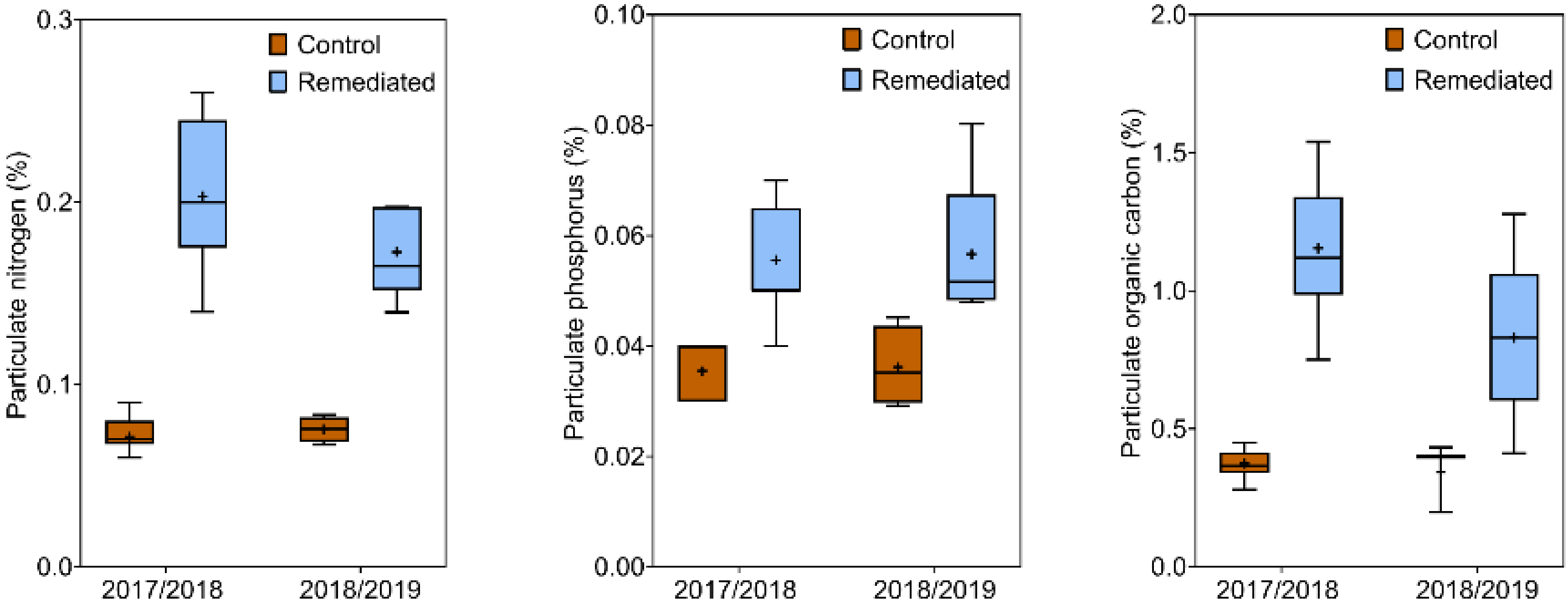
P = phosphorus, N = Nitrogen, POC = particulate organic carbon.

SI-10

Table SI-10B. Pearson's correlation analysis of SSC and nutrient fractions of samples collected from the remediated gully on 24/01/2018.

Remediated Gully							
Analytes compared	***r***	***95% confidence interval***	***R squared***	***P (two-tailed)***	***P value summary***	***Significant? (alpha = 0.05)***	***Number of XY Pairs***
SSC vs.Total OC	0.2898	-0.4636 to 0.7999	0.08397	0.4494	ns	No	9
SSC vs.Dissolved OC	0.19	-0.5426 to 0.7584	0.03608	0.6245	ns	No	9
SSC vs.POC	0.2312	-0.5114 to 0.7762	0.05347	0.5494	ns	No	9
SSC vs.Total N as N	0.4464	-0.3095 to 0.8566	0.1993	0.2284	ns	No	9
SSC vs.Organic N (dissolved) as N	0.655	-0.01613 to 0.9193	0.429	0.0555	ns	No	9
SSC vs.Total nitrogen (dissolved) as N	0.8752	0.5040 to 0.9735	0.766	0.002	**	Yes	9
SSC vs.Total N (suspended) as N	0.2812	-0.4708 to 0.7966	0.07909	0.4635	ns	No	9
SSC vs.Ammonium N as N	-0.1544	-0.7424 to 0.5680	0.02383	0.6917	ns	No	9
SSC vs.Oxidised nitrogen as N	0.7484	0.1676 to 0.9436	0.5601	0.0204	*	Yes	9
SSC vs.Total Kjeldahl N as N	0.3899	-0.3701 to 0.8372	0.152	0.2996	ns	No	9
SSC vs.Dissolved Kjeldahl N as N	0.657	-0.01269 to 0.9198	0.4316	0.0545	ns	No	9
SSC vs.Total P (suspended) as P	0.4864	-0.2626 to 0.8696	0.2365	0.1843	ns	No	9
SSC vs.Organic P (dissolved) as P	0.00184	-0.6631 to 0.6651	3.4E-06	0.9962	ns	No	9
SSC vs.Phosphate P as P	<LOD	<LOD	<LOD	<LOD	<LOD	No	9
SSC vs.Total Kjeldahl P as P	0.5362	-0.1987 to 0.8851	0.2875	0.1367	ns	No	9
SSC vs.Dissolved Kjeldahl P as P	-0.1127	-0.7227 to 0.5960	0.01271	0.7727	ns	No	9

P = phosphorus, N = Nitrogen, POC = particulate organic carbon.



SI-11. Nutrient concentration of suspended sediment presented as a percentage of SSC for samples collected during flow events in the remediated (blue) and control (brown) gullies 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. Nutrient content represents the mass of particulate nutrients as a component of the total suspended sediment mass, expressed as a percentage.

END OF THESIS