

Research article

Prioritising gully remediation in a Great Barrier Reef catchment: An approach using two independent methods of assessing erosion activity in 22,300 gullies

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ABSTRACT

The strategic reduction and remediation of degraded land is a global environmental priority. This is a particular priority in the Great Barrier Reef catchment area, Australia, where gully erosion a significant contributor to land degradation and water quality deterioration. Urgent action through the prioritisation and remediation of gully erosion sites is imperative to safeguard this UNESCO World Heritage site. In this study, we analyze a comprehensive dataset of 22,311 mapped gullies within a 3480 km² portion of the lower Burdekin Basin, northeast Australia. Utilizing high-resolution lidar datasets, two independent methods - Minimum Contemporary Estimate (MCE) and Lifetime Average Estimate (LAE) – were developed to derive relative erosion rates. These methods, employing different data processing approaches and addressing different timeframes across the gully lifetime, yield erosion rates varying by up to several orders of magnitude. Despite some expected divergence, both methods exhibit strong, positive correlations with each other and additional validation data. There is a 43% agreement between the methods for the highest yielding 2% of gullies, although 80.5% of high-yielding gullies identified by either method are located within a 1 km proximity of each other. Importantly, distributions from both methods independently reveal that ~80% of total volume of gully erosion in the study area is produced from only 20% of all gullies. Moreover, the top 2% of gullies generate 30% of the sediment loss and the majority of gullies do not significantly contribute to the overall catchment sediment yield. These results underscore the opportunity to achieve significant environmental outcomes through targeted gully management by prioritising a small cohort of high yielding gullies. Further insights and implications for management frameworks are discussed in the context of the characteristics of this cohort. Overall, this research provides a basis for informed decision-making in addressing gully erosion and advancing environmental conservation efforts.

1. Introduction

Gully erosion is one of the major drivers of land and water degradation globally (Castillo and Gómez, 2016; Vanmaercke et al., 2016, 2021), resulting in soil loss, sedimentation and reduced water quality in receiving waterbodies (McCloskey et al., 2021; Valentin et al., 2005; Yibeltal et al., 2023). The increased severity of gully erosion throughout the world is often attributed to anthropogenic drivers, such as land use change, land clearing and poor land management practices (Frankl et al., 2012; Gutiérrez et al., 2009; Poesen et al., 2003). Once gullying has initiated, site specific properties of climate, flow routing, sediment properties, and vegetative cover determine the rate of sediment loss

(Nearing, 2001; Parkner et al., 2006). In Australia, research over the past decade indicates gully erosion is one of the dominant processes threatening aquatic ecosystems (Bartley et al., 2017). In the Great Barrier Reef (GBR) catchments (Fig. 1), gully derived sources of fine sediment and particulate nutrient pollution contribute an estimated 40% of the anthropogenic sediment loss to the GBR Lagoon, which is up to five times higher than pre-colonial rates (Bartley et al., 2018; Lewis et al., 2021; McCloskey et al., 2021). Reducing the end-of-system fine sediment yield is the primary management objective for water quality improvement within the GBR. The World Heritage Committee has recently called for urgent action to identify priority areas of grazing land for gully repairs and significantly scale up restoration activities (Carter and

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Thulstrup, 2022, p. 5) as its first priority recommendation to protect the status of the GBR from being inscribed on the UNESCO List of World Heritage in Danger.

Consequently, gully remediation and sediment management are high priority areas of focus in the majority of GBR catchments with the objective of improving downstream water quality in a timely manner (Australian Government, 2021; State of Queensland, 2018). Over the past decade, more than \$900 million AUD has been invested in GBR water quality improvement programs (State of Queensland, 2022), with a further commitment for the next decade (Australian Government,

2023; Great Barrier Reef Foundation, 2019). The primary aim was to reduce fine sediment pollution reaching the GBR by 25% from the 2013 levels by 2025 (State of Queensland, 2018). Rapid upscaling of management activities and resources across numerous high-priority sites is required if managers hope to achieve this target (Carter and Thulstrup, 2022; State of Queensland, 2022). To facilitate these activities, primary sources of sediment pollution must be identified and targeted for remediation (Bainbridge et al., 2023; McCloskey et al., 2021). However, the identification and prioritisation of high yielding gullies is a challenging process requiring the collection of high-resolution data across

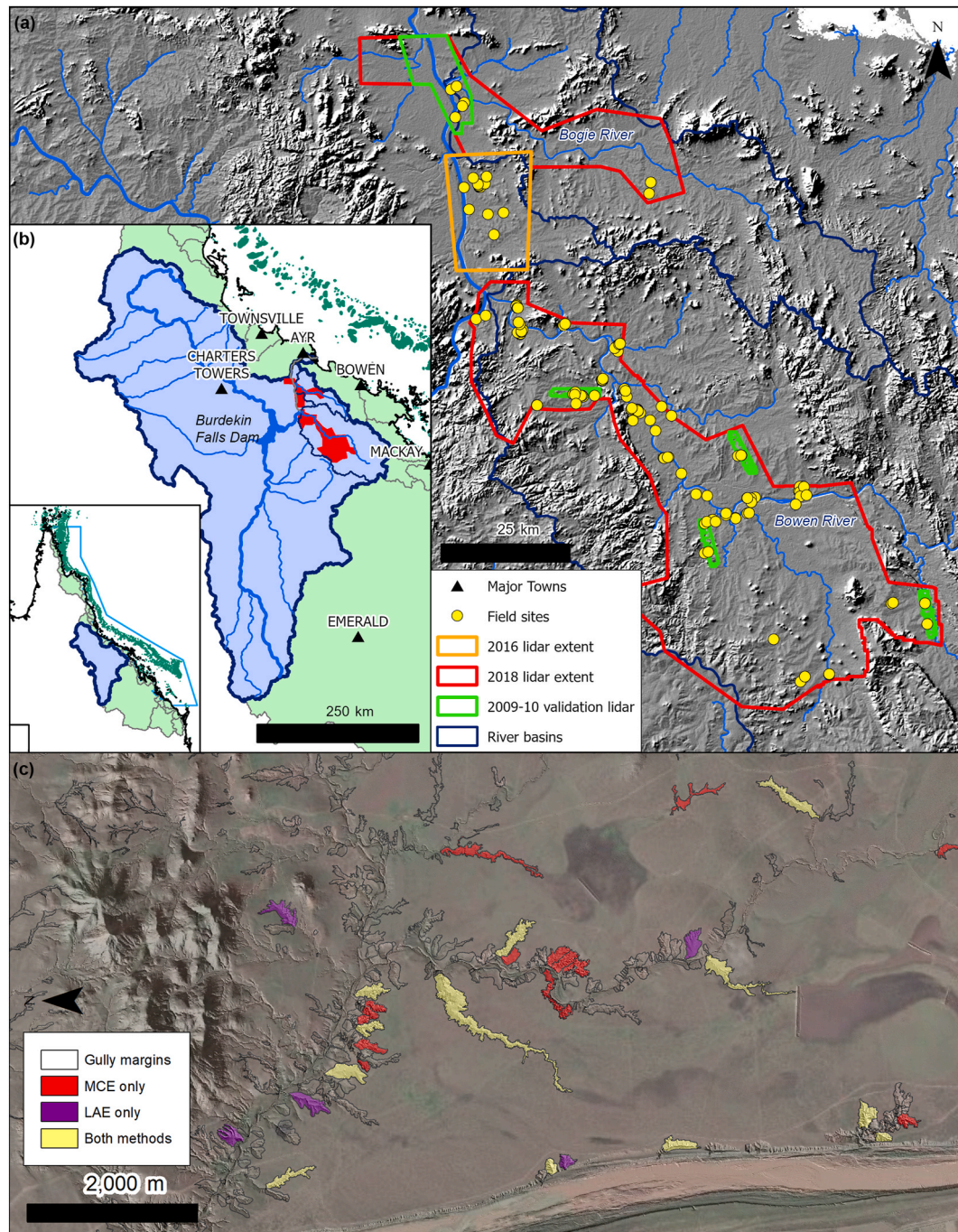


Fig. 1. Location of the study area. (a) The extent of the study area analysed using the 2016 and 2018 lidar in the Bowen and Bogie sub-catchments of the Burdekin Basin, as well as field and validation sites. Note, the gully margin data is of too fine a resolution to be displayed in the map. (b) The study area located within the Burdekin Basin, and GBR catchments in north-eastern Australia, with the extent of the GBR and UNESCO World Heritage site shown (inset). (c) An example of mapping output with the highest ranked 2% of gullies identified using the minimum contemporary estimate (MCE) and lifetime average estimate (LAE). While there are differences in the selection of exact gullies in the highest ranked 2%, many are near other high yielding gullies.

large areas to identify regions of increased gully erosion. Once hotspot regions are identified, the many thousands of gullies that can occur within those areas (Daley et al., 2021) pose considerable challenges for land managers who often have limited capacity to assess the sites on ground.

