

Worn down and wasting away: the impact of splash erosion in alluvial gullies

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Key Points

- Direct rain splash erosion is far more important in alluvial gully erosion than previously recognised
- 251 erosion plates were installed across 11 alluvial gullies
- Downwearing rates varied between 5-50 mm, with an average of 19 ± 11 mm across all surfaces
- The process yields over 70 t/ha/yr in additional erosion, with up to 1000 t/yr <20 μ m sediment being eroded from study gullies
- This represents between 30-80% of the total fine sediment load from gullies
- The results suggest management activities should prioritise direct treatment of exposed gully surfaces

Abstract

Accurately quantifying gully sediment yields has become increasingly important for achieving Great Barrier Reef water quality targets and more recently in determining cost structures for environmental crediting. Gullies are generally perceived to be dominated by overland flow and associated erosion processes such as mass failure. But downwearing caused by rain splash is at present an unknown variable in gully sediment yields. Across four sites in the Burdekin River Basin, 251 erosion plates were installed to monitor this process over the duration of the 2019-2020 wet season, a below average rainfall year. Erosion plates were placed at specific locations within the gullies that did not receive overland flow (i.e. isolating the process just to that driven by direct rainsplash erosion). All sites were coupled with rain gauges and soil material layers were sampled at each site to provide data soil properties. The majority (70%) of erosion plates formed pedestals 5-50 mm high over the wet season, while a further 28 had toppled over. Only 22 plates formed minimal or no pedestal. These pedestals provide a proxy for downwearing of the surrounding surfaces and suggests downwearing as a diffuse erosion source is quite important, yielding on average 360 ± 53 t/yr of fine sediment in the study gullies, previously unaccounted for in other short-term measurements or predictions. Rainsplash sediment yields account for 25-70% of total gully yields, suggesting common alluvial gully treatment options focused on catchment management and headwall retreat that don't consider surface treatment may be of limited success.

Keywords

Gully erosion, rain splash, downwearing, sediment yield

Introduction

Gully erosion is one of the major drivers of land and water degradation globally (Castillo and Gomez, 2016; Vanmaerke et al., 2016) and throughout Australia there has been increasing recognition over the last decade that gully erosion is a major threatening process to freshwater aquatic ecosystems. In the Great Barrier Reef (GBR) catchments, gully erosion is one of the dominant sources of fine sediment and particulate nutrient pollution, contributing an estimated 40% of the anthropogenic sediment load to the GBR Lagoon (Wilkinson et al. 2014; Bartley et al., 2017). In some catchments, such as the Bowen River, it is estimated at around 60%. Consequently, gully remediation and management is a high-priority activity, with federal and state government investments to date totalling more than \$100M. In order to meet the Reef Water Quality targets for the GBR Lagoon by 2030 and 2050, there is a pressing need to rapidly reduce sediment pollution from

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gully erosion by targeting the highest yielding gullies with the most effaceable approaches. Understanding gully erosion processes is fundamental in designing and applying management techniques that minimise erosion risk.

Gullies are largely perceived to erode via overland flow and associated erosion processes, namely headscarp retreat. Indeed, a commonly accepted definition of a gully is “(an) open depression... eroded by *channelled stream flow* [emphasis added] and consequent collapse and water-aided mass movement” (NCST, 2009). Crouch and Blong (1989) identified the importance of other gully erosion processes aside from headscarp retreat, but little other recognition has been given to the role of erosion by direct rain splash. Splash erosion is the initial mechanical detachment of sediment as raindrops impact a surface and displace particles from the point of impact (Le Bissonnais, 1996). Dispersion of these particles relates to physico-chemical properties of the sediment and results in downwearing of the eroding surface. While the process of splash erosion and subsequent dispersion and are well documented (Elison, 1948; Morgan 1978; Marzen et al. 2015; Fernández-Raga et al. 2017), the current literature on gully erosion has continued to largely neglect this process (Crouch and Blong, 1989).

Yet recent field observations of pedestal formation in alluvial gullies hint at the importance of this process (Figure 1a), as pedestals are associated with rapidly degrading soils (Elison, 1948). Forming under ephemeral objects such as pebbles, small woody debris and cow pats, pedestals up to several centimetres high suggest seasonal surface downwearing of an equal magnitude. But the process is largely unrecognised and unaccounted for in gully erosion processes. Currently, the most robust method for measuring erosion in gullies relies on multi-temporal change detection using lidar data. However, given the vertical accuracies of commonly utilised airborne lidar data, the critical limit of detection for such analyses is typically ~0.4 m, and ~0.1 m for high resolution lidar. This limit is at least an order of magnitude higher than observed pedestals, suggesting it is incapable of detecting the fine-scale process of surface downwearing.

