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RIDGE: rainfall impact detachment in gully erosion

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Abstract: Gully erosion is a significant contributor to poor down-stream water quality, limits agricultural production, and causes infrastructure damage. Consequently, land management and remediation to reduce gully erosion is a significant focus in many regions. In Queensland, gully erosion is the majority source of sediment transported from catchments to the Great Barrier Reef (GBR), and thus gully remediation is important to reach the Reef 2050 Water Quality Improvement Plan of reducing sediment reaching the GBR by 25% by 2025. Mathematical models of gully erosion are critical to support gully remediation activities, and to help target actions to where they will be most effective.

Gully erosion is due to two related processes: rainfall-driven detachment, and flow-driven detachment and transport. The MERGE gully erosion model was developed to support gully management activities and pro-vides a simple, one-dimensional model that can be used to test the effectiveness of different remediation actions at specific gullies. However, MERGE argues that flow-driven detachment will dominate, and therefore rainfall-driven detachment can be neglected. This assertion is tested in this paper by introducing an extension to MERGE to capture rainfall-driven detachment.

The RIDGE extension models rainfall-driven detachment from the gully floor providing an initial depositional layer mass to MERGE. The depositional layer consists of sediment that has recently been detached and then deposited on the gully floor and lacks the cohesive properties of the original soil matrix, and hence, is easier to entrain.

Six case studies, consisting of three soil types and two rainfall intensities, were explored to quantify the ef-fect of excluding rainfall-detached on the sediment yield, that is the rate at which sediment is delivered to the receiving environment, in an exemplar gully. These results were compared with MERGE simulations ex-cluding rainfall-driven detachment. In all scenarios, the sediment yield was greater including rainfall-driven detachment than neglecting this contribution, albeit marginally in the case of the firm soil. The inclusion of rainfall-driven detachment resulted in a pulse of sediment being transported from the gully in the initial moments of the simulation. Within the gully head, the region of highest erosion, the removal of the deposi-tional layer was near instantaneous. Not all sediment detached during the rainfall period was delivered to the receiving environment, even during extended simulations, in any of the case studies explored.

This study shows that rainfall-driven detachment can be an important contributor to the total volume of sedi-ment exported from a gully, particularly for soft (erosive) soils subject to short-duration events. The developed rainfall-detachment model may have further application in the study of large, amphitheatre gullies, where rain-fall and small flow events could have a larger role in destabilising a gully and driving gravity collapse than in the channel-like gullies for which MERGE was developed.

Keywords: *Erosion, gully, MERGE, rainfall-detachment*

1 INTRODUCTION

Gully erosion occurs on all continents and is linked to poor water quality in receiving environments, loss of agricultural productivity, infrastructure damage and even loss of life (Roberts et al. 2022). Gully erosion is the majority source of sediment delivered to the World Heritage Listed Great Barrier Reef. Sediment, and the nutrients transported with it, contributes to poor water quality, impacting coral health amongst other factors (Roberts 2020). The contribution of gully erosion to poor water quality on the Great Barrier Reef has motivated significant private and public investment to remediate gullies and reduce erosion.

The MERGE gully erosion model (Roberts 2020) was developed to provide a simulation tool for land managers to explore gully remediation options at individual gullies. Although MERGE has been applied in the field (Prentice et al. 2021, Roberts 2022) there are a number of simplifications in the model that warrant further examination. MERGE models the erosion due to a flow through a channel-like gully, but neglects any contribution from rainfall-driven detachment, arguing that gully-flow will quickly dominate and therefore rain-driven detachment can be neglected. However, for sheet flow rainfall-driven detachment is a significant cause of erosion (Hairsine et al. 1992). Moreover, even with channel flow dominating in the later stages of an event, small rainfall-dominated events could potentially be significant contributors to total sediment loss from gullies. This study explores the impact of neglecting rainfall-driven detachment in MERGE.

