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Porous Check Dams and the MERGE Gully Erosion Model

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Abstract: Gullies are hot spots of erosion. Gullies are the majority source of sediment that ultimately reaches the Great Barrier Reef despite occupying less than 1% of the catchment. Consequently, considerable investment and effort has focussed on preventing gully erosion through on-site remediation activities. Porous check dams (PCDs) are a common tool in erosion mitigation activities. PCDs are designed to slow the velocity of water through a channel, promoting the deposition of sediment, nutrients and seeds above the dam. Field observations suggest that, in some cases, PCDs can lead to increased scouring below the dam, risking a net increase in erosion relative to pre-intervention conditions.

This paper uses the MERGE gully erosion model to explore whether the installation of a PCD can trigger increased scouring below the dam, and consequently a net increase in the amount of sediment delivered to receiving waters. Eight scenarios, covering four flow regimes and two boundary conditions, are explored. We simulate constant depth flows of 0.1 m and 0.5 m depth in a reference gully channel with inflow concentrations from the head of 50 kg/m^3 and 100 kg/m^3. Varying depth flows are simulated with a sinusoidal function with amplitudes of 0.1 m and 0.5 m depth with the two different inflow concentrations. The reference gully is a small linear gully of 2 m width, 60 m long channel and 2% slope. The sediment is easily eroded, with a density of 1330 kg/m^3, and 10 μm particle size and with low cohesion. The PCD is installed 40 m from the start of the channel. The effect of the PCD is explored considering the growth of a depositional layer, and changes in the sediment delivery rate, that is the net sediment flux exiting the gully.

This modelling investigation demonstrates that the installation of a PCD can lead to an internal step (or head/waterfall) forming below the PCD. In all simulations the PCD reduced the sediment delivery rate at early times, however in five of the eight scenarios the PCD resulted in a net increase in the sediment delivery rate by the end of the simulation. The increased sediment delivery rate is a direct consequence of accumulation behind the sediment creating a step, or internal head, at the PCD. This introduces an increase in the power available to erode, and therefore a greater rate of entrainment below the PCD. These results highlight the importance of ongoing monitoring and maintenance of PCDs to ensure they continue to operate as intended.

Keywords: *MERGE,gully, erosion, remediation, porous check dams*

Figure 1. Photos at two porous check dam sites in the Fitzroy River Basin taken approximately 18 months apart. In these cases, the earlier photos (left) show significant scouring below the PCDs, which is later covered by sediment and leaf-litter providing a protective barrier against further erosion. Photos © K. Roots.

1 INTRODUCTION

The contribution of gully erosion to poor water quality on the Great Barrier Reef (GBR) is well established (Waterhouse et al. 2017). Consequently, considerable investment and effort has focussed on preventing gully erosion through on-site remediation activities. Porous check dams (PCDs) are one of the common tools to reduce erosion, particularly in smaller channel-like gullies. The objective of a porous check dam is to slow the speed of the flow through a section of gully, reducing the erosional power (stream power) of the flow and promoting deposition of sediments, nutrients and seeds on the upstream side (Wilkinson et al. 2019).

The accumulation of sediment has two main benefits, preventing eroded sediment from being transported to the GBR, and locally reducing the slope of the gully channel, which further reduces the stream power (and hence erosion). Furthermore, this deposited sediment provides a protective barrier to erosion (Figure 1) and can assist with the establishment of vegetation, which further prevents erosion by increasing the roughness of the channel (and further decreasing flow velocity), and increasing the effective cohesion of the soil. Observations have however suggested that, in some cases, the build up of sediment behind the gully could potentially be the cause of increased scouring observed in front of PCDs (personal communication).

This preliminary study explores the potential for PCDs to promote scouring in front of the dam using the MERGE gully erosion model. MERGE has previously been applied to explore related management approaches including leaky weirs, and roughening of the channel (Prentice et al. 2021, Roberts 2022, Prentice et al. n.d.). This study also serves as an exploration of the suitability of MERGE to model PCDs and the evolution of a gully over time.