This scoping study set out to investigate surface downwearing in gullies to first determine whether splash erosion is an important process and secondly to determine the relative contribution this process has on the overall sediment loads of gullies. The study has important implications in the management of gullies and treatment options for gully remediation.



Figure 1. Examples of pedestal erosion in the study Sites. (a) pedestal forming under a cow pat observed on the gully floor. (b) Rubber erosion plate at time of installation and (c) post-wet season. (d) Example of pedestal measurement technique using a contour gauge

Study Area

Four sites were selected in the lower Burdekin River Basin, with three of these sites in the Bowen River Basin, a major tributary to the Burdekin (Figure 2). The Burdekin basin has a highly seasonal, dry-tropical environment dominated by wet-season rainfall between December-February, though also features high interannual variability. Rainfall characteristics are spatially variable throughout the basin, with high local variations in rainfall distribution, but generally annually averages between 550-650 mm.

The area is characterised by extensive alluvial sediments of considerable depth interspersed with 'blacksoil' cracking clay alluvia. Much of the active and deep gullying in the region occurs in slaking/dispersive silty loam sediments of varying depth. The region is the highest contributor of fine sediment pollution to the Great Barrier Reef (GBR) (Wilkinson et al., 2013; Hancock et al., 2014, Wilkinson et al., 2014, Bainbridge et al., 2014). Many of these same studies have identified gully erosion as being the dominant source of this sediment. Gully erosion is also major issue both for local landholders (in terms of land degradation) as well as having a deleterious impact on the local stream network and associated aquatic ecosystems.

A total of 11 gullies were selected for investigation across three sites in the Bowen River basin and one adjacent in the lower Burdekin River. The gullies are large, alluvial gullies eroding into terraces adjacent to the present channels. All Sites have been identified as priority gully systems, with high sediment yields (Brooks et al. 2020; Daley et al. 2021a). Summary information for each site is detailed in Table 1. All sites had a rain gauge immediately adjacent to the Site and soil material samples collected in each layer for particle size and soil chemistry. Site 3 has previously been a focus for remediation, with an extensive diversion wall built around the headscarp of the gully to limit overland flow and cut off its upstream catchment, making it ideal for investigation of splash erosion as it is likely to be the primary mechanism of erosion in the gully.

Table 1. Site summary details. Lifetime yields have been estimated from volumes presented in Daley et al, (2021a) and assume a linear erosion rate since initiation.

Site	Basin	No. Gullies	Area (ha)	No. Plates	Total Rainfall (mm)	Average fine sediment fraction, <20 µm	Estimated lifetime fine sediment yield (t/yr)
1	Bowen	2	4.5	48	360	0.46	549
2	Bowen	2	4.3	57	469	0.52	593
3	Bowen	4	10.2	80	446	0.71	1892
4	Burdekin	3	8.8	66	462	0.65	1726

Methods

The methods employed in this study established a relatively simple field-based investigation of splash erosion by installing erosion plates flush to the ground surface. The plates were designed to mimic ephemeral objects observed in the field and provide conditions suitable to allow pedestals to form by protecting the underlying ground surface from splash (Hudson, 1993; Stocking and Murnaghan, 2002). Due to the novelty of the experiment, two designs were employed as it was unclear of the durability of the plates to exposure to the elements. The first consisted of a 50 mm x 50 mm x 5 mm rubber plate (Figure 1b), the second using temperature-resistant expanding foam. Both designs had a central pin to a maximum depth of 95 mm to key them to the ground surface and reduce the risk of being moved or washed away. 62 plates were placed with paired designs (31 pairs) to assess the variability in design type and determine whether one design was more suited to the experiment than others.

251 erosion plates were placed across the 11 gullies (Table 1) prior to the wet season, 190 rubber plates and 61 foam plates. Plates were deliberately positioned in locations across the gully surface that were perceived to not be influenced by overland flow or other erosion processes (i.e. headscarp retreat), such as buttress ridges within the gully. An initial geomorphic and soil materials assessment was undertaken to determine different soil materials layers and each layer targeted with erosion pins, providing an ability to assess different in erosion rates between different layers. Soil Materials were sampled for particle size, bulk density and dispersiveness. The plates were then left for the duration of the 2019-2020 wet season.