Accurate mapping of gullies and an initial assessment of their relative severity is an essential precondition to inform management of sediment sources. With the advent of high-resolution, remotely-sensed optical and topographic datasets, a range of methods have been developed to identify and map gully-like features. Approaches include manual delineation (Betts et al., 2003; Martínez-Casasnovas, 2003a; Martínez-Casasnovas et al., 2003b), object-oriented image analysis from satellite imagery (Knight et al., 2007; Shruthi et al., 2011, 2014), lidar-derived topographic and terrain data (Evans and Lindsay, 2010; James et al., 2007; Korzeniowska et al., 2018; Walker et al., 2020; Yang et al., 2017) and more recently machine learning (Saha et al., 2020; Shahabi et al., 2019). Such methods have demonstrated an ability to map depressions in the landscape and at many different scales. Fewer have demonstrated efficacy at scale.

The identification of gully-like features is the first challenge for managing and reducing gully erosion at a landscape scale. Determining whether mapped features are actively eroding and quantifying the degradation rate is a critical next step in the management process and is particularly pertinent for catchment-scale management (Martínez-Casasnovas et al., 2003b). Prioritisation and investment decision by managers require detailed understanding of the contributing sediment losses and even their relative sediment delivery ratio to the GBR Lagoon (sensu de Vente et al., 2007; Lu et al., 2006; Walling, 1983). Further steps are needed to both determine the rate of erosion for each gully and then prioritize these within a management framework. What is needed is a targeted approach to ensure strategic investments are appreciably reducing sediments and remediating gullies that are generating the majority of the sediment. This requires a process-based understanding that is analysed at the catchment scale.

Utilizing an existing dataset of 22,311 mapped gully boundaries in the Burdekin River Basin, Australia (Daley et al., 2021), the primary aim of this research was to estimate gully erosion rates using two independent methods to facilitate prioritisation for gully management. The specific objectives include 1) to determine the validity of the two methods in estimating erosion rates; 2) to analyze the distribution of the frequencies in the gully erosion rates; and 3) to investigate the characteristics of high yielding gullies. The results are placed within the context of gully management and remediation frameworks as well as their contribution to catchment sediment yields, providing direct insight for land managers and governing bodies in guiding targeted reductions in sediment pollution entering the Great Barrier Reef Lagoon.

2. Materials & methods

2.1. Regional setting

The study area is a 3480 km² region of the lower Burdekin River basin, mostly in the Bowen and Bogie sub-catchments (Fig. 1a). The Burdekin River basin (~130,000 km²) is the second largest basin of the GBR lagoon, north-eastern Australia (Fig. 1b), and the Bowen and Bogie Rivers are the major lower tributaries, comprising ~50% of the lower Burdekin downstream of the Burdekin Falls Dam (Fig. 1b). The Burdekin Basin has been identified as a major source of fine sediment pollution to the GBR, with particular attention on gully erosion from within these sub-catchments as a dominant contributor to that pollution (Bainbridge et al., 2014, 2023; McCloskey et al., 2021).

The Burdekin Basin has a highly seasonal, monsoonal dry-tropical, or *hot semi-arid* (BSH; Beck et al., 2023; 2018), climate dominated by wet-season rainfall. More than 70% of rainfall occurs during summer months (December–March) from monsoonal and cyclonic events strongly modulated by the El Niño–Southern Oscillation and the

Inter-decadal Pacific Oscillation (Crimp and Day, 2003; Power et al., 1999). Highly localised variations in rainfall and storm distribution occur throughout the basin along with high intra-annual and inter-annual variability. Annual average rainfall varies throughout the Burdekin basin but is generally 550–650 mm in the study area. Runoff and flow variability are characterised by high variability (Rustomji et al., 2009), with sediment dominantly mobilised during large discharge events, with negligible flows in between (Amos et al., 2004; Bainbridge et al., 2023).

The study area is characterised by low undulating hills, with steeper ridges in the upper catchment, and an incised valley floors dominated by extensive terrace fills. The main river channels generally flow northwest to their junctions with the Burdekin River. Located on the passive, continental margin of eastern Australia, the geology is mostly comprised of Phanerozoic marine sedimentary sequences and intrusive volcanic (granitoid) rocks. Prominent soil types along the eastern margin are the red-brown earths and yellow podsolics/soloths associated with easily weathered parent materials, and extensive areas of black earths (Vertisols) forming linear gilgai (patterned microrelief mounds and depressions caused by shrink-swell processes in expansive clays). Surface soils of the river terraces (including most gully sites) consist of yellow to brown Sodosols (Solonetz or Sodic soils) or Chromosols (Lixisols) of varying depth 7+ m thick. However, much of the gullied areas are poorly described as *Quaternary Alluvium* or *Not Applicable – Eroded Land* in available soil mapping. Gully soil materials are typically highly erodible with high proportions of exchangeable cations (Daley et al., 2023a).

Most of the catchment features semi-arid savannah woodlands and is grazed with cattle on unimproved pasture. Throughout the GBR, fine sediment pollution increased with associated land use changes following European occupation in the 1800s, including the clearing of native vegetation and introduction of exotic grasses and ungulates for agricultural purposes (Bartley et al., 2017, 2018; Lewis et al., 2021). Gully erosion in the BBB initiated with land use change and intensification in the late 19th century to early 20th century. A range of gully types occur throughout the area, which reflect differences in landscape domain, soil types and form. For management purposes, these are typically separated into broad, initial categories of hillslope and alluvial gullies (Brooks et al., 2019).

2.2. Input data

2.2.1. Aerial lidar surveys

Aerial lidar and near-coincident high-resolution aerial photography were acquired for ~3160 km² area of the Lower Burdekin basin (Fig. 1a) in 2018 using a RIEGL VQ-780i sensor at an average point density of 16 points per m² by Aerometrix as part of Australian Government Reef Trust lidar acquisition project. The surveyed area included identified gully erosion hotspots in the Bowen and Bogie River basins (Darr and Pringle, 2017). A half-metre resolution DEM was derived from this data for use throughout the study. An additional ~320 km² of lidar was surveyed in 2016 adjacent to this extent and allowing expansion of the gully mapping and analysis. The lidar was surveyed using a Trimble AX60 and a point spacing of 3 points per m². Due to the lower resolution of this data, a 1 m DEM was generated during post-processing by RPS Australia™. Five additional lidar blocks that overlapped with the areas of the 2018 lidar survey were obtained to undertake multi-temporal change analyses and construct a validation dataset of contemporary gully erosion rates. These blocks were between 12 and 120 km² and surveyed in 2009 and 2010 using a Harrier H68i lidar sensor, with an average point density of 4 points per m². The data was post-processed by Terranean™ to produce 1 m DEMs. Their extent is shown in Fig. 1a.

2.2.2. Satellite imagery

Bare ground was derived as an input for estimating gully erosion rates based on evidence provided by Daley et al. (2023a). Bare ground was developed using PlanetScope Analytic data (Planet Team, 2020)

and the modified soil-adjusted vegetation index (MSAVI2; Qi et al., 1994). Planet provides 4-band multi-spectral ortho scene data for analytic and visual applications. The provided product is orthorectified, radiometrically calibrated into top-of-atmosphere radiance data and then atmospherically corrected to surface reflectance, resampled to 3 m (Planet Team, 2020). Selected imagery was cloud free and surveyed within a one-month period of the lidar acquisition date at each site. Imagery was collected from the late wet season period, as vegetation growth and ground cover should be at a maximum, and hence bare ground areas are likely to be permanently bare and exposed (Daley et al., 2023a). MSAVI2 was used to select bare ground by applying a threshold of 0.35 based on visual comparison with high resolution aerial photography acquired in conjunction with the 2018 lidar.

2.2.3. Gully margins

An existing gully boundary dataset of 22311 erosional landscape features was used as the primary input spatial dataset for erosion activity assessments (Daley et al., 2021). The dataset was created for management purposes of identifying significant sediment sources that could be targeted in a cost-effective manner using direct interventions. It includes 55 environmental attributes, including geographic, geometric, vegetation, soils and erosion attributes. Gullies were mapped by adapting and integrating mapping principles described by Yang et al. (2017) and Korzeniowska et al. (2018) for large scale processing, using hillshade and roughness metrics derived from the DEM. Automated mapping tools were developed by Daley et al. (2021) to digitise gully margins, which were combined with Arc Hydro tools to derive specific drainage units and delineate segmented erosional features across the 3480 km² study area. A detailed methodology is provided by Daley et al. (2021).