2 MODEL

Consider an ideal homogeneous gully of rectangular geometry consisting of a head region at the start of the gully connecting with a channel region below (Figure 1). The gully geometry and parameters are constant and do not evolve over time, that is the gully length L [m], width W [m], slope, depth, channel roughness, and soil properties remain constant. Erosion from the gully is due to two distinct, but related actions. Firstly, rainfall detaches sediment from the floor of the gully, forming an initial depositional layer where the soil cohesion has been broken. Secondly, flow within the gully scours the floor and walls and transports suspended sediment along the gully, which is also subject to deposition. The MERGE gully erosion model (Roberts 2020) is used to model this second process. Although Roberts (2020) identifies the contribution of rainfall-detachment to an initial depositional layer, and despite the incorporation of an initial depositional layer within the model, Roberts (2020) does not consider rainfall-detachment directly. To better account for it, a new model for rainfall-detachment is introduced and coupled to MERGE through the initial depositional layer.

2.1 Rainfall-detachment

The mass of sediment detached per unit gully length by rainfall action, $M_r(t)$ [kg m^{-1}], is modelled by equating the power available from the rainfall with the power required to detach sediment from the soil matrix – an analogous approach to the entrainment calculations in MERGE.

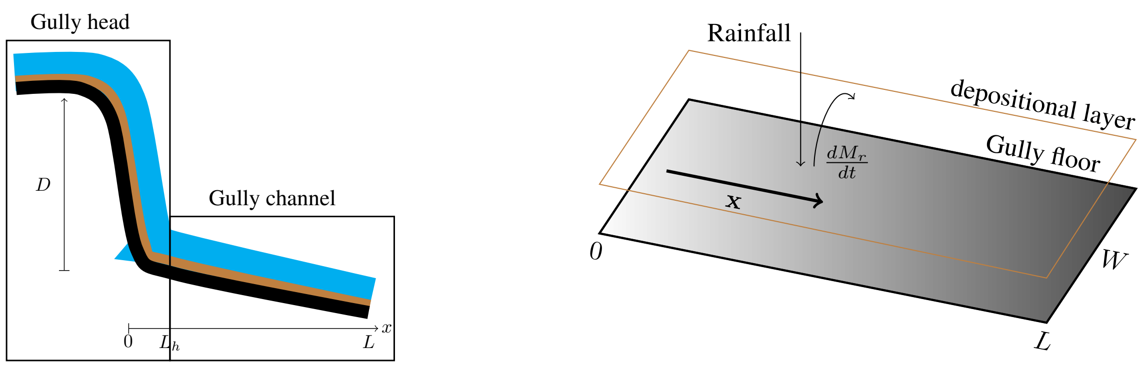

Figure 1. Left: Geometry of the ideal gully of width W [m], head length L_h [m], length L [m] and gully head height D [m]. MERGE splits the gully into two regions the gully head $x \in [0, L_h]$ and the gully channel $x \in (L_h, L]$. Right: Dynamics of the depositional layer across the entire length of the gully by rainfall action. Sediment is detached from the soil matrix, regardless of location within the gully, and deposited at a rate $\frac{dM_r}{dt}$ [kg m^{-1} s^{-1}] into a depositional layer atop the gully floor.

The rainfall power available for erosion is due to the rate of change of kinetic energy from the rainfall, attenuated due to the protective behaviour of a building flow depth and limited by the proportion of the gully channel that is protected. Let G be the proportion of the gully width covered by nondetachable material such as large rocks and vegetation. It is assumed that these materials fully absorb the rainfall impact but are not so high off the ground as to introduce a new raindrop velocity class. As the depth of water in the gully d [m] increases with rainfall, the power available for erosion reduces according to $A(d, R_r) = \exp(-1.8d/2R_r)$ for raindrops of average radius R_r following Gabet & Dunne (2003). For a rainfall of intensity I [m s^{-1}] falling uniformly on the gully floor with area $L \times W$, the rate of change of kinetic energy limited by the groundcover G and depth attenuation term A is

$$\frac{dE_k}{dt} = \frac{A(d, R_r)(1-G)LW\rho I v^2}{2}, \tag{1}$$

where v [m s^{-1}] is the velocity of the raindrops. The raindrop velocity v is 6.73 m s^{-1}, which is a conservative estimate based on Gabet & Dunne (2003, Eq. 19) for a 1 mm droplet radius.

