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Climate change and gully erosion in Queensland - a preliminary investigation

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Abstract: Climate change is intensifying hydrological extremes across Australia, with Queensland experiencing increased rainfall variability and more frequent extreme precipitation events. These changing precipitation patterns have significant implications for erosion processes and subsequent water quality degradation in receiving waters. While research has examined erosion under historical climate conditions, there remains a critical knowledge gap regarding how shifting rainfall patterns will affect sediment dynamics in Queensland catchments.

This study presents a pilot study to assess climate change impacts on gully erosion and to explore methodological approaches. We combined climate projections with the process-based MERGE gully erosion model to explore changes in gully erosion under future climate scenarios. We explored runoff scenarios corresponding to the maximum daily precipitation under three climate scenarios (shared socioeconomic pathways) across four modelling periods. These scenarios were applied across four gullies, two each in South-East Queensland (Brisbane River Basin) and the Fitzroy River Basin. We further considered how vegetation as a gully rehabilitation tool, might mitigate any potential increase in erosion due to rainfall intensification.

We found that variation in projected erosion, explored through the sediment delivery rate, was small ($< \pm 8\%$) across all scenarios and modelling periods. Some simulations predict an increase in erosion, while others predict a decrease in total erosion over the event. The Fitzroy River Basin gullies were more likely to simulate a decrease in sediment delivery, while the South East Queensland gullies exhibited more variable responses with a mix of simulations showing increased and decreased erosion. Our study indicates that increasing in-channel vegetation coverage would likely mitigate the effects of climate change induced variations in rainfall, and in most cases would reduce the erosion rate well below the historical state.

This pilot study further highlights the need for spatially distributed event-scale climate projections of rainfall to inform understanding of how erosion dynamics may be impacted by climate change. With the expected intensification of rainfall in Queensland due to climate change, the use of daily precipitation values without remit to the distribution of rainfall within an event, is likely to underestimate total erosion, and could give misleading results.

Keywords: *MERGE, gully, erosion, climate change*

1 INTRODUCTION

Climate change impacts on soil erosion is a global concern and intensification of rainfall events, together with a shortening of the return time for extreme events, is expected to present a significant risk to soil security (Nearing et al. 2004). Soil erosion is an inherently event-driven process, where the majority of annual erosion may be linked to only a small number of high-intensity events (Wu et al. 2018). Furthermore, drier climates risk decreased vegetation coverage, which protects against erosion. Therefore, even where annual precipitation rates decline, there remains a risk of increased annual erosion.

Climate projections for Queensland indicate shifts in precipitation patterns are expected under future climate scenarios. Current climate models project that extreme rainfall events across Queensland will become more intense (CSIRO 2025), with the magnitude of changes varying regionally. However, projections remain uncertain, with some regions expected to experience drying trends (CSIRO 2025). Despite significant advances in climate projections, substantial uncertainties remain, with higher uncertainties the more localised the spatio-temporal scale of interest.

Gully erosion represents a particularly significant environmental challenge in Queensland, contributing disproportionately to sediment loads in major water bodies. Gully erosion accounts for approximately 40% of fine suspended sediment pollution reaching the Great Barrier Reef (Brooks et al. 2018), and is recognised as a major contributor to water quality challenges in Moreton Bay.

Understanding how climate change might influence gully erosion processes will help guide adaptive management strategies, given the infeasibility of rehabilitating all gullied landscapes. Changes in rainfall intensity and patterns could significantly alter gully formation and expansion, potentially accelerating erosion in vulnerable landscapes or altering the effectiveness of current remediation approaches.

This study employs downscaled climate projections under multiple emission scenarios as a preliminary investigation into the potential climate change impacts on gully erosion processes in Queensland, and explores the suitability of existing public datasets for such investigations. Using the MERGE gully erosion model (Roberts 2020), we analyse four gullies: two located in Southeast Queensland and two in the Fitzroy River Basin. By applying physically-based erosion modelling to climate-adjusted precipitation inputs, we aim to quantify how projected changes in rainfall patterns might influence future gully erosion rates under different vegetation scenarios. This pilot study further provides insight into some challenges of using daily precipitation projections to explore the potential impacts of gully erosion, which is inherently an event-driven process.

2 METHODS

2.1 Study sites

Four gullies, Fernvale Gully (-27.436389°, 152.6175°) and Riverside South Gully (-27.533611°, 152.734167°) located in South East Queensland, and Bluff Amphitheatre Headcut (-23.575065°, 149.065928°) and Duaringa Triplets (-23.734810°, 149.685412°) located in the Fitzroy River Basin, were selected for this pilot study.