2 METHODS

An implementation of the dynamic MERGE gully erosion model is used to explore the effect of a PCD, without management of the site, on net erosion and scouring below the PCD over time. MERGE is a one-dimensional conservation of mass model for the concentration of sediment within the flow. Sediment is advected through the gully with the flow, entrained from the floor and walls (source), and is deposited on the floor of the gully due to settling processes (sink). MERGE includes the dynamics of the depositional layer as first introduced by Hairsine & Rose (1992). For a full description of MERGE refer to Roberts (2020).

The dynamic (time-dependent) MERGE model is solved in Python (v3.9) using the Method of Lines discretised along the length of the gully (refer to Roberts (2020) for details). The original MERGE model tracks the development of a depositional layer, which is an accumulation of recently deposited sediment on the floor of the gully, but does not account for variations in the flow due to changes in the underlying gully morphology. That is, the model does not consider changes to the gully length, depth, slope, or width within a simulation. In order to explore the potential for an internal step (or gully head) to form because of a PCD, modifications to the model were necessary.

If scouring in front of the PCD is greater than behind it, a step will form in the gully channel. This step will introduce a local waterfall, shifting the regime from 'channel flow', where the power available for erosion is solely due to the stream power, to 'head flow', where the power due to the waterfall must also be considered. This increased power is accounted for in the model by modifying the entrainment term in the channel to include the waterfall power, that is $\Omega \to (\Omega + \Psi)$, where Ω [W/m] is the stream power and Ψ [W/m] is the waterfall power, a function of the step (or waterfall) height $D(x,t)$ [m].

The development of such as step is tracked through the depositional layer. The mass in the depositional layer, $M(x,t)$ [kg/m] is given by

$$\frac{\partial M}{\partial t} = \delta - \eta_{\text{floor}} \tag{1}$$

where δ [kg/ms] is the rate of deposition and η_{floor} [kg/ms] is the rate of entrainment from the gully floor (per unit length). The original MERGE model is modified to allow the depositional layer mass M to go negative when erosion from the floor exceeds deposition, and thus $M > 0$ provides the mass of the depositional layer, and $M < 0$ provides the net mass of sediment eroded from the gully floor. The mass of the depositional layer is converted to a layer depth [m] with $l(x,t) = M(x,t)/(\sigma W)$, where σ [kg/m^3] is the sediment density and W [m] is the width of the gully. A positive layer depth indicates a depositional layer is present, while a negative value indicates a step is forming. The local step height $D(x,t)$ [m] is given by the local change in the layer depth. The height is locally smoothed across adjacent nodes to avoid unrealistic spikes in the step height by setting the step at node i to be $D[i] = \frac{1}{2}(l[i-1] + l[i-2]) - l[i]$, where $l[i]$ is the layer depth at node i. Variation to the flow Q [m^3/s] due to local accumulation of sediment is neglected, that is the step height D is assumed strictly non-negative. Variation in the slope due to scouring and local changes in the depositional layer are also neglected, therefore we assume the slope is constant in space and time.

Following Roberts (2020), the PCD affects the flow through the Manning's roughness coefficient n, which modifies the velocity of the flow via the flow (flux) term Q in accordance with Manning's Equation, which relates the flow rate to the depth as a function of the slope, Manning's roughness coefficient, and the wetted perimeter of the flow. The flow volume, and hence depth, is assumed to be unaffected by the PCD. The change in the Manning's roughness coefficient is modelled by

$$n_{\text{pcd}} = \frac{0.05\, pcd_{\text{height}}}{d(t)} \times \begin{cases} \exp\big[0.3(x - pcd_x)\big], & x < pcd_x \\ \exp\big[-5(x - pcd_x)\big], & x \geq pcd_x \end{cases}, \tag{2}$$

where pcd_x [m] is the location of the PCD, and pcd_{height} [m] is the height of the dam. This models a dam that slows flow as it approaches the PCD, with an effect that rapidly diminishes after the flow. For the case studies explored, this equates to a maximum effect of increasing the Manning's roughness coefficient by 0.05.