The power required to detach a unit mass of sediment is composed of two factors: a lifting and a soil detachment factor. The power required to overcome gravity and lift sediment to the height h [m] at the volumetric rate V_d [m^3 s^{-1}] is $V_d\sigma g h$, where σ [kg m^{-3}] is the soil density, and g [m s^{-2}] is the gravitational acceleration. Modelling raindrop impacts as a compressing pressure, the resistance to detachment for a unit volume of sediment τ [kN m^{-2}] is expressed using the Mohr-Coulomb equation for shear strength $\tau = C_s + \tilde{\sigma_n}\tan\varphi$ (Gautam 2018) where C_s [kN m^{-2}] is the soil cohesion, $\tilde{\sigma_n}$ [N m^{-2}] is the normal stress, and φ the internal friction angle. Given the small impact depth, the normal stress $\tilde{\sigma_n}$ is assumed to be proportionally very small compared to soil cohesion C_s, and is captured by $F_s \approx \tilde{\sigma_n}\tan\varphi$. The power required to erode is therefore

$$\frac{dE_P}{dt} = V_d\left(\sigma g h + \tau\right). \tag{2}$$

Equating (1) with (2), and converting the volumetric detachment rate to a mass rate, the mass of detached sediment per unit length of gully [kg m^{-1}] is

$$M_r = \int \sigma \frac{k_p A\left(d, R_r\right)\left(1-G\right) W \rho I v^2}{2\left(\sigma g h + \tau\right)} dt, \tag{3}$$

where k_p is a constant that represents energy lost in the transference between the rain and soil.

Hairsine et al. (1992) suggest that droplet-driven detachment ceases at six times the average raindrop radius after which the flow-driven processes dominate sediment detachment. It is assumed that no net water drainage occurs and that rainfall is the only source of flow, so the within-gully flow depth increases linearly with rainfall intensity, $d(t) = It$. Therefore, M_r in Eq. (3) is calculated over the time domain $[0, 6R_r/I]$.

2.2 Integrating with MERGE

MERGE allows for an initial depositional layer, $M(x, 0) = M_0(x)$ to be present at the start of an event, and takes as an input parameter the user-defined mass of sediment (per unit gully length) in that layer. This initial depositional layer mass is used to couple the rainfall-detachment model to MERGE using Eq. (3), that is $M_0(x) = M_r$.

Some modification to MERGE is required to accommodate a depositional layer within the head, which MERGE assumes cannot form. The entrainment equations for the gully head are therefore modified to allow for an initial depositional layer, while still preventing a depositional layer from forming under overland flow. The rainfall-detached depositional layer is available for re-entrainment, and provides a shielding effect on the underlying sediment while present. Any sediment deposited within the head is immediately re-entrained, and thus the depositional layer cannot grow. The mass in the depositional layer is therefore tracked using $\frac{\partial M}{\partial t} = \delta - \eta_r$, where δ [kg m^{-1} s^{-1}] is the rate of deposition and η_r [kg m^{-1} s^{-1}] the rate of re-entrainment (as within the channel), and limited such that $\frac{\partial M}{\partial t} \geq 0$. The entrainment term in the head is also modified to account for re-entrainment of the depositional layer in an analogous way to within the channel, albeit incorporating the waterfall power Ψ [W m^{-1}] in addition to the stream power Ω [W m^{-1}].

The rainfall-detachment model provides the initial condition for the depositional layer in MERGE; during the rainfall-detachment period $t \in [0, 6R_r/I]$ erosion due to gully flow is not modelled. The transition between rainfall-detachment dominated flow and gully flow is simplified by assuming an instantaneous change to the

Table 1. Parameter values used in the rainfall-detachment model and MERGE simulations