Following the wet season, erosion plates were located and assessed for pedestal formation. Pedestals were measured using a contour gauge (Figure 1c-d) across two perpendicular planes of the erosion plate and recorded. These measurements were then digitized and averaged for each pedestal and assessed at the gully scale. In circumstances where an erosion plate had collapsed or been removed, field observations were made to determine the processes by which this had occurred. Downwearing rates were applied using equation 1 if collapse of the erosion plate appeared to be related to downwearing of the surrounding surface and exceedance of the central pin.

$$\Delta e = 0.3l \tag{1}$$

where Δe is the change in surface elevation and l is the length of the pin. The downwearing rate factor was determined empirically by comparison with paired designs and was a conservative estimate, as the difference varied between 0.3-0.5.

To calculate sediment yields, the area of bare soil was derived from aerial and satellite imagery using the modified soil adjusted vegetation index (MSAVI2) after Qi et al. (1994). This provides a more realistic metric than total gully area as only bare surfaces are likely to be prone to splash erosion. Using the bare soil area, fine sediment yield was calculated from volumetric change using equation 2.

$$y_r = \frac{\Delta e \cdot A \cdot BD \cdot f}{1000} \tag{2}$$

where y_r is the fine sediment yield from splash erosion in tonnes, A is the bare soil area in metres, BD is the bulk density of soil material, using a standardized value of 1.65 and f is the fine sediment (< 20 μm) fraction shown in Table 1. The average annual yields reported in Table 1 are estimated lifetime averages taken from Daley et al. (2021a), which does not distinguish between erosion processes but assumes an average rate of erosion by dividing total lifetime erosion by years since initiation, with a prior drainage line or swale before gully erosion. The method relies on an empirically-derived area-to-volume relationship.

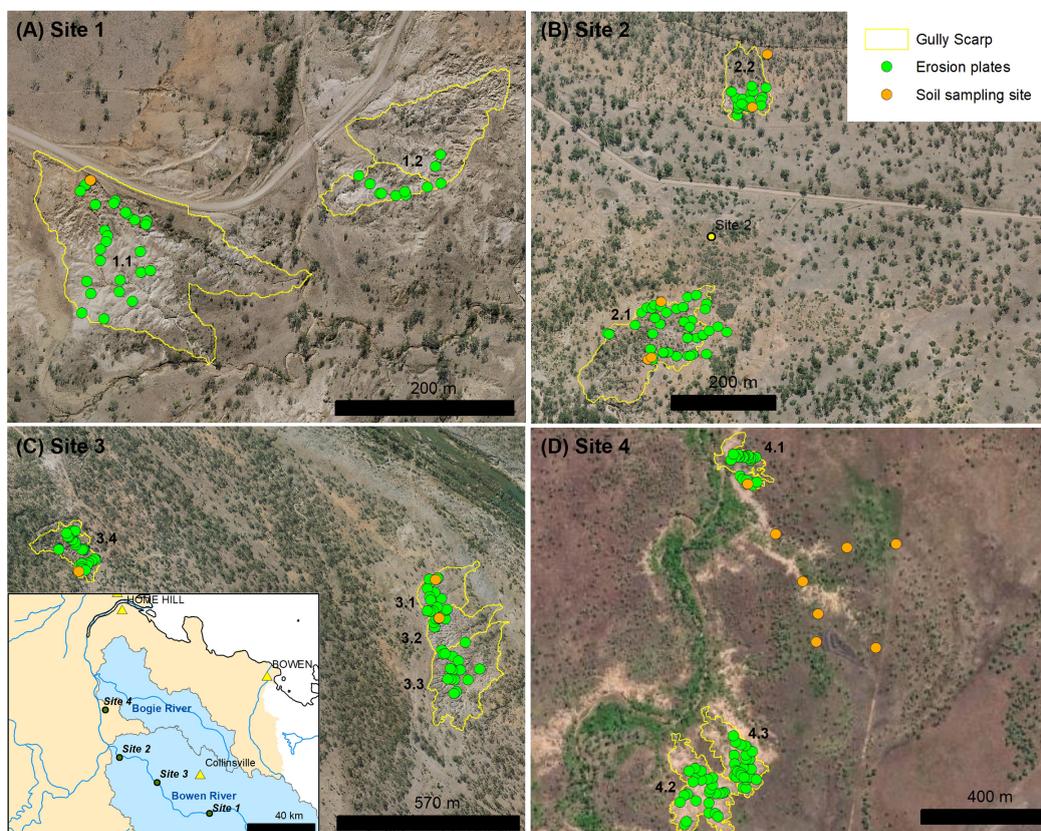


Figure 2. Site maps highlighting the location of erosion plates and soil material sampling. Inset shows the regional site locations in the lower Burdekin River Basin