As the focus of this study is on the effect of the PCDs, and PCDs are not appropriate for controlling head flow (Wilkinson et al. 2019), we ignore the dynamics from an initial gully head. We therefore implement MERGE with only channel flow and capture the sediment eroded in the head through a non-zero boundary concentration C_0 [kg/m^3]. In this study we consider a 2 m wide gully of 60 m length, 2% slope and of bare soil (Manning's roughness coefficient $n = 0.02$). The gully is highly erosive, with a soil cohesion of 400 Ws/m, particle size of 20 μm and sediment density of 1300 kg/m^3. The PCD is installed 40 m from the start of the gully channel and is 50 cm high. Refer to Table 1 for a summary of all model parameters.

Eight case studies (Table 2) are explored considering combinations of four flow conditions and two different sediment concentration boundary conditions, $C_0 = 50$ and $C_0 = 100$ kg/m^3. The constant flow depths are $d = 0.1$ and 0.5 m. The time-varying flow depths are periodic piecewise continuous curves

$$d(t) = \begin{cases} 0.1 & 0 < \tau < 0.1 \\ 0.1 + a \sin\left(\frac{\pi\tau}{2}\right) & 0.1 \leq \tau \leq 2.1 \\ 0.1 & 2.1\tau \leq 2.2 \end{cases} \tag{3}$$

where $\tau = \text{mod}(t/3600, 2.2\text{hours})$ and $a = 0.1$ or $a = 0.5$.

3 RESULTS AND DISCUSSION

In the short term, the installation of a PCD decreased local erosion (Figure 2), the local sediment concentration

Table 1. Parameter values used for exploring steady state and dynamic solutions.

Gully length	L	60 m	Width	W	2 m
Slope	S	0.02	Step head length	L_h	0.5 m
Sediment density	σ	1330 kg/m^3	Settling velocity	w_s	0.05 m/s
Particle radius	R	10 μm	Soilcohesion	J	400 Ws/kg
Base Manning's roughness*	n_{base}	0.02s/m$^{1/3}$	Initial concentration	C_0	50 or 100kg/m^3
PCD height	pcd_{height}	0.5 m	PCD location	pcd_x	40 m
Initial layer mass	M_0	0kg	Carrying capacity	C^*	260 kg/m^3
Power proportion	k	0.2	Concentration gradient	b	1
Fluid density	ρ	1000 kg/m^3	Friction term	F	0 Ws/kg

Table 2. Concentration boundary condition, C_0, and flow depth, $d(t)$ for the eight case studies. The time-varying flow depths have the pattern of 0.1m for the first and final 0.1 hours, and a sinusoidal curve described by $a\sin(\pi\tau/2)$ for the intervening 2 hours, where the amplitude a is indicated in the table and τ is the time in hours. The time-varying profile is repeated throughout the simulation (period 2.2 hours).

	Constant Depth				Varying Depth			
	A	B	C	D	E	F	G	H
C_0	50	100	50	100	50	100	50	100
$d(t)^*$	0.1	0.1	0.5	0.5	0.1 sin	0.1 sin	0.5 sin	0.5 sin