Parameter	Symbol	Value
Rainfall-detachment model		
Droplet terminal velocity	v	6.73 $\mathrm{m\,s^{-1}}$
Average droplet radius	R_r	1 mm
Friction	F_s	0 $\mathrm{N\,m^{-2}}$
Height of detachment	h	5 mm
Proportion of power available to detach	k_p	1
Soil cohesion (low, medium, high)	C_s	(12.5, 62.5, 150) $\mathrm{kN\,m^{-2}}$
Rainfall intensity (low, high)	I	(7.5, 45) $\mathrm{mm\,h^{-1}}$
MERGE		
Erosion resistance (low, medium, high)	J	(25, 100, 400) $\mathrm{W\,s\,m^{-1}}$
Depth of flow (low, high)	d	(0.1, 0.6) m
Rainfall-detachment model and MERGE		
Length of Gully	L	100 m
Head length	L_h	20 m
Width of Gully	W	2 m
Proportion of gully width under ground cover	G	0
Gravity	g	9.81 $\mathrm{m\,s^{-2}}$
Sediment density (low, medium, high)	σ	(1750, 1875, 2000) $\mathrm{kg\,m^{-3}}$

gully-flow conditions of a flow depth d, and corresponding flux Q. While MERGE is able to simulate time-dependent flow conditions, a constant value is assumed in these simulations.

The effect of excluding rainfall-detachment on the total sediment delivered to receiving environments is explored for two different rainfall events and three soil scenarios. The two rainfall events are a low-intensity event, with $I = 7.5\,\mathrm{mm\,h^{-1}}$ and $d = 0.1\,\mathrm{m}$, and a high-intensity event with $I = 45\,\mathrm{mm\,h^{-1}}$ and $d = 0.6\,\mathrm{m}$. Low (soft soil), medium (medium soil) and high (firm soil) resistances to erosion are modelled. As the ranges for the MERGE erosion resistance J is still largely unknown, three values from Prentice et al. (2021), which assessed the applications of MERGE in a case study, have been selected. These were matched to low, medium, and high values for cohesion C_s and soil density σ to represent three different soil types (Subramanian 2008, App. C). The soft soil has $C_s = 12.5\,\mathrm{kN\,m^{-2}}$, $\sigma = 1750\,\mathrm{kg\,m^{-3}}$, and $J = 25\,\mathrm{W\,s\,m^{-1}}$; the medium has $C_s = 62.5\,\mathrm{kN\,m^{-2}}$, $\sigma = 1875\,\mathrm{kg\,m^{-3}}$, and $J = 100\,\mathrm{W\,s\,m^{-1}}$; and the firm $C_s = 150\,\mathrm{kN\,m^{-2}}$, $\sigma = 2000\,\mathrm{kg\,m^{-3}}$, and $J = 400\,\mathrm{W\,s\,m^{-1}}$. All other parameters are held constant as per Table 1. The total sediment yield is used to compare the effect of including or excluding rainfall-detachment. A six-minute simulation of MERGE is used for comparison, which follows the rainfall-detachment period.

3 RESULTS

Rainfall-detachment results in an initial depositional layer that varies with the soil properties, namely soil cohesion and density (Figure 2), but not with the rainfall intensity. Under low rainfall intensity, the soft soil generates an initial layer of 6.97 $\mathrm{kg\,m^{-1}}$ (1.99 mm), the medium soil 1.50 $\mathrm{kg\,m^{-1}}$ (0.400 mm), and the firm soil 0.668 $\mathrm{kg\,m^{-1}}$ (0.167 mm). Under high rainfall intensity, the soft soil generates an initial layer of 7.01 $\mathrm{kg\,m^{-1}}$ (2.00 mm), the medium soil 1.51 $\mathrm{kg\,m^{-1}}$ (0.403 mm), and the firm soil 0.671 $\mathrm{kg\,m^{-1}}$ (0.168 mm).

Once erosion due to flow commences, that is the MERGE model is triggered, this depositional layer is rapidly depleted, especially within the head (Figure 3a and c). Within the gully head, the depositional layer is exhausted within a matter of seconds in all scenarios. Within the channel, the layer is depleted but not exhausted, and then transitions to the dynamics observed in the simulations without rainfall-detachment (Figure 3b and d).