Results

Across the 251 erosion plates placed at four sites, 177 (70%) were found to have formed measurable pedestals varying between 5 – 55 mm, with an average of 19 ± 11 mm, with distinct differences between sites and gullies (Figure 3). Another 28 plates had toppled over, indicating that downwearing exceeded the depth of the plate's central pin (up to 95 mm long). Eight plates had been removed by other erosion processes (primarily scarp retreat), five had been manually removed by animal or human interference, while another 11 had been removed and could not be accounted for. Only 22 plates formed minimal (<5 mm) or no pedestal (< 2mm). Of these, 45% were located on topsoils adjacent to gullies anticipated to be relatively stable compared with associated subsoils. Topsoils were found to have an erosion rate of 1 ± 2 mm cumulatively across all sites.

Considering pedestal height as a proxy for downwearing of the surrounding surface, the average downwearing rates for each gully area presented in Figure 3 and highlights distinct differences between gullies. Downwearing rates vary between 13 – 25 mm across the gullies with a variation of approximately 9 mm across the sites, although all gullies display different rates of downwearing between soil material layers. While surface layers were found not to be appreciably downwearing at any site, the highest rates of downwearing were found in sub-surface layers 2 and 3 generally 0.15 m – 2 m in depth, consistent with the erodibility hazard of these layers (Daley et al., 2020). Individual sub-surface layers experienced as much as 45 mm of downwearing across exposed surfaces of the soil material layer. Site 1 had lowest rate of overall downwearing at 15 mm, which in part may be explained by the lower seasonal rainfall received at the site (Table 1). All four gullies at Site 3 experienced over 20 mm of surface downwearing across the gully (Figure 3), with every sub-surface layer having rates that exceeded this value. This site also features the highest proportion of fine sediment, with < 20 μ m fraction of 71% (Table 1).

Rainfall analysis at two BoM rain gauges indicates a moderately below average wet season within the basin. At Site 3 (station no 33292), total rainfall over the season was 434 mm while the average is 551 mm since 1999. At nearby Strathmore Station (station no. 33082) the long-term average was 560 mm, while 2019-20 water year was 483 mm. Local wet-season rainfall for each site is provided in Table 1. At the site scale, there is no consistent pattern in the relationship of surface downwearing to total seasonal rainfall ($R^2 = 0.0073$). But a measure of seasonal rainfall intensity, using the skewness of rainfall event intensity multiplied by the maximum intensity, yields a highly significant relationship ($R^2 = 0.9126$) indicating the degree of downwearing is highly correlated to rainfall intensity as opposed to the quantity of rainfall.

The rates of downwearing presented in Figure 3 translate to sediment yield by the volumetric increase in erosion across bare soil surfaces throughout each gully, increasing the annual fine sediment yield by over 70 t/ha across all sites. Predicted downwearing yields vary across the study gullies, dependent on gully area, but across the gullies splash erosion increases the sediment yield by an average of 360 ± 53 t/yr. Only Gully 2.2 had a yield lower than 100 t/yr primarily due to the area of bare surfaces in the gully.

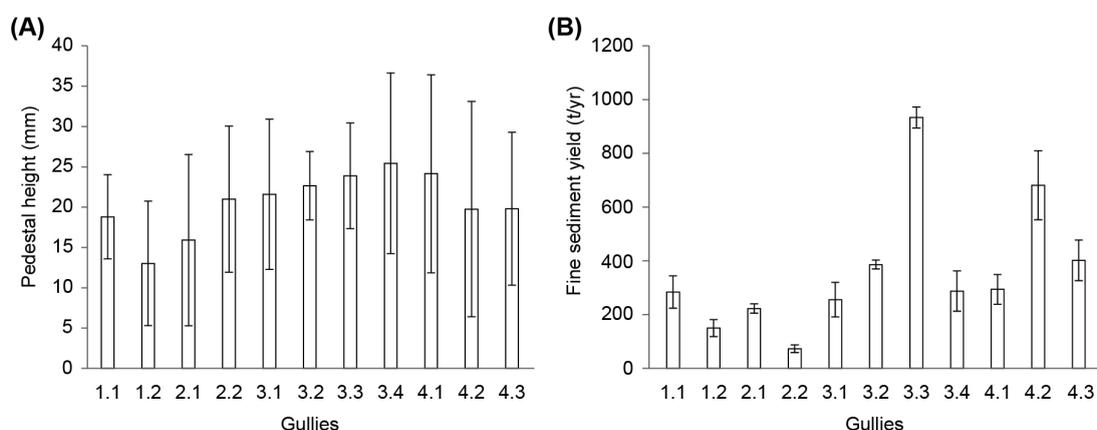


Figure 3. Summary erosion rates for each gully. (A) Average gully pedestal heights; and (B) gully fine sediment yield from rainsplash downwearing component. Error bars represent 1 std dev from the mean