The dataset was further filtered to remove potential non-gully or very low yielding landscape features that may have been captured in the automated production of the dataset. Based on field observations, gullies with greater than 25% canopy cover taller than 5 m high or less than 20% bare ground were removed from the dataset as anomalies or not priorities for management. An additional 15 gullies with areas greater than 12 ha were individually assessed and removed as these were deemed to be low order streams incorrectly mapped as gullies. Automated filtering parameters were determined using a combination of field validation at 42 sites and desktop verification of greater than 100 sites. The filtering process reduced the dataset of 22311 gullies to 21280 gullies. This is not to assume that the excluded features had no erosion processes occurring but were considered less likely to be major sources of sediment compared with more active gully erosion. The focus of this study is on gullies as active sources of sediment pollution that can be managed, as opposed to investigating all erosional features.

2.3. Estimating erosion activity

To estimate erosion activity for each mapped gully, two independent methods and a separate validation method were used. The two methods developed represent different timeframes of erosion activity for each gully (whole-of-life average cf recent rates). By utilizing distinct and independent methods, derived from independent variables, there is greater confidence in the estimation of gully erosion. All erosion rates are total gully sediment loss (m³ y⁻¹).

2.3.1. Lifetime average estimate (LAE)

The LAE represents the whole-of-life average erosion rate for each gully, based on an estimated initiation date and an equally distributed annualised rate. The lifetime eroded volume of each gully was an attribute of the gully dataset (Daley et al., 2021) and was determined using a method comparative to Evans and Lindsay (2010). An artificial surface was projected across each gully to represent a Prior Land Surface DEM (PLS DEM), which was then subtracted from the existing lidar DEM to determine the eroded volume. However, a conservative PLS was estimated by assuming a swale, or depression, existed along the drainage

line prior to gullying, comparable to observed non-gullied drainage features in the surrounding landscape. Contemporary drainage lines within the gully were used to project from the margins to drainage lines elevations 80% of their current depth (Daley et al., 2021).

To convert this volume into an average annual rate, an assumption of the gully initiation date was used to divide the lifetime total by the gully age. There are likely to be considerable basin-wide differences in gully ages and applying a rate across the whole basin is a crude tool. However, without a detailed, spatially distributed analysis of such ages, it nonetheless provides a useful proxy. Following Saxton et al. (2012) methodology, a basin-wide 81 ± 3 year estimate of gully age of was applied across all gullies based on detailed estimates of initiation dates from 51 sites within the study area (see supporting information). Historical air photos were used to calculate gully growth rates and back-project gully initiation dates. While there was a spread of ages across gullies within the basin, a mixture model analysis identified a central age 81 ± 3 years, which is broadly associated with basin-wide intensification of land use. Two age populations were identified at 73 ± 5 years and 131 ± 8 years. The reported error on the annual rate for the LAE is the range between these two gully ages.

2.3.2. Minimum contemporary estimate (MCE)

The MCE presents an estimate of the expected minimum annual rate in the present gully form, based on process-form assumptions whereby erosion activity within gullies is associated with (1) identifiable erosional forms, such as fluting, rilling and scarps, that produce high surface roughness; (2) bare soil materials exposed to direct rainfall and runoff. The assumptions of process rates are deliberately conservative, in line with the lower limits of detectable erosion with the input data. Actual measured rates are therefore likely to be higher than the MCE estimated values.

It was derived by integrating digital mapping of a potential erosion activity (PAE) index (Daley et al., 2019) and bare ground within the gully margins. The PAE index was determined by integrating a surface roughness metric (μ) derived from the log-transformed standard deviation of terrain curvature within a 3 m kernel window (Korzeniowska et al., 2018). The index identified areas with high values of surface roughness that reflect above-mentioned erosional forms. The PAE prediction was compared to measured erosion rates from lidar-derived DoD data, showing good agreement in identifying actively eroding areas within gullies (Daley et al., 2019). Threshold values of roughness were obtained following Korzeniowska et al. (2018), with pixel-scale accuracies exceeding 86% and F1 statistics ranging from 0.2 to 0.4 across the validation sites (Daley et al., 2021, p. 74). At the gully scale, the proportion of eroding area was compared to the summed DoD data at 408 gullies across three sites within the study area, demonstrating R² values of 0.71–0.90 (Daley et al., 2021, p. 76).

PAE-mapped areas were assigned an erosion rate of 0.035 m³ yr⁻¹ per pixel based on limit of detection thresholds used in the DoD training data of Daley et al. (2019). A mutually exclusive geospatial layer of bare ground was derived from Planetscope imagery, whereby if pixels were identified by both PAE and bare ground layers, only the PAE erosion estimate was used. Bare ground cells were assigned an average rate of 0.025 m³ yr⁻¹ based on rates of fine-scale erosion described by Daley et al. (2023a) within the same study area. As those described rates were observed during a below-average rainfall year, they have also here been assumed to represent the minimum process rate. Combining these two processes within each gully provides an estimate of the minimum rate of erosion occurring in each gully.

2.3.3. Multi-temporal change detection and detailed gully assessment

A validation dataset of annualised erosion volumes at 1786 gullies was constructed from repeat lidar data using multi temporal change detection (Wheaton et al., 2010). The 2018 lidar data was degraded to 1 m resolution to align with the lower-quality 2009 and 2010 datasets. Quality assessment checks were conducted to horizontally align the

survey data and adjust for any systematic vertical offset. A 1-m resolution DoD was subsequently created for each block by subtracting the elevations in each DEM on a cell-by-cell basis. Following quantification of uncertainty protocols of Wheaton et al. (2010), critical thresholds of error were established between 0.25 and 0.4 m, with values below that range in each data discarded from the final estimates. The estimates derived from these analyses are limited in their ability to completely characterise erosion rates and finer scale processes due to issues related to data resolution and survey length (Daley et al., 2023a; 2023b). As such, they do not necessarily represent a point of truth for validation purposes but provide a useful approximation of erosion activity using

well-established protocols and high-resolution data.

2.4. Field assessment

Field geomorphic assessments were undertaken at 118 sites throughout the study area (Fig. 1). At each site, field surveys were undertaken to assess erosion activity by identifying geomorphic forms, gully type descriptions (after Brooks et al., 2019), vegetation extent and other evidence active erosion (identification of head cuts, scarps, fluting, pedestals, tree roots). Validation exercises of bare ground extent and potential erosion activity mapping (sensu Daley et al., 2019) and modelled