The total sediment yield for the 6 scenarios, with and without rainfall-detachment, is shown in Figure 4. For the soft soil, in the low-intensity, low-flow case, 197.41 kg of sediment was delivered when rainfall-detachment was accounted for, in comparison to the 78.23 kg without rainfall-detachment. In the high-intensity, high-flow case rainfall-detachment gave a delivered sediment yield of 5398.82 kg in contrast with 5037.10 kg when

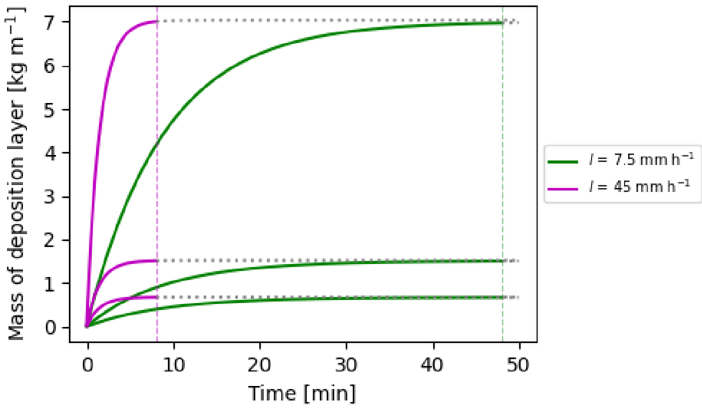

Figure 2. Mass of the depositional layer per unit length of gully from rainfall-detachment for the three soil types (top: soft, bottom: firm) and two rainfall intensities (purple: high, green: low). The vertical lines indicate the time threshold at which rainfall detachment ceases, this is when $d = 6R_r$, the purple dashed line for high-intensity rainfall, and the green dashed line for the low-intensity event.

neglecting rainfall effects. The medium and firm soils are shown in Figure 4.

4 DISCUSSION

Including rainfall-detachment increases the total sediment yield in all scenarios relative to the baseline, albeit marginally for the firm soil case. Not all sediment detached during the rainfall period is transported from the gully, even with extended simulations (not shown). For the soft soil under low-intensity rainfall, 697 kg of sediment was detached by rainfall, yet after six minutes of flow-driven erosion, only an additional 119.18 kg was exported from the gully. Under high-intensity rainfall, the soft soil saw 701 kg detached by rainfall with only 361.72 kg being delivered to the receiving environment. The greater erosion power from the increased flow depth (0.6 m) of the high-intensity rainfall simultion resulted in more sediment being delivered.

With no further feedback, once stabilised, the depositional layer will no longer fluctuate as seen in Figure 3 meaning that the dynamics observed prior to this are the only ones that determine the difference in delivered sediment. The medium and firm soils responded similarly.

The depositional layer introduced by rainfall-detachment is rapidly depleted, especially within the high-power environment of the head. The system quickly transitions to the solutions of the baseline cases. Within the channel, the depth of the depositional layer initially reduces before growing in line with the base case, which is in the re-entrainment regime for all scenarios - that is with a growing depositional layer. This increase in the depositional layer is due to high erosion within the gully head (and hence high concentrations within the water column), which is then transported into the lower power environment of the channel and deposited out. The simulations assume a ‘clean’ inflow ($C(0, t) = 0$), and thus the sediment concentration within the head will increase to the steady value over time (see for example Roberts (2020, Fig. 2)). For the low-intensity, low-flow case the depositional layer is thickest at the start of the channel, while for the high-intensity, high-flow case the layer builds along the length of the gully. This is the same dynamic seen in the medium and firm soil types; except the depth of the depositional layer at all time steps is scaled down the firmer the soil.

The simulations exhibit numerical error-induced fluctuations (see Figure 3) at the transitions between a growing and near-constant depositional layer. These errors have a negligible effect on the total sediment yield. The depositional layer will not in practice achieve a true constant value (Roberts 2020), however, where the scouring of the gully walls is small in comparison with the scouring of the floor, the variation will be small.

The invariance with rainfall intensity is a direct consequence of excluding infiltration, and the assumption that rainfall-detachment ceases when the depth is six times the raindrop radius, a threshold that is consistent with the attenuation expression of Gabet & Dunne (2003). The total detached mass estimation, and the rate at which it is reached, are predominantly due to the shape of the attenuation function A. Different selections would likely lead to varying results and the contributions of laboratory data would aid in verifying the shape of the attenuation function.

