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

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Abstract

Gully erosion is a significant source of fine suspended sediment (<63µm) 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.

Introduction

Gully erosion is globally recognised as a significant source of soil loss and can directly influence the water quality of downstream aquatic ecosystems by the presence of fine suspended sediment (<63 µm) and suspended sand (63-2000 µm) (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 Marine Park, 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.

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.

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 simulated 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 (measurement range 40-4000 nephelometric turbidity units (NTU)) 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 ($< 2\% \pm 1\%$ 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).

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). 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){Braatz, 1961 #362}. 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).

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 90th 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.

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).

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.

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.

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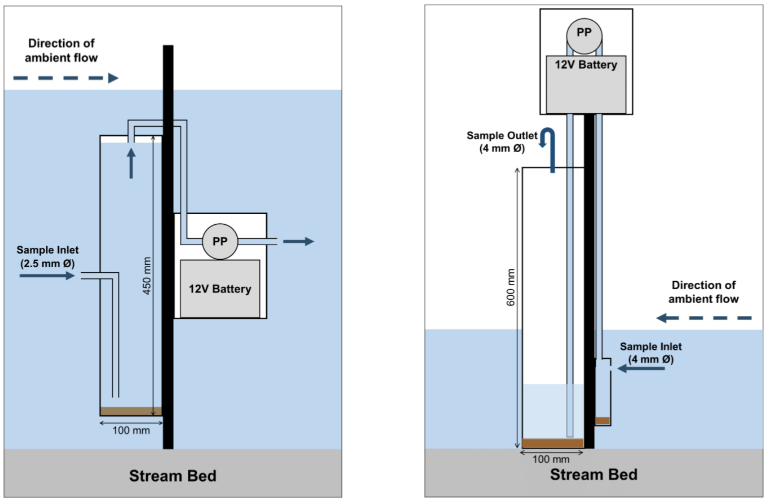
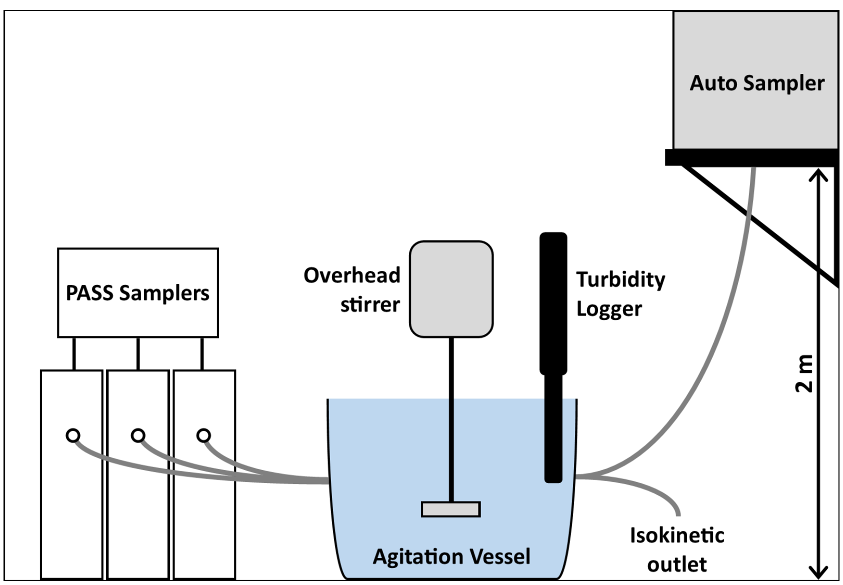
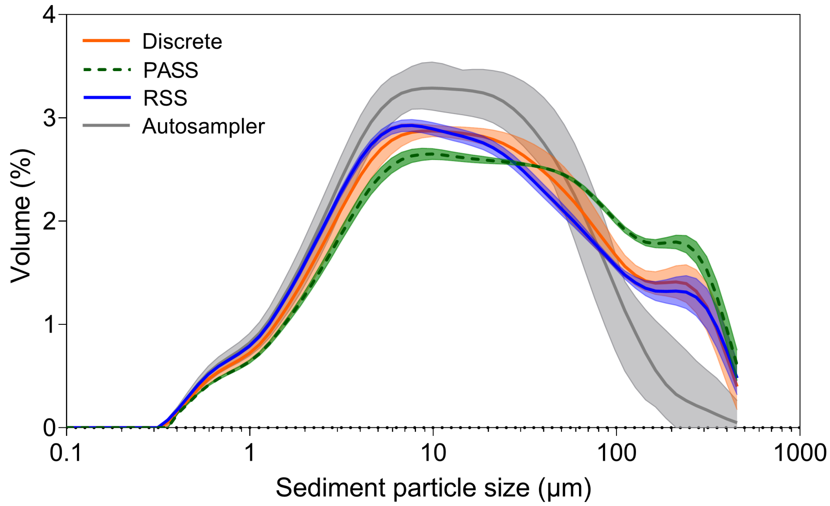
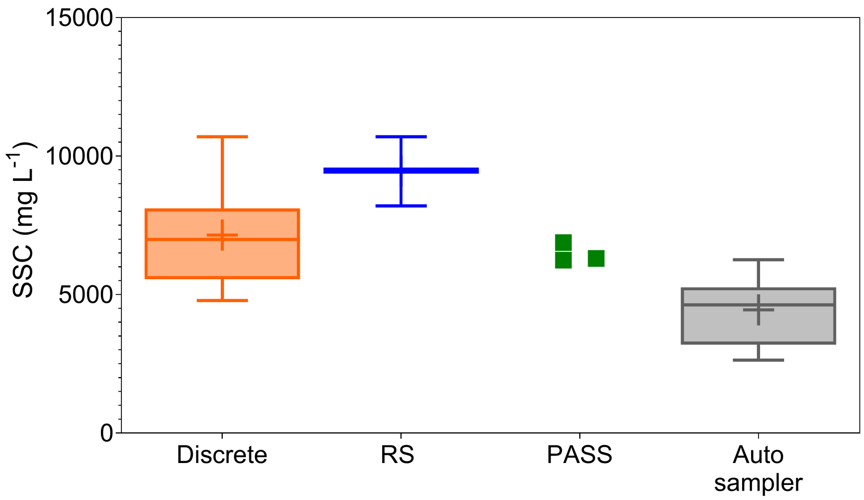
Original PASS sampler design *Modified PASS sampler design*