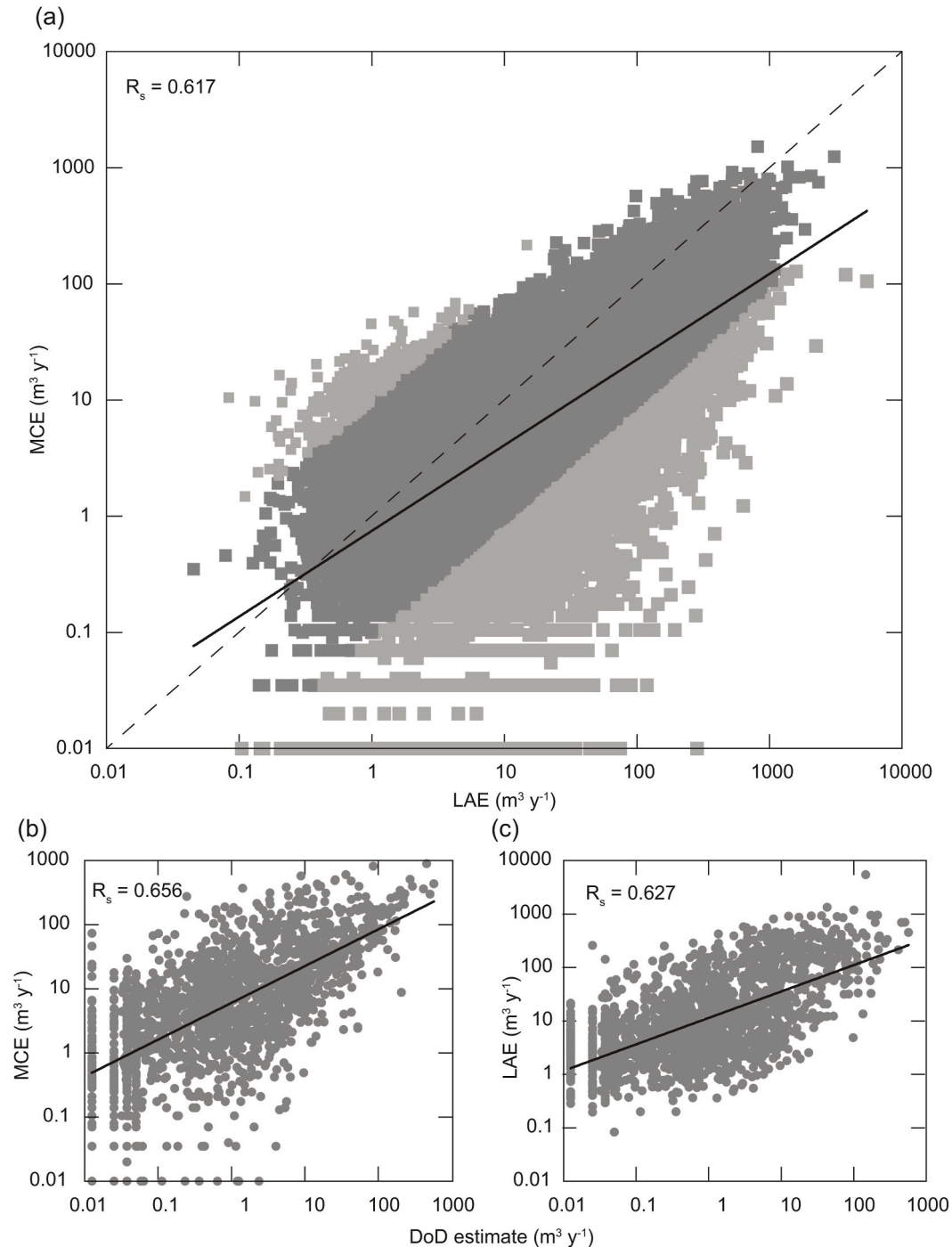


Fig. 2. Correlation between different erosion activity methods. (a) Correlation between the LAE and MCE methods of gully erosion rate. The light grey markers represent gullies with dissimilar estimates greater than an order of magnitude difference. Validation with lidar DoD-derived estimates across lidar blocks, showing correlation with (b) MCE and; (c) LAE. See supporting information S2 for correlation of individual sites.

erosion rate estimates were also undertaken. Soil materials were described in profile and samples collected for sedimentary and soil chemistry analyses to address gaps in previous soil mapping data. While gully soil material data has been collected in association with field assessments of this study, the mapping, interpolation and interpretation of that data is beyond the scope of this study.

3. Results

3.1. Consistency and validation of erosion estimates

While the erosion rates between methods are not expected to align in their absolute values, as they present different measurement scenarios (i.e. contemporary rate vs. lifetime average), rates were assessed for comparison and consistency between methods and validation data. The MCE and LAE methods provide strong, positive correlation in identifying the highest yielding gullies, $R_s(21278) = 0.62$, $p < 0.001$ (Fig. 2a). The absolute values vary over several orders of magnitude, particularly in estimates $< 10 \text{ m}^3 \text{ yr}^{-1}$, which vary up to four orders of magnitude. Between the MCE and LAE, there were 3941 gullies that had inconsistent erosion rate estimates that varied by more than an order of magnitude. These irregularities represent 16.4% of the gully dataset, with most caused by high LAE values and low MCE values. The majority of these were in the lower 25th percentile of estimates and 62% had an estimated rate of $< 1 \text{ m}^3 \text{ yr}^{-1}$ in the MCE. Variability decreases with increasing yield, with higher estimates mostly having less than an order of magnitude difference (Fig. 2).

Observations undertaken during field surveys largely conformed with the input spatial datasets for the MCE, with approximately $\pm 15\%$ difference in the extent of erosion indices across the gully sites. Field observations generally conformed with remotely-derived interpretations of contemporary erosion rates and activity, noting visible signs of highly active erosion features including block collapse, slumping and tunnelling at headwalls, bare surfaces with pedestals, fluting, rilling and secondary incision. At some locations, bare ground was underpredicted by the remote sensing approach, which appeared to be related to the moderate resolution of the input imagery, sparse vegetation growth and gully morphology. At two sites, areas mapped as bare ground were sparsely covered with tussock grasses, which had $< 30\%$ ground cover.

Comparison with the multi temporal lidar change detection analyses (Fig. 1) provides valuable validation data for both methods. Both methods correlate strongly with the lidar-derived estimates. The MCE has a marginally stronger correlation ($R_s = 0.65$ (1784), $p < 0.001$) than the LAE ($R_s = 0.62$, $p < 0.001$) across all five validation blocks (Fig. 2b and c). Both datasets show two to three orders of magnitude variation with the DoD estimates. There are differences in the correlation with each DoD that likely related to a combination of the uncertainties in each multi temporal analysis and differences in the landscape setting and gully types at each location. All validation blocks demonstrate strong, positive correlation, with spearman's rank correlations between the DoD estimates and MCE to be 0.66–0.75 with corresponding p-values of < 0.001 . Correlation coefficients with the LAE were 0.60–0.78 in each lidar block, with corresponding p-values of < 0.001 .

A hundred of the gullies with inconsistent erosion rates were randomly investigated, as well as a selected sample featuring high rates, to determine the nature and cause of the discrepancy between erosion activity estimates, and assess which rate provided a more reasonable estimate based on visual indicators of erosion. Sites were investigated using the input and derived geospatial datasets, and six sites were assessed in the field. Many of these gullies were densely vegetated, with 78.9% of all irregular gullies featuring $> 20\%$ woody vegetation cover, and 86% of gullies with LAE rates $> 50 \text{ m}^3 \text{ yr}^{-1}$. The field sites all had high LAE estimates, featured high vegetation cover and deep drainage features. While some observations of active erosion were noted, these sites were correctly identified as low yielding in the MCE and mostly

appeared stable and not gullying.

The two primary causes for disagreement between the estimates related to the assumptions of the topographically derived estimates and assumed lifetime age. The main cause of disagreement was due to the presence of a stabilised or palaeo gully feature or swale that had been incorrectly identified as the gully margin, while in few instances the threshold for hillshade detection (described in Yang et al., 2017) intercepted an incorrect location of the surrounding slopes of a gully. In both cases, this resulted in the LAE overestimating the lifetime erosion volume. Investigation of these gullies in the field highlighted the long-term stability of these swales, which showed soil development and were often well-vegetated, providing conservative estimates of attribute selection for filtering described in the methods. A third cause for disagreement, but to a lesser extent, related to a lack of detection of erosion activity indices by the automated processing and resolution of input data for the MCE. Of the 100 gullies assessed, visual evidence of erosion activity in spatial datasets suggest 86% were better described by the lower estimate. As such, the erosion rates of the remaining inconsistent gullies were adjusted to reflect the lower estimate for further analyses. An additional 271 gullies with estimates separated by two orders of magnitude or had rates greater than $500 \text{ m}^3 \text{ yr}^{-1}$ were manually investigated and adjusted accordingly to the most appropriate value for further analyses.

3.2. Assessment of gully sediment losses

A total of 21280 gullies were selected from the complete dataset for modelling sediment losses, representing 4374 ha of gully erosion in the study area. The contemporary total volume of gully sediment loss from the MCE method was $514,000 \pm 49,500 \text{ m}^3 \text{ yr}^{-1}$ throughout the study area. The LAE method produced a lifetime volume of $1.35 \times 10^8 \text{ m}^3$, translating to an annual average rate of $1,670,000$ ($-637,000/+183,000$) $\text{m}^3 \text{ yr}^{-1}$ assuming the age of all gullies is 81 years. Adjusting for the inconsistent anomalies described above, the LAE produces an annual average of $1,358,000 \text{ m}^3 \text{ yr}^{-1}$. The distributions of gully erosion rates from both methods are strongly positively skewed (Fig. 4a). While gully erosion rates range up to $1518 \text{ m}^3 \text{ yr}^{-1}$ for the MCE and $4968 \text{ m}^3 \text{ yr}^{-1}$ for the LAE, average erosion rates were $5.3 \text{ m}^3 \text{ yr}^{-1}$ and $9.2 \text{ m}^3 \text{ yr}^{-1}$, respectively.

Relatively few gullies are contributing a large proportion of the net catchment sediment loss, consistent across both datasets (Fig. 3). The highest ranking 2% (426 gullies) in the MCE and LAE are respectively producing 29.0% and 30.6% of the total sediment loss, and the highest ranking 20% (4256) are producing 80.0% and 86.8% of the total annual sediment loss from gullies in the study area (Fig. 3). The top 5% of gullies, which represent $\sim 50\%$ of the sediment loss in each population, fall entirely within a cohort of statistical outliers (Fig. 4). Cumulative distribution plots demonstrate both datasets feature a steep initial slope of the curve, that flattens out by $\sim 40\%$ of the ranked dataset. Both datasets feature a long tail in their distribution of gullies with low yields that do not significantly contribute to the overall catchment sediment loss rates. Summary statistics for the total dataset and the highest ranking 20% and 2% of gullies for each method are shown in Table 1 and their distributions visually presented in Fig. 4. The MCE featured 2613 (12.3% of dataset) statistical outliers in the upper range of erosion rates.