Fernvale and Riverside South gullies are classical gullies that are linear in structure, and are located in a region with a sub-tropical climate. The gullies each have sections that are both grazed and non-grazed (refer to Prentice et al. (2023) for a detailed description of the gullies). In this study we model the full gully structure from inflow at the head through to the outflows into the Mid-Brisbane River. The structural characteristics and morphometric parameters of the South East Queensland gullies were obtained from Prentice et al. (2023).

In contrast, Bluff Amphitheatre Headcut and Duaringa Triplets (Table 1) are subsections of larger gully systems, delineated and extracted to ensure feasibility in applying MERGE. The gullies are located on historically grazed lands in a semi-arid climate. Morphometric data were extracted through analysis of high-resolution LIDAR imagery, with catchment area identified through analysis of a SRTM-derived Hydrological 1 Second Digital Elevation Model (Version 1.0 from Geosciences Australia).

2.2 Climate Data and Runoff Scenarios

Climate projections for Queensland were obtained from Queensland Government's Future Climate Dashboard – CMIP6 (Queensland Government 2025*c*), under three shared socioeconomic pathways (a sustainable pathway: SSP 1-2.6, middle of the road pathway 2-4.5, and a regional rivalry pathway 3-7.0, see Queensland Government (2025*b*) for an overview of the pathways). The Future Climate Dashboard reports a bias-corrected (using Cannon's N-Method) ensemble average of the regional climate model results for extreme precipitation

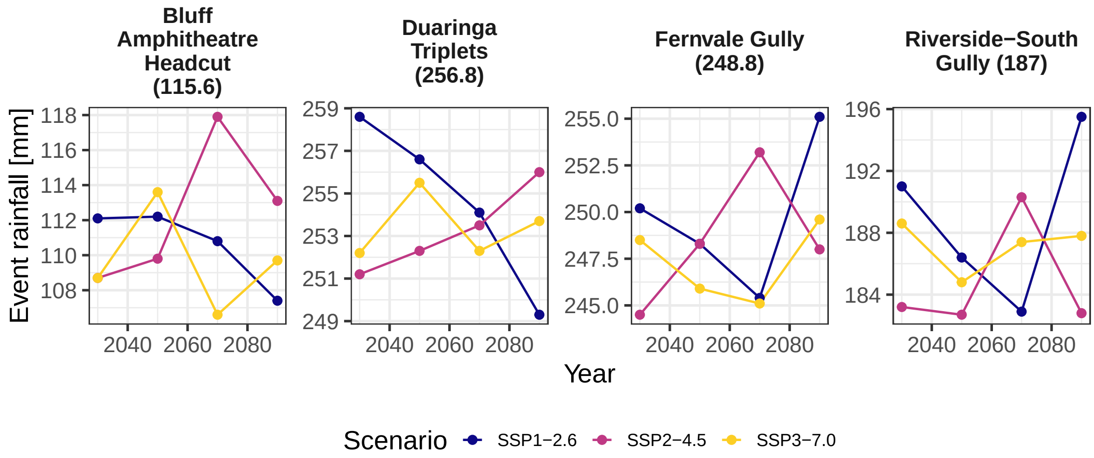

Figure 1. Design daily rainfall scenarios under future climate for the four gullies for the modelling periods 2020 - 2039 (2030), 2040 - 2059 (2050), 2060 - 2079 (2070), and 2080 - 2099 (2090), and three shared socioeconomic pathways. The maximum daily precipitation $[mm]$ during the reference period identified for each gully are indicated in brackets for each gully.

(and other variables not used in this study) (Queensland Government 2025a,c). Change in maximum daily precipitation during the wet season (November - March) were obtained for each gully location based on their respective coordinates, providing spatially relevant climate inputs for the erosion modelling. Data were obtained from the 'Extreme Precipitation Indices' tab while selecting the 'Maximum 1-day precipitation' variable and 'Wet' season options, which reports the projected maximum 1-day precipitation total during November – March. Single data points representing the periods 2020 - 2039 (year 2030), 2040 - 2059 (year 2050), 2060 - 2079 (year 2070), and 2080 - 2099 (year 2090) were available in the portal via a graphical interface; with change reported relative to data from the reference historical period 1995 - 2014.