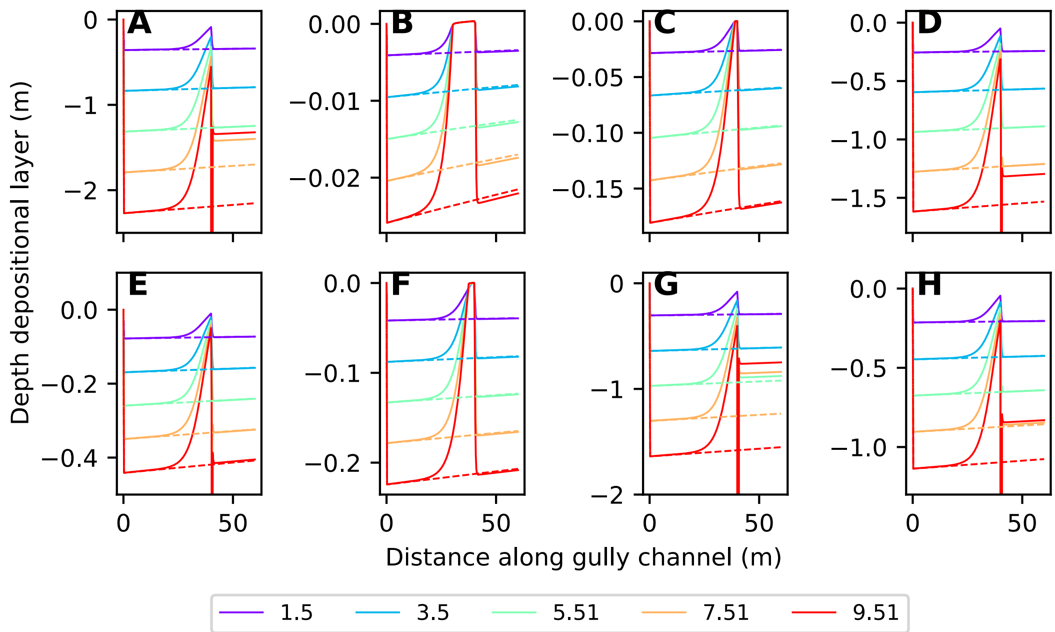

Figure 2. Height of the depositional layer along the length of the gully at selected times for the eight scenarios summarised in Table 2. The time is indicated by the line colour, with dashed lines indicating a simulation without a PCD and solid lines indicating the presence of a PCD.

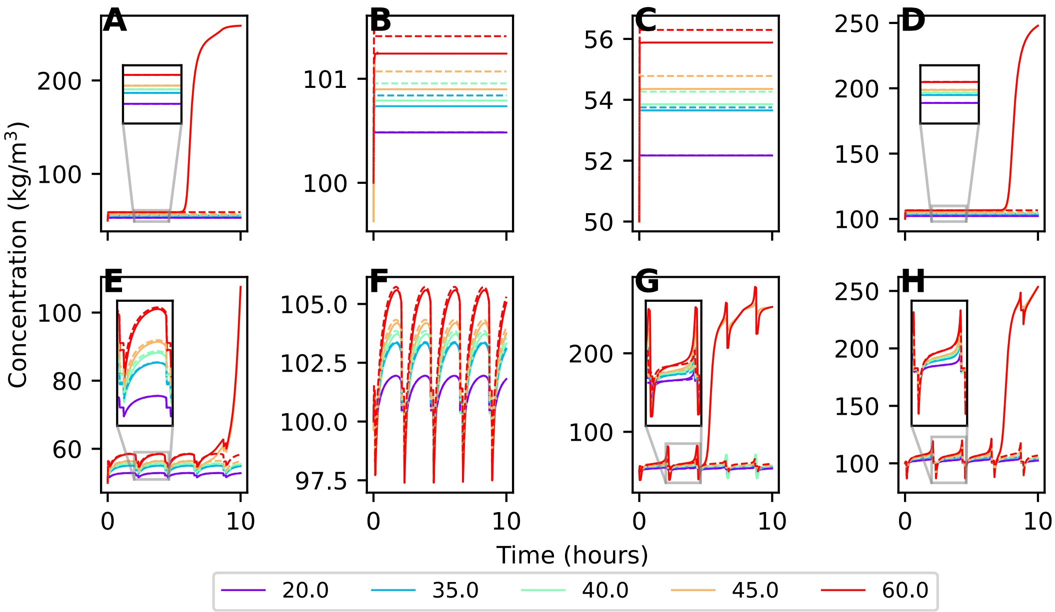

Figure 3. Sediment concentration within the water column at selected locations over a ten-hour simulation for the eight scenarios summarised in Table 2. The location down-gully of the head is indicated by the line colour. Dashed lines indicate a simulation without a PCD and solid lines indicate the presence of a PCD.

in the water column (Figure 3) and the delivery of sediment to the receiving environment (Figure 4) in all scenarios investigated. However, over time the discrepancy in the power available for erosion, and hence the rate of entrainment, before and after the PCD led to the development of an internal step, ultimately resulting in the simulated sediment concentration reaching the theoretical maximum carrying capacity, and sediment delivery rates as much as four times the case without a PCD present (see Figure 4A, D, E, G, H). For the three other scenarios (B, C & F) it is likely that extending the simulation time would ultimately result in an equivalent result, since these cases also developed in an internal step after the PCD, which grew over time (Figure 2). However, in these scenarios the internal step did not reach a critical value to magnify the net erosion.