3.3. Characteristics of high yielding gullies

The highest yielding cohort of gullies have notably different characteristics to many of the gullies found in the BBB study area. The highest yielding 2% of gullies, which represent approximately 30% of the total gully sediment loss (Table 1), are all statistical outliers of the total dataset, as are the upper half of the highest yielding 20% (Fig. 4). The erosion activity methods consistently identify 72.6% of the same gullies in the highest 20%. While 43.3% of the highest yielding 2% are consistent between the two methods, 113 of the highest 200 gullies rank

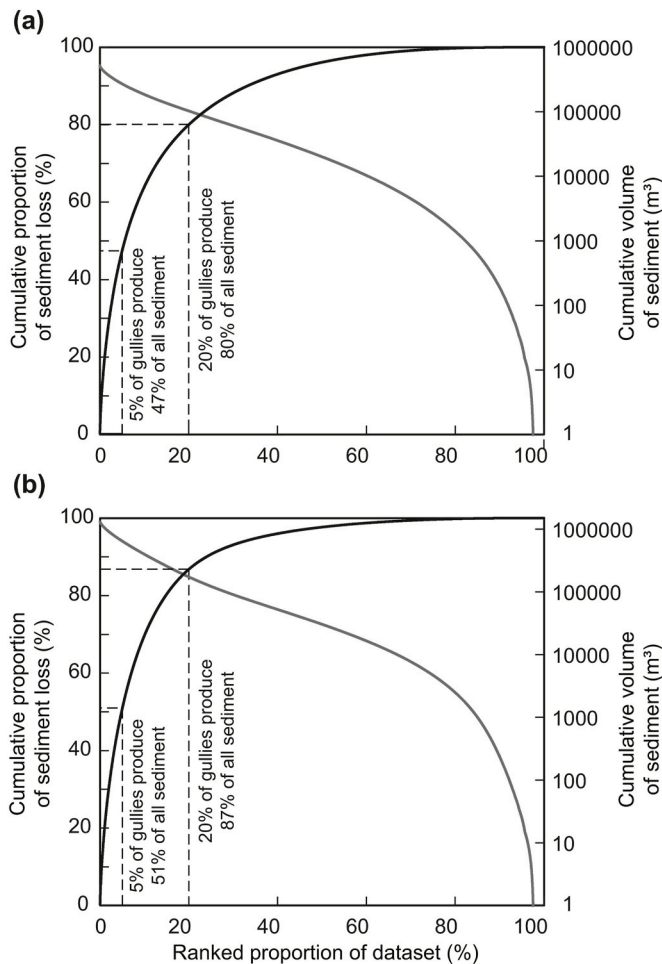


Fig. 3. Cumulative proportional erosion activity for (a) MCE; and (b) LAE methods. The black line represents the cumulative proportion of sediment loss for all gullies ranked from highest yielding to lowest. The grey line is the cumulative volume of sediment loss across the study area.

in the highest yielding 2% of both datasets. An example of the differences in selection of the highest ranked 2% of gullies is presented in Fig. 1b. However, the majority of high yielding gullies between the two methods are in close spatial proximity of each other. Within the highest 2% of gullies, 66.4% identified by the LAE are within 500 m of a gully identified by the MCE, while 80.5% are within 1 km. Both the highest yielding 20% of gullies and 2% of gullies have significantly higher average erosion rates than the total population, almost two orders of magnitude higher than the total population (Table 1). The highest yielding 2% of gullies have an MCE mean of $321 \text{ m}^3 \text{ yr}^{-1}$ (SE = 8.4) and an LAE mean of $890 \text{ m}^3 \text{ yr}^{-1}$ (SE = 22.2).

The strongly skewed nature of erosion rates in the gully population is also reflected in the dimensions. The highest yielding gullies across both landscape domains are typically much larger in their dimensions than the majority of gullies in the catchment (Table 2 and Fig. 5). In general, these gullies do not represent the classical gully that features a relatively narrow drainage along a concentrated flow path (Fig. 5). On average, they are over 2 ha in area and have an average width of 38.5 m, compared to 775 m^2 and 6.6 m for the total dataset, respectively. The specific yields of the highest yielding gullies are also higher (averaging $69 \text{ m}^3 \text{ ha}^{-1}$ [SE = 2.5] and 108 [SE = 3.85] $\text{m}^3 \text{ ha}^{-1}$ for MCE and LAE, respectively) than of the total population average ($32 \text{ m}^3 \text{ ha}^{-1}$ [SE = 0.3] and $48 \text{ m}^3 \text{ ha}^{-1}$ [SE = 0.3], respectively). Both high yielding alluvial and hillslope gully types have comparable distributions in their areal extent. However, alluvial gullies are notably wider (median = 46 m) and

deeper (median = 1.5) than hillslope gullies (30 m and 1.2 m, respectively), while hillslope gullies tend to have greater lengths (excepting nominal outliers of the alluvial gullies), with a median of 868 m compared to 505 m for alluvial gullies. Alluvial gullies tend to display a larger spread across all geometry variables and have a greater number of outliers (Fig. S9). Across all methods, erosion rates had no correlation with catchment area, catchment ratio (catchment area/gully area) or slope.

Apparent within the data is the disproportionate representation of alluvial gullies to catchment sediment losses, particularly in the highest yielding cohort of gullies (Fig. 6). Across the total datasets, hillslope gullies occupy a 32% greater area than alluvial gullies. However, the sediment contributions from hillslope ($2.5 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$) and alluvial gullies ($2.17 \times 10^5 \text{ m}^3 \text{ yr}^{-1}$) estimated from the ME are similar, with a 15% difference. The LAE data demonstrates a similar 17% difference. However, in the highest yielding 20% and 2% of gullies the difference is more pronounced. In the top 2% of gullies, which represent 30% of the catchment sediment loss, alluvial gullies account for 57–58% of the sediment loss (Fig. 6c).

4. Discussion

This study provides practical and quantifiable means of determining relative erosion activity in gullies. While a range of gully mapping approaches are available (James et al., 2007; Korzeniowska et al., 2018; Walker et al., 2020; Yang et al., 2017), the MCE and LAE methods represent independent approaches to identify relative sources of gully erosion at scale, and hence form the basis for prioritising management effort. Mapping alone without some estimate of erosion activity is not a basis for prioritising management effort. The combination of independent lines of evidence presented herein forms a basis for an initial prioritisation based on the sediment contribution from individual gullies (Fig. 7). It enables prioritisation of management efforts to target and mitigate the significant environmental impacts of gully erosion (Valentin et al., 2005). Identifying the highest yielding gullies, using both approaches presented, allows managers to focus on a small proportion of the landscape rapidly and confidently for remediation (Fig. 7).

4.1. Comparison between erosion activity methods

While for many gullies the observed absolute rates of erosion varied considerably between the two methods, erosion activity rankings were strongly correlated between the methods and against validation datasets. Both methods identify 72.6% of the same gullies as the highest ranked 20% of gullies, and 43% in the highest yielding 2%.

Variation in erosion activity rates between methods is expected and does not reflect an error in either method, as is the rank order of gullies, given they characterise different aspects of the gullies' life cycles. The MCE approach was designed to characterise the lowermost limit of contemporary erosion rates, based on contemporary evidence for erosion in the present gully form. By contrast, the LAE method presents the average annual erosion rate since gullying initiated, based on quantifying the erosional void of a gully. These distinct characterisations of rate will often vary, as gullies often experience significant changes in growth rates over their evolutionary development (Sidorchuk, 1999). The lifetime average was expected to generally yield higher estimates than the contemporary estimate and was higher in 76.3% of gullies. This may represent a decline in erosion rates in many gullies, as expected in most conceptual understandings of gully evolution (Sidorchuk, 1999; Vandekerckhove et al., 2003; Rutherford et al., 1997).