Discussion and Conclusions

From this study, we can suggest that splash erosion is particularly relevant to alluvial gullies, which are disproportionately the dominant source of gully erosion in the GBR (Daley et al. 2021a). While overland flow is important, inducing erosion processes such as block collapse, slumping and entrainment, the extensive nature of downwearing across all exposed (bare) surfaces of the gully result in extensive albeit far less apparent erosion. As such, significant quantities of fine sediment runoff can be generated through this process. Despite below average seasonal rainfall and limited storm events, rainsplash erosion has resulted in an average downwearing of 19 ± 11 mm and an average additional annual fine sediment yield of 360 ± 53 t/yr and up to 1000 t/yr in some gullies (Figure 3). Given the predicted sediment yields from these gullies (Table 1), splash erosion appears to be at least equally important to other erosion processes and in some cases may be the dominant erosion process. Comparison with 0.1 m resolution lidar change detection undertaken at Site 4 (Daley et al., 2021b) indicates downwearing comprises 30-80% of the total sediment budget. In gully 4.1, change detection over the 2019-20 wet season suggested 113 ± 21 tonnes of fine sediment, using a detection limit of 0.09 m (Daley et al., 2021b). By contrast, 277 ± 55 tonnes of fine sediment was generated by splash erosion, representing 71% of the total fine sediment eroded from the gully.

Importantly, the observed downwearing is an order of magnitude below the critical limit of detection in airborne lidar data. As such, the sediment yield is previously unaccounted for in other short-term predictions and may indicate greater non-linearity in gully growth rates and higher baseline yields than reported. In all gullies, these yields comprise at least half of the estimated lifetime annual yield (Table 1), and overall yields 83% of the total estimated amount. In some gullies, such as Site 3, these values exceed the lifetime annual average yield, indicating significant acceleration in erosion in recent years. Downwearing is likely to exacerbate the non-linearity of the yield curve, as positive feedbacks between soil material erodibility and splash erosion affect subsequent growth rates. As gullies grow larger, more sub-surface material is exposed and prone to splash erosion. By contrast, hillslope gullies tend to be more linear, with a single headcut and potentially more likely to be dominated by overland flow from the upper catchment.

Assuming consistent rates of downwearing, over the longer term this process may well be integrated by long-term rates. But accurately identifying this process would likely require a greater than ten-year interval between datasets. Current methods for determining long-term erosion rates tend to account for gully headwall retreat from areal expansion. Such methods assume that erosion occurs with each time step change to the presently observed depth (Wilkinson et al., 2019) or relies on area to volume relationships (Daley et al., 2021a). While the latter non-linear method may account for downwearing, such methods still likely bias higher yields in earlier years than latter years. This is particularly true where erosion is annualised over a defined period. While further data is required to understand the rainfall relationship, the consistency in average erosion rates across multiple sites (Figure 3) hints at a potential to parameterise this process within a modelling framework and understand the long-term implications within gully sediment budgets.

From a gully management perspective, the results presented in this study are critical in relation to the yield and treatment options available for gully remediation. Typical treatment options often consider (1) catchment grazing management; (2) rock chute construction; and (3) reshaping. Recently, these treatment options have been suggested as effective solutions to gully erosion (Wilkinson et al. 2018; 2019). However, these options will be of limited success in gullies experiencing downwearing. If splash erosion is a dominant erosion process, then limiting upstream overland flow will be ineffective in remediating erosion from the gully. Interestingly, the highest rate of downwearing and largest estimated yield was from a gully that had an existing diversion wall constructed to mitigate gully erosion and, as such, had no upstream contributing catchment. Unless the surface of the gully is treated via capping material, alluvial gullies will continue to be affected by splash erosion and have significant sediment yields.

In addition, accounting for downwearing has important implications in determining yield calculations for treatment effectiveness and sediment abatement in managed gullies. This is particularly relevant for short-term monitoring programmes and where change detection monitoring is coupled and compared with water quality data. As discussed above, the degradation process impacts exposed erodible surfaces and the use of

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mulch or other medium substantially reduces or negates the downwearing process. Thus, if treatments are designed with such options, they are likely to achieve a higher abatement than baseline or control/impact comparisons that do not account for downwearing. This has important implications for gully remediation sediment budgeting under being undertaken in GBR water quality improvement programmes.

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