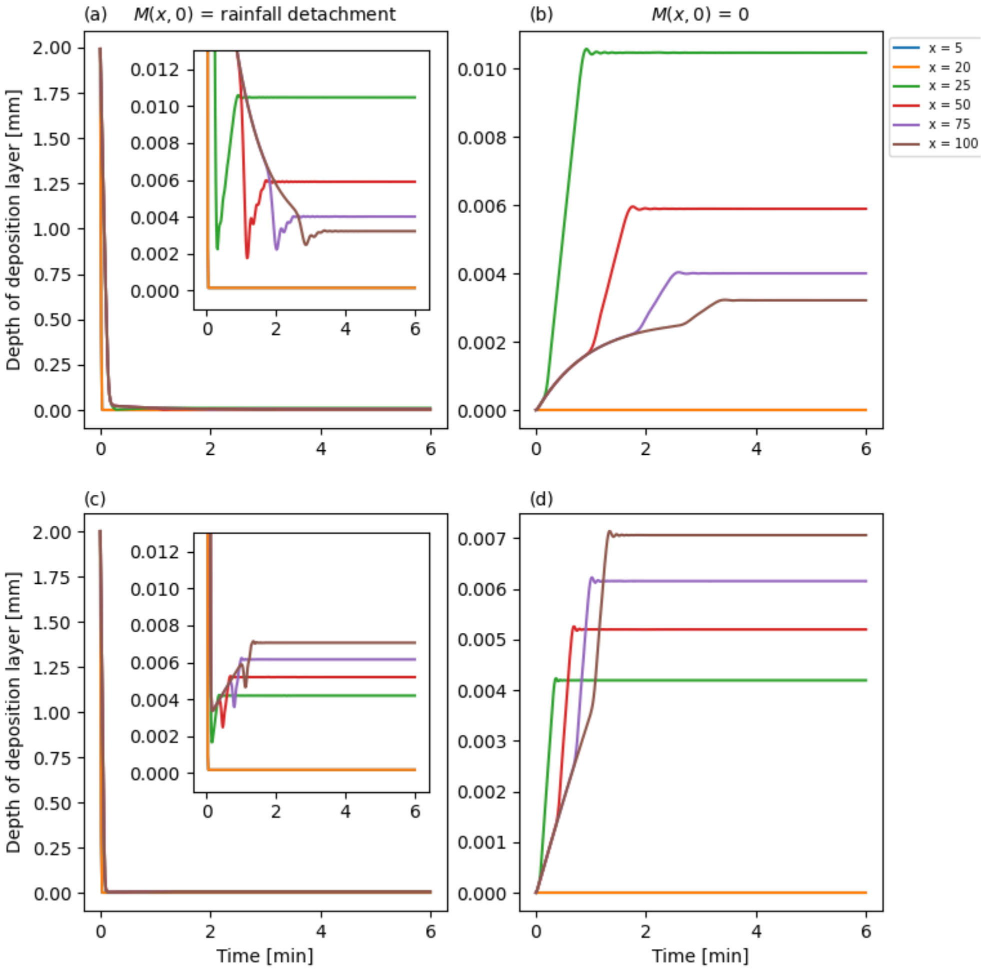

Figure 3. Depositional layer depth at select locations throughout the length of the gully for a six-minute MERGE simulation, with (left) and without (right) rainfall detachment, for the soft soil. Top: Low-intensity rainfall ($I = 7.5\,\mathrm{mm\,h^{-1}}$, $d = 0.1\,\mathrm{m}$) (a) where $M(x, 0) = 6.97\,\mathrm{kg\,m^{-1}}$ and (b) where $M(x, 0) = 0$. Bottom: high-intensity rainfall conditions ($I = 45\,\mathrm{mm\,h^{-1}}$, $d = 0.6\,\mathrm{m}$) (c) where $M(x, 0) = 7.01\,\mathrm{kg\,m^{-1}}$ and (d) where $M(x, 0) = 0$.