Some gully growth rates rapidly decline after an early peak in erosion (Sidorchuk, 1999; Rutherford et al., 1997), while others continue to expand over much greater lengths of time (Daley et al., 2023a; Daley et al., 2023b). Integrating an understanding of a gully's age and historical trajectory is fundamental to characterising its contemporary and future erosion risk. The LAE is limited by representing an evenly

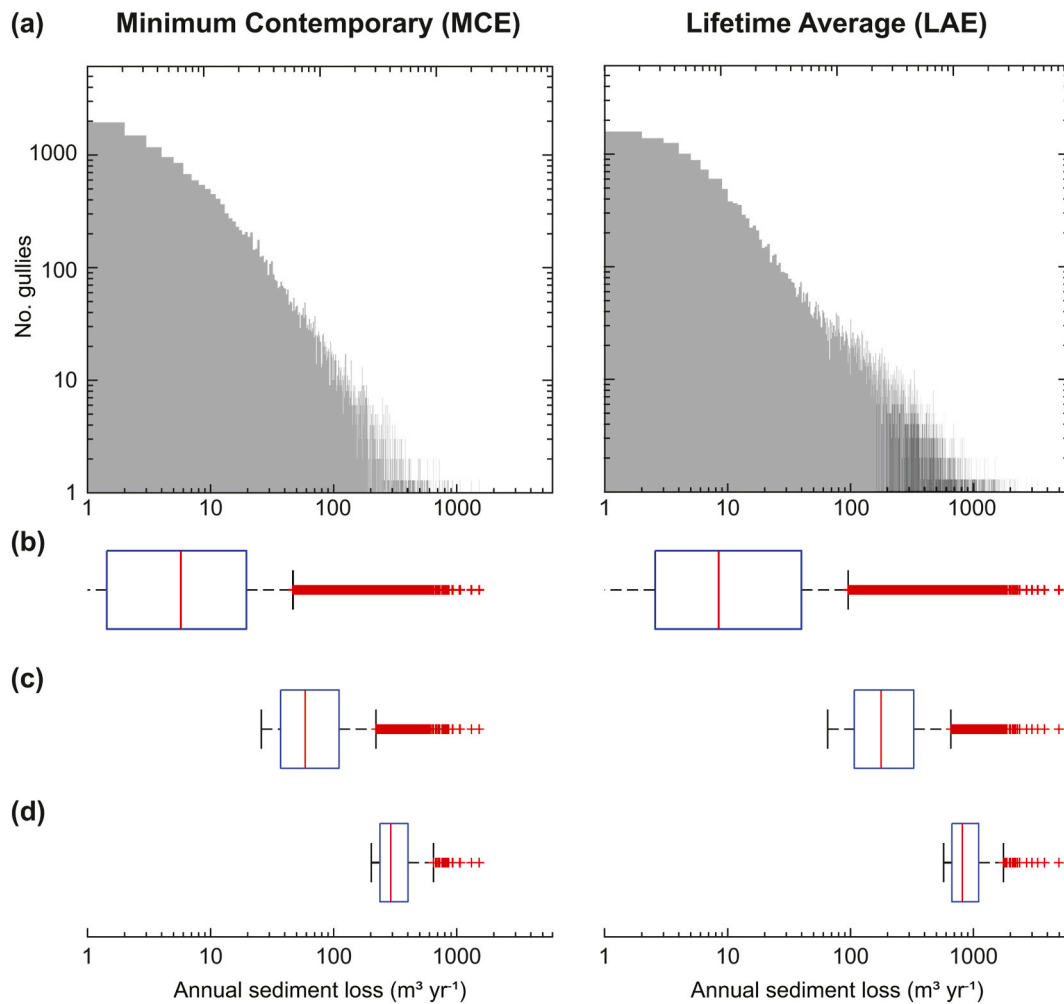


Fig. 4. Distribution of annual erosion rates for MCE and LAE erosion activity estimates. (a) Frequency histograms and (b) box plots for total population; box plots for (c) highest ranking 20% of gullies and (d) highest ranking 2% of gullies.

Table 1

Average gully annual erosion rates for different gully erosion activity methods, in cubic metres per year ($\text{m}^3 \text{yr}^{-1}$), values in brackets are standard errors.

	no.	MCE					LAE				
		median	mean	std error	skewness	kurtosis	median	mean	std error	skewness	kurtosis
Total pop.	21280	6.1	5.3	0.42	7.1	82.9	8.53	9.24	1.14	7.1	95.5
Top 20%	4256	58.7	68.7	1.7	4	28.2	177.3	198.2	4.5	4.1	35.4
Top 2%	426	291.3	321.7	8.4	2.5	11.6	812.4	890.1	22.2	3.3	21.9

distributed spatial and temporal age estimate across the whole dataset. While catchment land use pressures can be relatively widespread, localised differences in those pressures cause site-specific differences in the initiation age of gullies (Saxton et al., 2012; Shellberg et al., 2016). Some of the features captured may be far older or younger than the average, which will significantly impact the derived rate from this method. As such, accounting for historical growth factors can be an important addition to prioritising those with expanding trajectories (Fig. 7).

It is also worth noting the DoD validation data from the change detection analyses do not present a point of truth in erosion rate yet provides a valuable assessment of relative erosion rates. The short duration of the survey period, coupled with the resolution of the lidar and high limit of detection, restricts the ability of this data to accurately represent the erosion rate during the eight-year period. Daley et al. (2023a) demonstrate the significant volume of sediment that can be

generated from fine-scale erosion processes in gullies within the study area, and also the limitations of lidar data to accurately detect such change (Daley et al., 2023b). The DoD data biases higher rates of a detectable change from sources such as headcut retreat. As such, while the exact rates presented in the validation dataset are likely underestimated. Nonetheless, the relative erosion activity and strong correlation values > 0.62 presented in this data are important to providing confidence in the methods.

4.2. Comparison with catchment sediment yield estimates

The benefit of independent lines of evidence is the increased confidence in the generalised assessment of sediment contributions within sediment budgets and modelling. Bainbridge et al. (2023) highlight the importance of utilizing multiple lines of evidence for providing confidence in estimating catchment sediment losses, presenting three

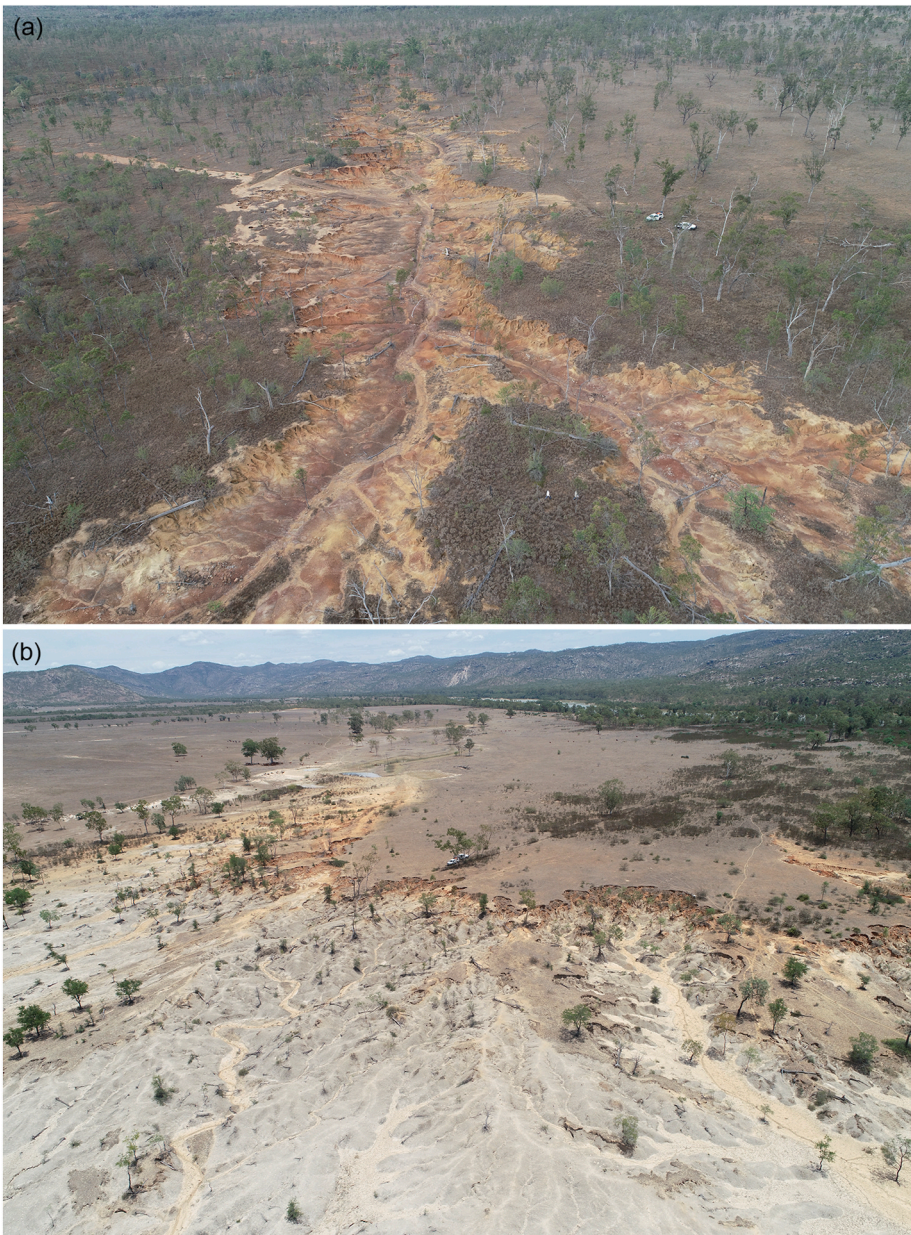


Fig. 5. Oblique aerial photos from field validation of gullies in the highest yielding 2% of gullies, with example of a (a) hillslope gully and (b) alluvial gully. Note the vehicles in each photo for scale.