The constant depth scenarios presented (A - D) all have net scouring of the gully floor. In contrast, the sinusoidal scenarios had net deposition during the rising phase of the flow in some cases. This rate of deposition was not however sufficient to rebuild the layer in any of the scenarios during the simulation time (10 hours). Further, in these scenarios, net deposition behind (above) the PCD was negligible at best, and thus although entrainment was reduced it provided for only a very slow accumulation of the depositional layer. These scenarios were however selected to explore scouring regimes below a PCD, with parameter values chosen accordingly.

The theoretical parameter values for which net deposition will be locally observed are shown in Figure 5 for the case study gully. Three cases are explored: net deposition both above ($n = 0.07$) and below ($n = 0.02$) the PCD, net entrainment both above and below the PCD, and net entrainment above the PCD with net deposition below. This analysis shows, that for this case study, unless an internal step forms, the gully will be in a re-entrainment regime (net deposition) both above and below the PCD. However, once an internal step forms, there exist flow depths under which the gully will transition to net scouring below the PCD (and potentially above). This transition is inevitable – the decrease in stream power above the PCD results in the rate of change in the depositional layer mass, $\frac{\partial M}{\partial t}$, being larger behind the PCD than immediately after. Thus, under an entrainment regime the depositional layer will grow more quickly behind the PCD, introducing an internal step at the PCD, even in the absence of scouring. In practice, once the depositional layer is as high as the PCD, the PCD ceases to have any impact, however this feedback was not incorporated in the simulations.

PCDs are commonly installed in series, that is with multiple dams in a channel section (see Figure 1 for an example). This provides some level of protection against the formation of an internal step, as the area in front of one PCD is itself behind another. However, care must be taken to ensure that the deposition in this region is sufficient to protect the underlying soil matrix from rapid entrainment. As with all engineering structures,

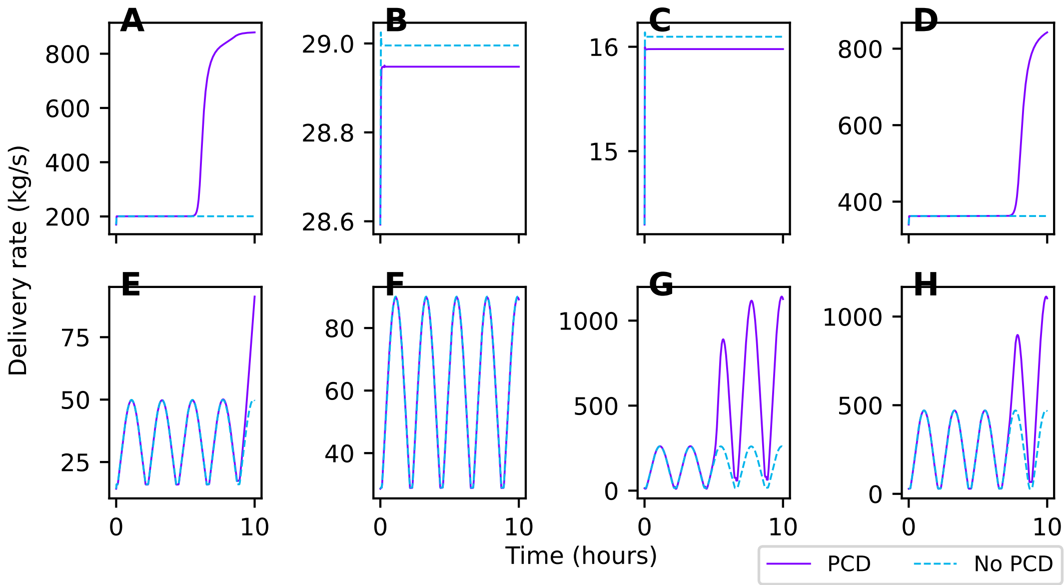

Figure 4. Sediment delivery rate [kg/s] to receiving waters for the eight scenarios summarised in Table 2. The solid purple line indicates the presence of a PCD, with the blue dashed line indicating no PCD.

PCDs will also remain vulnerable to extreme events.