Baseline maximum daily rainfall were identified from the closest Bureau of Meteorology station open over the reference period, namely stations 040763 (Wivenhoe Dam), 040115 (Lake Manchester), 035132 (New Caledonia), and 035026 (Duaringa Post office). The highest precipitation recorded at each station during the wet season corresponding to a single day was selected as the baseline rainfall. Design rainfall events for this study were constructed for each combination of shared socioeconomic pathway and modelling period by applying the identified precipitation change from the climate data to these maximum daily precipitation observed during November to March over the reference period for each gully (Figure 1).

Rainfall events were generated by assuming the daily rainfall (at each of the event thresholds) fell uniformly over a 1-hour and 6-hour period. Runoff rates $[m^3/s]$ were estimated using the simplified model

$$\text{Runoff rate} = \text{Rainfall rate} \times \text{Catchment area}, \tag{1}$$

with runoff dividing equally between the gully heads. This provides a first-order approximation of surface water availability for gully erosion processes, acknowledging that more complex hydrological processes (infiltration, evapotranspiration, baseflow) are excluded.

2.3 Gully Erosion Modelling

Gully erosion rates were simulated using the MERGE model under quasi-steady state conditions (Roberts 2020). That is, we assume a constant runoff rate (flux Q $[m^3/s]$) through the gully. MERGE has been applied in previous studies examining gully erosion processes and the potential impacts of different management activities (Prentice et al. 2021, Roberts 2022, Prentice et al. 2023, Roberts & Roots 2023). The quasi-steady approximation used in this study has been shown to be a good approximation of the fully dynamic model (Roberts 2020). The model calculates erosion based on hydraulic parameters, soil properties, and vegetation characteristics, making it suitable for assessing climate change impacts on gully development.

Vegetation effects on erosion are modelled through changes to the Manning's roughness coefficient

Table 1. Gully structure and section parameters: width, slope, depth, Manning's roughness coefficient n, and length. A secondary branch indicates where two gully sections join to form a third section. Empty data indicates parameters not required for that gully section (e.g. gully depth for channel sections).

Gully	Section	Previous sections	Width	Slope	Depth	n	Length
Fernvale	FG head 1	NA	3	0.007	1	0.027	2
	FG channel 1	FG head 1	3.5	0.007	1	0.027	93
	FG head 2	FG channel 1	4	0.061	2.5	0.027	6
	FG channel 2	FG head 2	3.5	0.061	2.5	0.027	32
	FG head 3	FG channel 2	3.25	0.082	1.5	0.045	9
	FG channel 3	FG head 3	4	0.082	1.5	0.045	8
Riverside South	RS head1	NA	2.5	0.085	1.2	0.035	3.5
	RS channel1	RS head 1	2.25	0.085	1.2	0.035	55.5
	RS head2	RS channel 1	2	0.113	0.4	0.025	1
	RS channel2	RS head 2	2.25	0.113	0.4	0.025	17.5
	RS head3	RS channel 2	2.5	0.067	1.8	0.025	3.5
	RS channel3	RS head 3	2.5	0.067	1.8	0.025	25
Bluff Amphitheatre	GullyHead	NA	8.93	0.0712	2.58	0.02	11.9
	GullyChannel	GullyHead	9.8	0.1373	NA	0.02	102.74
Duaringa Triplets	primary head	NA	4.04	0.0509	1.18	0.027	29
	primary channel	primary head	10.58	0.0343	NA	0.027	81.3
	secondary head	NA	3.15	0.072	1.21	0.027	10.6
	secondary channel	secondary head	17.3	0.0134	NA	0.027	92.6
	main channel	primary & secondary channels	7.4	0.0111	NA	0.027	221
	lower head	NA	2.68	0.0401	0.65	0.027	2.4
	lower channel	lower head	3.16	0.0134	NA	0.027	16.5
	lower main	main & lower channels	7.4	0.0111	NA	0.027	48.9

(n $[s/m^{1/3}]$) such that

$$n = n_{\text{base}} + 0.1768v \exp(-0.016 * d) \tag{2}$$

where $n_{\text{base}} = 0.027$ is the roughness coefficient in the absence of vegetation or other obstructions, v is the proportion of the gully floor that is vegetated, and d $[m]$ is the depth of flow through the gully. Vegetation is applied as a management modification (in increments of 5%) to gully channels (not heads or internal steps) following Roberts (2020), where increases in the Manning's roughness coefficient drives a decrease in the flux Q through the gully, while holding the depth of flow d constant. Channel sections with established leaky weirs (and hence a higher baseline roughness coefficient) are assumed to only increase roughness once the modification due to increased vegetation cover exceeds that due to the leaky weir.

To apply MERGE, the gully is divided into discrete head and channel sections, with internal steps modelled as gully heads. The width, depth and slope specific to each section is recorded individually along with the length of the section.