Table 2
Comparison of average gully geometries for different gully domains between the total population and highest yielding gullies. The values in brackets are the standard error of the mean.

	Alluvial gullies		Hillslope Gullies	
	Total	Top 2%	Total	Top 2%
No.	9490	228	11791	198
Width (m)	11 (0.1)	44 (1.7)	9 (0.09)	32.3 (1.2)
Depth (m)	0.63 (0.005)	1.7 (0.05)	0.52 (0.003)	1.2 (0.04)
Length (m)	188 (2.5)	757 (41)	250 (2.5)	972 (39)
Area (ha)	0.24 (0.005)	2.35 (0.09)	0.257 (0.005)	2.65 (0.11)

methods within the BBB for fine sediment loss. Fine sediment <20 μm is considered the most ecologically sensitive sediment fraction in the GBR, being readily transported through catchments as suspended load and having the most deleterious impact in receiving ecosystems (Bainbridge et al., 2014, 2018; Haynes et al., 2007; Waterhouse et al., 2012). Within

the BBB catchment modelling, gully erosion is currently predicted to contribute 81% of this fine sediment (McCloskey et al., 2021).

The cumulative gully contributions of sediment in this study are estimated at 514,000 $\text{m}^3 \text{yr}^{-1}$ with the MCE and 1,358,000 $\text{m}^3 \text{yr}^{-1}$ with the LAE. Fine sediment proportions vary considerably between gully soil types throughout the catchment, but average measurements of fine sediment proportions (Brooks et al., 2020) suggest average minimum losses of 399,000–485,000 t yr^{-1} , while average whole-of-life estimates from the LAE are 0.89–1.59 Mt yr^{-1} (supporting information S1). Noting that the study area does not cover the whole BBB catchment area but captures most of the high yielding areas (McCloskey et al., 2021), these losses conform with current measuring and modelling estimates of fine sediment.

Annual sediment loss rates are highly variable within the basin (Amos et al., 2004), related to monsoonal and cyclonic conditions. However, McCloskey et al. (2021) predict an average fine sediment catchment load of 1.28 Mt yr^{-1} from all erosion sources, which

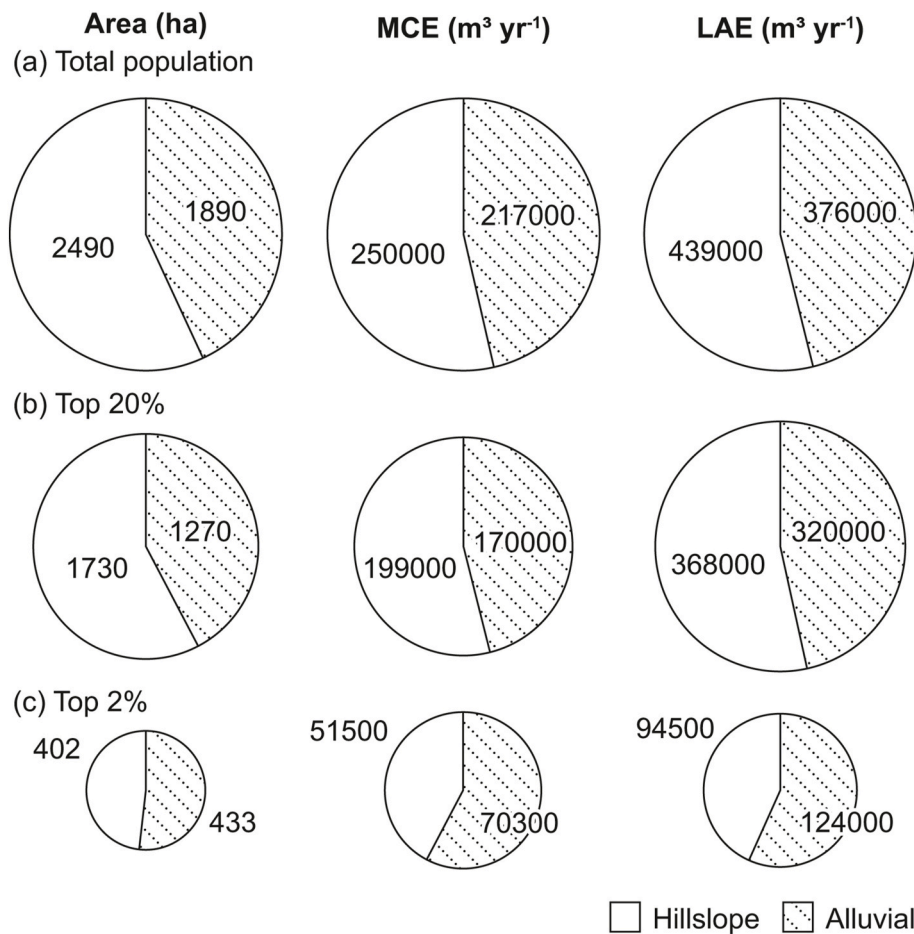


Fig. 6. Proportions of gully areas and total yields for (A) the whole population; (b) the top ranking 20% and; (c) the top ranking 2% of gullies, highlighting the disproportionate representation of alluvial gullies in high yielding gullies.

corresponds to an annual of ~ 1 Mt from gully erosion. Bainbridge et al. (2023) collected event-based suspended sediment samples over four wet seasons, including one above-average rainfall year and determined a higher total load of 2.1 Mt yr^{-1} of fine sediment over the 2018–2022 period. While initially this rate appears to considerably exceed the predicted range presented in this study, a significant catchment source upstream of the lidar mapping extent used in this study (Fig. 1) was generating $488,800 \text{ t yr}^{-1}$. As such, removing this quantity and using the source proportions of McCloskey et al. (2021) suggests a load of 1.3 Mt yr^{-1} of fine sediment from gully erosion in the rest of the BBB catchment, comparable with the assumed LAE loads predicted in this study and annual fine sediment loads predicted by Brooks et al. (2020).

4.3. The pareto 80-20 principle for gully prioritisation

The Pareto Principle, or the “80-20 rule”, is a philosophical theory that 80% of outcomes are due to 20% of the causes. It has largely been applied to social and economic situations (Dunford et al., 2014; Grosfeld-Nir et al., 2007; Lamouroux et al., 2015; Sanders, 1987) but is also recognised in some natural phenomena (Cooper et al., 2019; Verstraete et al., 2007). It is apparent in our data that the principle also applies to gully-derived sediments in the BBB study area. The MCE and LAE methods consistently identify that approximately 80% of the sediment pollution from gullies is generated by 20% of the population (Fig. 3), while 30% of the sediment is generated by only 2% of the population. The strong skew in the distributions from both methods, resulting from the significant contribution of a small proportion of the 22311 gullies, presents an important opportunity for gully management. These sites

function as point sources of sediment pollution, and directing interventions (Brooks et al., 2021; Frankl et al., 2021) toward only several hundred gullies can rapidly reduce catchment sediment pollution. Implementing targeted management not only enhances this opportunity but also offers a high benefit-to-cost ratio in terms of outcomes (Bartley and Brooks, 2021; Uthes et al., 2010).

4.4. Implications for gully management

A global priority for environmental management is achieving effective reductions in land degradation (Vanmaercke et al., 2021), particularly within the GBR (Carter and Thulstrup, 2022). The identification of high priority gullies enables a strategic approach to undertaking more detailed analyses, improving site-specific erosion rate predictions, and refining the prioritisation to a select number of high priority sites for environmental outcomes (Fig. 7).