This study has demonstrated the risk of PCDs resulting in a net increase in erosion and the delivery of sediment to receiving waters. This study has also demonstrated limitations in using MERGE to model the evolution of a gully over time without further modification. Although modifications to the original MERGE model were introduced to track scouring and the formation of internal steps, other feedback was neglected, including variation in the channel slope, variation in the height of the PCD relative to the depositional layer (positive or negative) and scouring of the gully walls (likely less critical).

A further, and likely more critical, limitation of this study is neglecting variation in the flow due to changes in the gully – other than the internal step that was the focus of this gully and the slowing of the flow via the Manning's roughness coefficient. Furthermore, the model provides no limitation on erosion at the base of the step, resulting in a feedback loop where the height of the step increases without bound, which is not physical. As the step height increases, the power available to erode similarly increases, resulting in increased erosion, and hence a higher step (or deeper hole). While a smoothing term was introduced over local nodes, this nonetheless resulted in unrealistic step heights immediately after the PCD (Figure 2 A,D,E,G,H). Further research is required to resolve this modelling challenge – the literature related to waterfall erosion and bedload transport may provide a way forward. In addition, changes to the flow due to upwards-sloping sections was also neglected.

4 CONCLUSIONS

PCDs are installed in gullies in order to reduce the amount of sediment that is delivered to receiving waters. PCDs obstruct the flow, reducing the flow velocity and hence reducing the stream power, which drives erosion in the channel. PCDs also promote deposition by increasing the time for the flow to exit the gully.

This modelling study shows that while PCDs can be effective in reducing the delivery of sediment to receiving waters, if not managed they can accelerate scouring and increase the delivery of sediment. The Gully Toolbox (Wilkinson et al. 2019) recommends that where multiple PCDs are installed the top of lower PCDs is greater than the toe of the PCD above to address this issue. This study suggests that in some cases, this may not be sufficient. Careful construction of PCDs, and ongoing monitoring and maintenance, is required to ensure they continue to perform as designed.

This study has demonstrated that although MERGE can explore the effect of PCDs on net erosion, care must be taken due to the absence of feedback modulating the flow once an internal step forms.

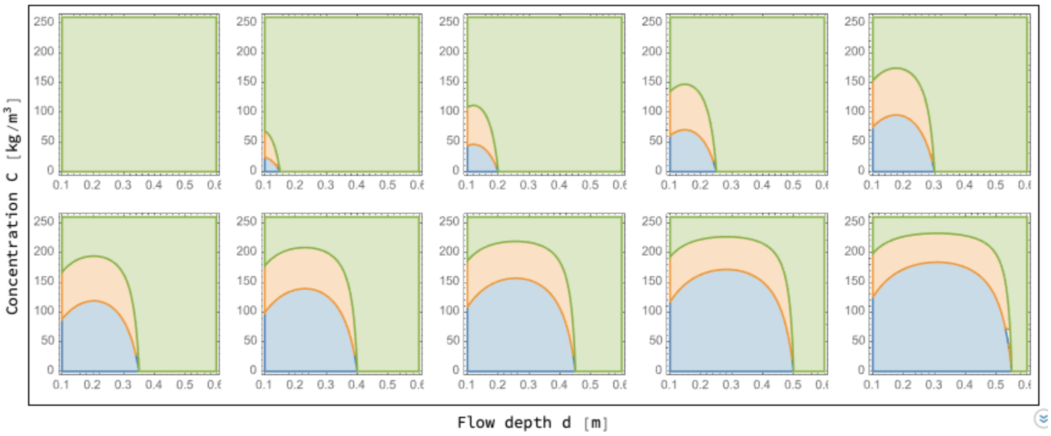

Figure 5. Exploration of flow depth and concentration conditions for scouring (net erosion) and accumulation (net deposition) for different step heights in the presence of a PCD. A Manning's Roughness coefficient of $n = 0.07$ is applied immediately above the step to represent a PCD, and a coefficient of $n = 0.02$ is applied immediately below the step. Three regimes are illustrated: scouring both above and below the step (blue), accumulation above and scouring below (orange), and accumulation both above and below the step (green). 10 step heights are illustrated, a zero step height in the top left, increasing by increments of 0.05 (left-to-right then top-to-bottom) to a maximum step height of 0.5m in the bottom right.

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