Changes to the infiltration assumptions and how the flow within the rainfall-detachment phase is modelled, would likely change the total mass detached. During the rainfall-detachment phase, overland flow from the catchment could enter the gully head, reducing the time until the depth threshold for rainfall-detachment to cease is reached. Conversely, infiltration would extend the time until reaching this threshold. While incorporating infiltration and catchment inflow to the gully would provide a more realistic model, the overall conclusions of this study are not likely to change. That is, the rainfall-detachment contributes an otherwise neglected load of sediment to the receiving environment.

5 CONCLUSIONS

Rainfall impact can detach large masses of sediment within a gully channel. This recently detached sediment forms a layer analogous to a depositional layer, in that the sediment is easy to entrain and lacks cohesion. This paper has introduced a new model for rainfall-driven detachment, RIDGE, and demonstrated the effect rainfall-driven detachment in gullies can have on the delivery of sediment to receiving environments by coupling the model with MERGE. Given that RIDGE does not account for sediment re-detachment or shielding effects, incorporating this dynamic is a priority for development. The sensitivity of RIDGE to input parameters will also need to be investigated. Improved coupling of the gully flow dynamics with the rainfall event, and including bedload transport are future development opportunities.

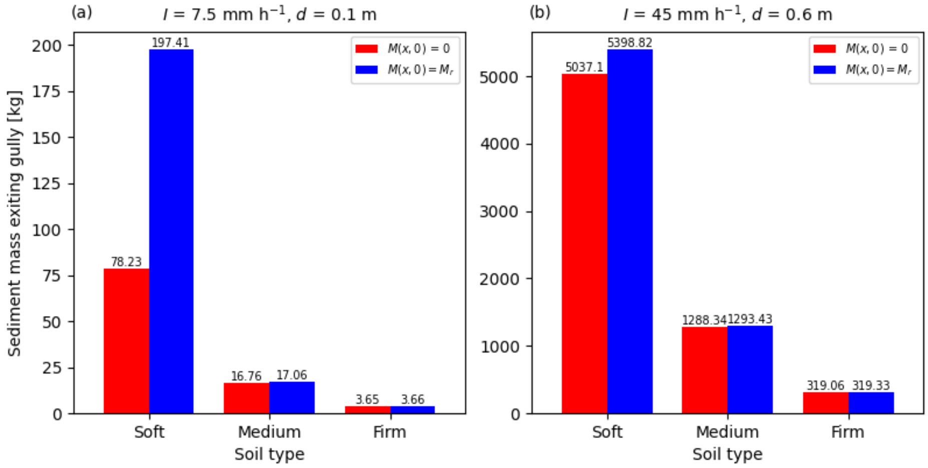

Figure 4. Total sediment mass delivered to receiving environment for (a) low- and (b) high-intensity rainfall scenarios after six minutes of flow.

Across all scenarios explored, the total mass of delivered sediment was greater when rainfall-detachment is included than excluded. It was observed that the maximum amount of rainfall-detached sediment was delivered within the six-minute simulations for all soil types and rainfall intensities. This was less than the total found within the initial depositional layer. Whilst adding the rainfall-detached mass to the MERGE quasi-steady solutions would obtain a sufficiently adequate estimation, this is not truly reflective of the observed dynamic, at least in the re-entrainment regime explored in this study. Especially for shorter-duration events, explicit modelling of the detachment dynamics will provide more information, which could be significant when incorporating interventions. Further research is required to understand under what conditions the rainfall-detached sediment could be fully delivered to the receiving environment.

This study considered channel-like gullies with a constant flow throughout the gully, as appropriate for MERGE. Further work is required to understand how rainfall-driven detachment impacts erosion in larger amphitheatre gullies where such approximations are less valid. The developed rainfall-detachment model may have further application in the study of these gullies, where rainfall and small flow events may have a larger role in destabilising a gully and driving gravity collapse than in the channel-like gullies for which MERGE was developed. Future work to compare the model results with field observations is important to both validate the model and provide evidence as to the suitability of the attenuation functions used.

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