While the soil parameters may be characterised by gully section, such detailed information was not available for this pilot study. We therefore assumed constant values of $J = 1700\,Ws/m$, $\sigma = 1470\,kg/m^3$, and $R = 10\,\mu m$ for the soil cohesion, sediment density and particle radius respectively. Following (Prentice et al. 2023) we assume a power proportion constant of $k = 0.005$, and a carrying capacity of $C^* = 0.1\sigma$. Sensitivity analysis has demonstrated that variations in the gully width and slope of less than 30% has minimal impact on sediment delivery rates across a range of scenarios (Bennett et al. 2023). Standard model parameters (e.g. dynamic viscosity, water density etc.) are as per Prentice et al. (2023).

3 RESULTS AND DISCUSSION

The impact of climate change and vegetation scenarios on gully erosion is explored through the sediment delivery rate $[kg/s]$ for each gully, that is the mass rate of sediment exported out of the gully during the event.

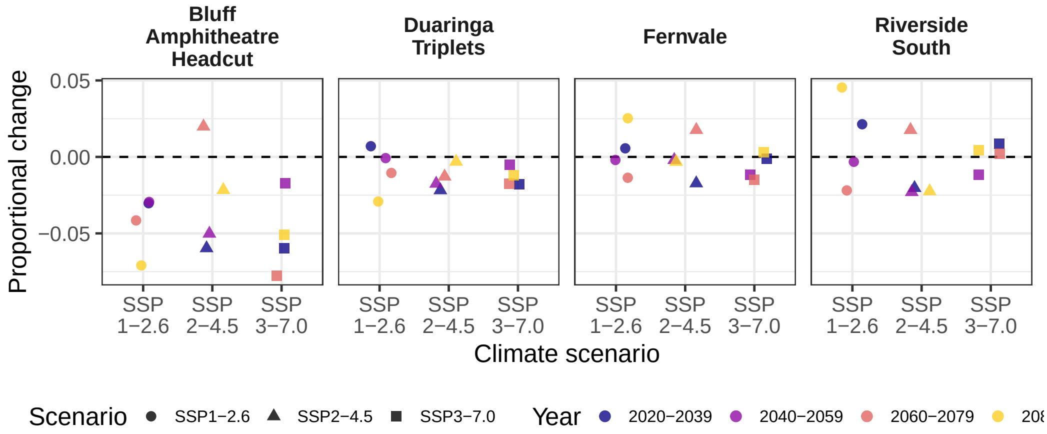

Figure 2. Proportional change in sediment delivery rates $[kg/s]$ without vegetation management relative to the historical baseline by modelling period for the three future climate scenarios: SSP1-2.6, SSP2-4.5, and SSP3-7.0.

As the runoff scenarios are constant, these rates remains constant for the duration of the event, which is a consequence of the quasi-steady approximation.

No clear trend is evident from the impact of climate change on gully erosion for the four gullies included in this pilot study. In some simulations, projected erosion rates are greater than the historical simulation, while in others it is reduced (Figure 2), which is consistent with the relative change in daily rainfall explored. Variation in sediment delivery was simulated to be within 8% of the historical baseline for all gullies across all combinations of climate pathway and modelling period. While the Fitzroy River Basin gullies (Bluff Amphitheatre Headcut and Duaringa Triplets) showed a general trend of decreased erosion, the South East Queensland gullies (Fernvale and Riverside South) had more mixed results. However, as the proportional variation simulated is small, land use or other catchment changes could have a greater impact on future erosion.

The model results show expected response patterns to combinations of changed rainfall intensity and increasing vegetation cover (Figure 3). That is, increasing vegetation cover reduces the delivery rate across all gullies, climate scenarios, and modelling periods, while increasing rainfall intensity increases the delivery rate.

This study indicates that across all scenarios increasing vegetation coverage in gully channels is likely to mitigate any potential increase in erosion due to climate change at these sites. This result is consistent with the global study of Eekhout & de Vente (2022), which found that improved soil conservation practices could mitigate the effects of climate change on erosion. Although, maintaining vegetation coverage is challenging, and therefore may not be feasible across all sites, especially under a drying climate.