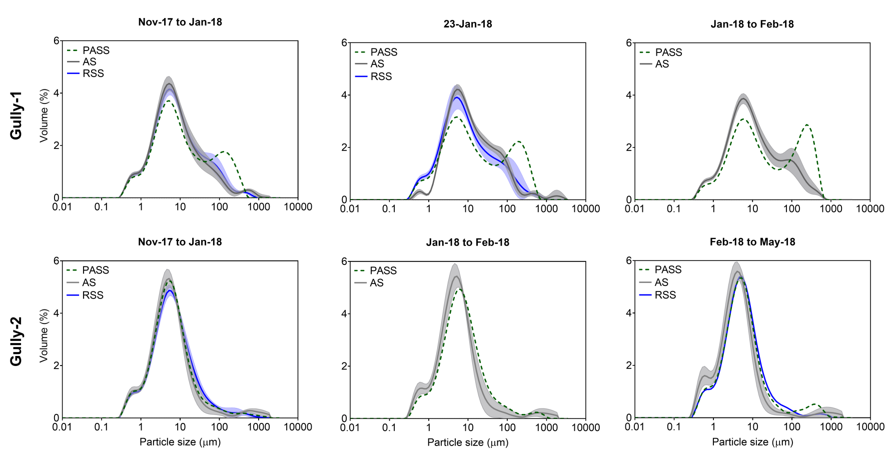




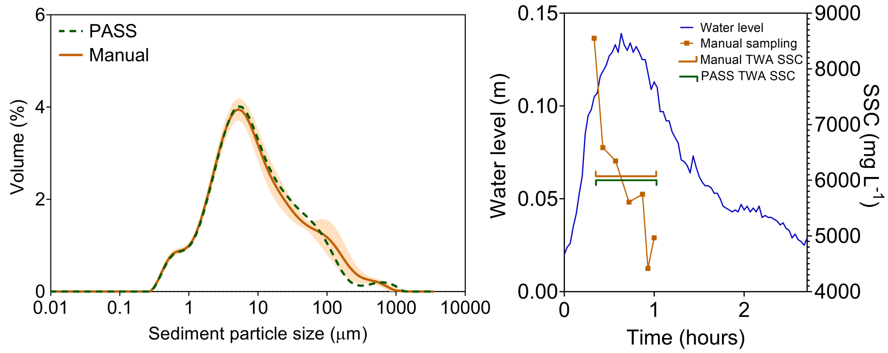
Discrete
PASS
RSS
Autosampler
Volume (%)
Sediment particle size (µm)



SSC (mg L-1)
Discrete
RS
PASS
Auto sampler



Nov-17 to Jan-18
23-Jan-18
Jan-18 to Feb-18
Feb-18 to May-18
PASS
AS
RSS
Gully-1
Gully-2
Volume (%)
Particle size (µm)


PASS
Manual
Volume (%)
Sediment particle size (μm)
0.01
0.1
1
10
100
1000
10000
Water level
Manual sampling
Manual TWA SSC
PASS TWA SSC
Water level (m)
SSC (mg L-1)
Time (hours)