The two methods outlined in this article can be refined to provide greater reliability at localised scales by adjusting parameters and thresholds (Korzeniowska et al., 2018; Yang et al., 2017), particularly in concert with additional assessments of erosion activity (Daley et al., 2023a). A prioritisation approach may integrate other gully attributes, such as specific yields or proximity to other sites. An interesting feature of the highest yielding 2% that there was a strong spatial affinity between the two high yielding cohorts. The close proximity of many of these gullies indicates there are certain characteristics of the landscape and nature of the soils in those areas that has resulted such high gully densities. Selecting the highest ranked gullies from a combination of both methods, despite differences, nonetheless presents a focused

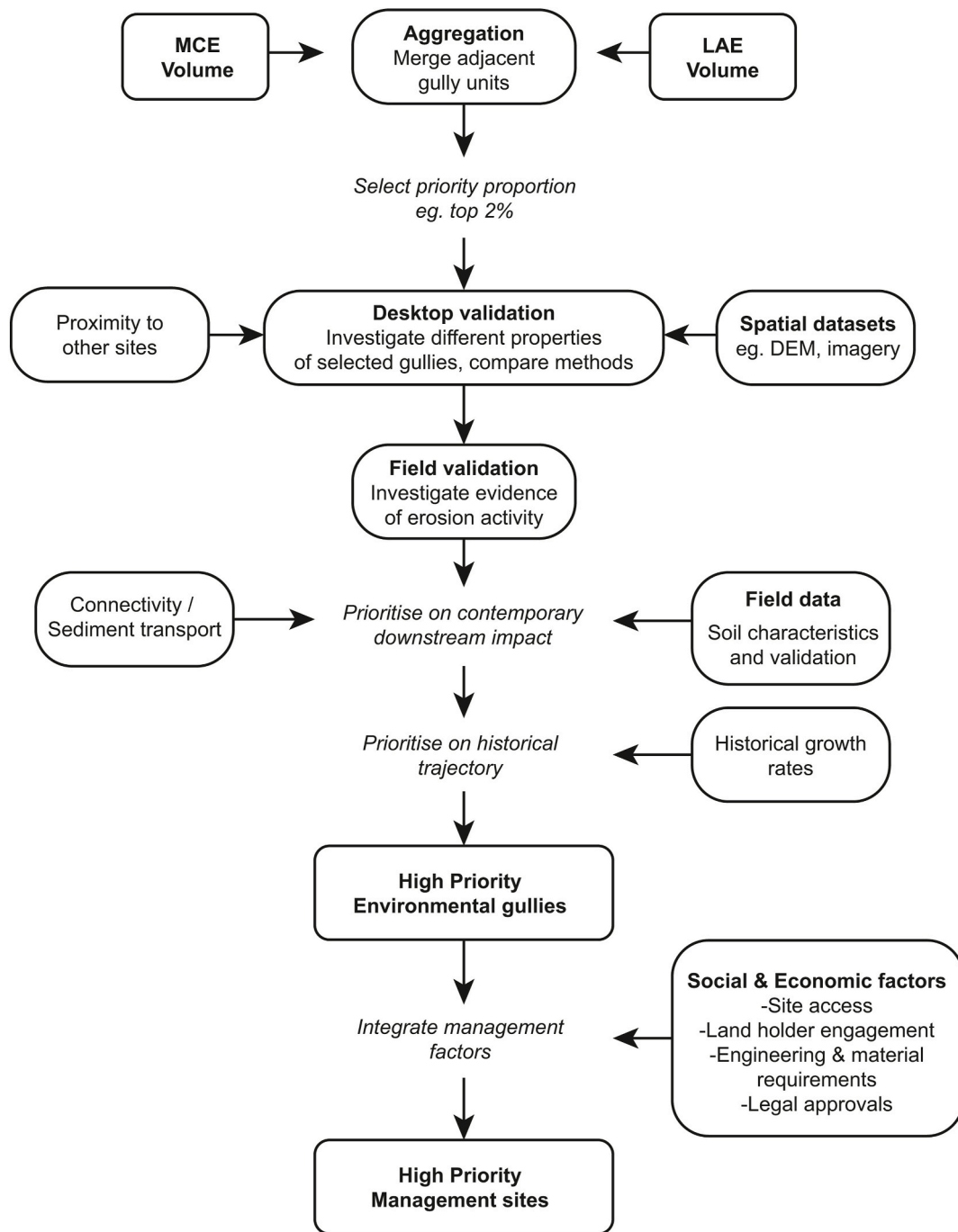


Fig. 7. Conceptual model of steps for detailed assessment in prioritising gullies by integrating additional information to develop high priority sites for environmental outcomes and remediation potential.

proportion to assess on ground and with other data sources. The proximity of such gullies also provides opportunities for reduced mobilisation costs in remediation planning.

Additional detailed site geomorphic investigations may be may enhance prioritisation plans through field sampling of gully soil materials and chemistry, historical air photos interpretation, and investigation of local initiation times and growth rates (Fig. 7). For example, integrating soil characteristics for different gullies provides capacity to further inform catchment management based on the deleterious ecological and water quality impacts of the fine sediment fraction (i.e. < 20µm; Bainbridge et al., 2023, 2018).

Land managers can then evaluate additional logistical and practical factors before proceeding to on-ground remediation. These factors may

include the tractability of remediation (Koci et al., 2021); site and resource access, financial constraints, and interpersonal relationships. However, to achieve significant environmental outcomes, namely reduced land degradation and improved water quality, managers must focus attention on sites that will have the greatest environmental impact (Fig. 7). Targeted remediation can then be undertaken using approaches similar to those outlined in Brooks et al., (2021; 2024), and Bartley et al. (2018).

4.4.1. Management as a function of gully type

While the overall cumulative contribution of gully erosion rates is distributed relatively evenly between gully domains (Fig. 6), alluvial gullies comprise a dominant proportion of high yielding gullies.

Representing 57–58% of the load in the high yielding cohort, these gullies have a 29–31% higher contribution to their total represented area. This ratio is likely to be more significant in terms of the downstream fine sediment contribution. The often-deep alluvia and weathered materials of valley floors in the study area (Daley et al., 2023a) typically have a larger proportion of fine sediment than soil materials mantled on hillslopes and derived from weathered bedrock (Brooks et al., 2009, 2019). Additionally, alluvial gullies are well connected to the river channel network and have high sediment delivery ratios. They have different geometries to hillslope gullies, have a more Open form and are often spatially concentrated with other gullies. Hillslope gullies in the top 2% have comparative areas but on average are longer, more linear, and more isolated. Integrating these factors provide critical next steps in developing a prioritisation plan (Fig. 7).

Given the considerable size of gullies in the high yielding cohort (Fig. 6), their high specific yields and formation in erodible soils, it is unlikely that passive management measures will produce a measurable response in gully sediment yields. These characteristics necessitate targeted intervention to achieve large scale reductions in sediment losses. Brooks et al. (2021; 2024) demonstrate that the remediation of large alluvial gullies can be rapidly remediated using engineering-scale treatments including earthworks and regrading, soil amelioration, and rock and mulch capping, achieving 96–99% reductions in fine sediment loss after 1–2 years. These treatments have been designed for a greater than 25-year lifetime, with reasonable evidence five years post treatment that this is a realistic design life, with minor maintenance undertaken.

While studies has identified check dams as a means for managing small gullies (Frankl et al., 2021; Koci et al., 2021), this would be expending effort on the 80% of the population tail, which collectively are producing 20% of sediment loss. The reported 7%–19% effectiveness of check dams on reducing fine sediment loss (Koci et al., 2021) coupled with the low contribution to catchment loads (Fig. 3) would require the remediation of this entire cohort to achieve the same sediment pollution reduction as remediating the 10–60 highest yielding gullies using methods outlined by Brooks et al. (2021, 2024; see supporting information). Based on the above effectiveness values for large and small gullies, the cumulative resources required to remediate the significant number of gullies in the population tail would involve a prohibitive cost approximately two orders of magnitude greater than the treatment costs reported for the highest yielding gullies (Brooks et al., 2021).

5. Conclusions

The World Heritage Committee has recently urged rapid prioritisation and escalation of gully remediation in the GBR catchment area to protect the UNESCO site. Two novel methods for estimating erosion activity demonstrate comparative statistics in high yielding gullies and have inadvertently demonstrated Pareto's 80-20 rule in gully erosion – that 80% of the sediment loss is coming from <20% of the highest yielding gullies. Further, the highest yielding 2% of gullies are producing 30% of the total sediment loss. The results of this work highlight the importance of integrating different lines of evidence for validating data and providing confidence in derived erosion rate estimates. The methods have a strong, positive correlation and further correlate strongly with erosion rates in a validation datasets of 1786 gullies. Further confidence in the estimated total sediment losses is provided by comparison with other catchment load predictions. Important differences also emerge in the highest yielding cohort, highlighting the importance of appreciating differences in gully types in remediation planning. These findings have important implications for the management of gully erosion in the GBR catchment area, particularly the concentration of high volumes of erosion in relatively few gullies. A robust and confident prioritisation of gully erosion can be achieved by targeting significant erosion activity sources. By targeting the high-yielding cohort of gullies, there are opportunities to rapidly achieve large reductions in sediment pollution

when coupled with effective remediation and management approaches.

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CRediT authorship contribution statement

James S. Daley: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Justin C. Stout:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Andrew P. Brooks:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: James S. Daley reports financial support was provided by National Environmental Science Program. James S. Daley reports financial support was provided by NQ Dry Tropics. James Daley reports a relationship with NQ Dry Tropics that includes: consulting or advisory. James Daley reports a relationship with National Environmental Science Program that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for this research is available at <https://eatlas.org.au/data/uuid/ba7a78b5-e262-4ffd-8837-d367fc918db1>

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.120688>.

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