With similar results obtained for both the 1-hour (Figure2) and 6-hour (not shown) events generated (albeit varying in magnitude), this pilot study does not provide conclusive evidence of a distinct signal linking climate change to gully erosion processes in Queensland. These results are consistent with a global study on climate change impacts on soil erosion, which saw global erosion rates increase under some climate scenarios and decrease under others (Borrelli et al. 2020). The absence of a clear trend is not however conclusive, as firstly this study considered only four gullies across two regions, and in the case of Bluff Amphitheatre Headcut only one lobe of a larger gully system. Secondly, several methodological limitations constrain the interpretation of these findings. The study excluded evapotranspiration and infiltration processes, both of which exhibit non-proportional relationships with rainfall and contribute to the nonlinear nature of runoff response. Furthermore, climate-driven shifts in vegetation structure and cover within the catchment will modify evapotranspiration and infiltration, and thus drying regions that see reduced canopy and ground cover could potentially see an increase in runoff despite decreased rainfall (Bosch & Hewlett 1982).

More critically, this pilot study employed design runoff scenarios derived from changes to daily precipitation data, despite erosion being fundamentally an event-driven phenomenon. The temporal structure and intensity distribution of individual rainfall events are primary determinants of total erosion magnitude, making any approach based on ‘average’ runoff conditions highly problematic and likely to substantially underestimate

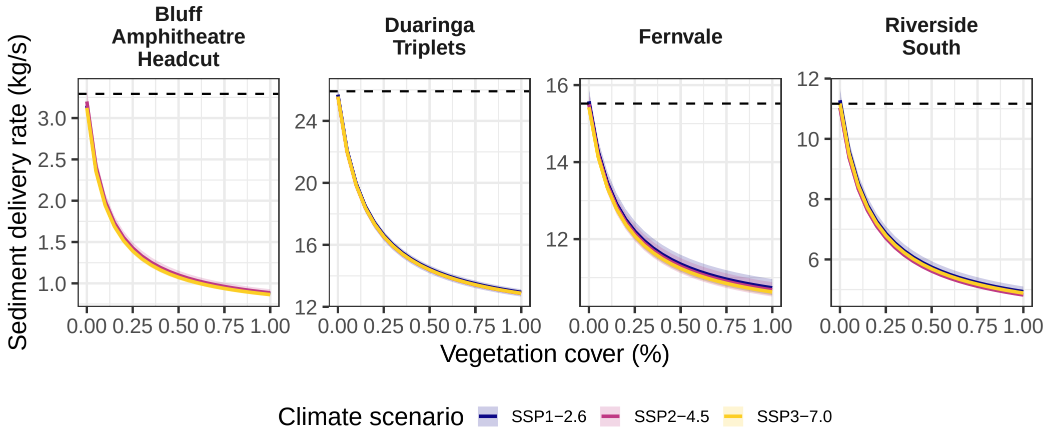

Figure 3. Sediment delivery rates $[kg/s]$ across different vegetation cover percentages (x-axis) for three future climate scenarios: blue (SSP1-2.6), red (SSP2-4.5), and yellow (SSP3-7.0). Solid lines represent ensemble means across the modelling periods, with the full range (minimum to maximum) of model outputs indicated by the ribbons. The black dashed line shows the delivery rate associated with the historical rainfall scenario.

erosion potential. This limitation has particular relevance for climate change projections in Queensland, where rainfall intensification is expected even without increases in total precipitation volume. The projected shift toward more intense, shorter-duration events could result in significantly greater erosion impacts than would be predicted from daily rainfall analysis alone. Consequently, event-scale rainfall scenarios are essential for accurately assessing the magnitude of climate change impacts on erosion processes. Such scenarios could potentially be developed using convection-permitting climate models, with bias correction applied at sub-daily timescales.

4 CONCLUSIONS

This pilot study provides important preliminary insights into the potential impacts of climate change on gully erosion processes in Queensland catchments. While our modelling framework successfully demonstrates the feasibility of integrating climate projections with erosion models, the findings underscore a critical limitation in current climate change impact assessments: the inadequacy of daily precipitation data for capturing erosion dynamics.

The projected intensification of rainfall in Queensland, even without increases in total precipitation, represents a fundamental shift in erosion drivers that cannot be adequately assessed using existing daily-scale climate data. This intensification could result in dramatically greater erosion impacts than current projections suggest, with profound implications for water quality management. However, quantifying these impacts requires high-temporal resolution climate scenarios that can capture the characteristics of individual erosive events.

As a pilot study, this work establishes the methodological foundation and identifies key research priorities for future investigations. Future research should focus on developing techniques to generate sub-daily precipitation scenarios, validating event-based erosion models against observed data, and extending the analysis to encompass the full range of erosion processes across diverse Queensland catchments. This pilot study demonstrates that while the modelling tools exist to assess climate change impacts on erosion, the realisation of this potential depends critically on advances in event-scale climate projection capabilities.

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