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Modelling the effects of vegetation on mitigation of gully erosion using Computational Fluid Dynamics (CFD)

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Abstract: Gully erosion is a significant global environmental concern as it limits agricultural productivity, destabilises landscapes, impacts housing and other essential infrastructure, and contributes to elevated erosion rates and poor water quality. Vegetating the gully channel has been well recognised as an intervention to mitigate gully erosion. In previous studies, the effects of vegetation on gully erosion have been modelled using MERGE with an analytical approach by using Manning's coefficient to represent the surface roughness and thereby calculate an adjusted flow through the gully while assuming a constant flow depth. However, questions remain as to the appropriateness of this approach. The current study presents a novel approach to model the effects of vegetation on the flow hydrodynamics in a gully using Computational Fluid Dynamics (CFD). In CFD, the Volume of Fluid (VOF) model was employed to resolve the interactions between the air and water phase to examine the variation of water level in a gully. The vegetation was treated as a porous media with flow resistance coefficient to simulate the vegetation-induced drag on the flow. The study was a small classical gully (approximately 20 m long) located in the Fitzroy River basin approximately 2km west of Rockhampton, Queensland, Australia. The morphology of this gully included an initial head and second step (2 m and 0.4 m, respectively), followed by the first channel (length = 7.2 m, slope = 0.25) and second channel (length = 11 m, slope = 0.33). The height and velocity of runoff water was 1 m and 3 m/s, respectively. Three characteristics of the vegetation were varied to examine their effects on the flow hydrodynamics. Namely, i) the vegetation density (which was represented by the flow resistance coefficient of porous media, 2 to 10 m-1), ii) the length of the vegetated area in the second channel 2 to 10 m downstream), and iii) the angle of the vegetated area (0o to 60o relative to the vertical axis). The simulation results included i) water level in a gully, ii) flow velocity, and iii) surface shear stress. A simulation in which no vegetation occurs in a gully was undertaken to be a reference case. Time-transient two-dimensional (2D) simulations were employed and the steady state was achieved at 120 s. The results at the steady state were used in the current study.

The study found that the presence of vegetation resulted in a significant change of the flow hydrodynamics in a gully. Flow velocity decreases through the vegetated area (the porous media) and the magnitude of the flow velocity reduction is dependent on the vegetated density (the flow resistance coefficient). The greater vegetated density also facilitates the occurrence of flow turbulence, which is indicated by the mixture of water/air, upstream of the vegetated area. Introducing vegetation in a gully results in an increase of water level, particularly above the vegetated area. Water level, however, decreases progressively downstream of the vegetated area. The increase of water level is not significantly dependent on the vegetation density. The length of the vegetated area, however, significantly influences the water level, as extending the vegetated area results in an extent of elevated water level in a gully. The angle of vegetation only influences the hydrodynamics upstream of the vegetated area, flow turbulence occurs when the angle of vegetation is 0^o, but does not occur when the angle of vegetation is 60^o. The flow hydrodynamics downstream of the vegetated area is not significantly influenced by the vegetation angle. The surface shear stress of the vegetated area decreases significantly when vegetation is introduced (approximately 100 Pa versus 10 Pa). This emphasises that introducing vegetation is an effective intervention in reducing the potential of gully erosion. However, it is important to note that flow begins to recover downstream of the vegetated area, resulting in an increase of surface shear stress. The rate of flow recovery is not significantly dependent on the vegetation characteristics (i.e. density, length, angle). It is, therefore, recommended that extending the vegetated area in a gully is important to increase the effectiveness of vegetation for mitigation of gully erosion. The current study also demonstrated that CFD could be an effective tool to examine the gully erosion in various scenarios (e.g. different runoff conditions, gully morphologies) and interventions (e.g. different vegetation characteristics).

Keywords: *Computational Fluid Dynamics (CFD); Volume of Fluid (VOF); Porous Media; Flow hydrodynamics; Vegetated gully.*

1. INTRODUCTION

Gully erosion is a major process contributing to elevated erosion rates, reduction in land productivity, and excess sedimentation and poor water quality across the globe (Bartley et al., 2020). In Australia, gully features cover just 0.1% of the catchment area draining to the Great Barrier Reef (GBR) World Heritage Area, however, sediment source tracing, erosion mapping and sediment load monitoring indicates that gully erosion supplies ~40% of the fine sediment exported from river basins to the GBR lagoon (Khan et al., 2024) contributing to poor water quality and degradation of the health of the reef (Lambert et al., 2021). In New Zealand, it is estimated that 48% of the total sediment generated by gully erosion between 1950 and 1988 was stored in the channel along the lower 8 km of Te Weraroa Stream (Gomez et al., 2003).

Vegetating the gully channel has been well recognised as an intervention to mitigate gully erosion (Prentice et al., 2024). To date, there are a number of methods to study the effects of vegetation on gully erosion including field observations, field-based experiments, and modelling (reviewed in Roberts et al., 2022). In the modelling method, the effects of vegetation on the flow are modelled using an analytical approach, such as applying Manning's coefficient to represent the vegetation-induced roughness. For example, in MERGE (Modelling Erosion Resistance for Gully Erosion, Roberts, 2020), the Manning's coefficient is modified for simulations with interventions to calculate the modified flow while holding the depth of flow constant (Prentice et al., 2024).

The current study presents a novel modelling approach that extends from the analytical approach (e.g. MERGE) to examine the effects of vegetation on the flow hydrodynamics to mitigate gully erosion using Computational Fluid Dynamics (CFD). In this approach, the interface between water/air in a gully is modelled using volume of fluid (VOF) method, which was commonly used for open channel flow (e.g. Jebelli et al., 2023). Vegetation is treated as a porous media that produces flow resistance (e.g. Cintolesi et al., 2023). This study aims to examine the characteristics of vegetation including i) vegetation-induced flow resistance, ii) the length of vegetated area in a gully, and iii) the angle of vegetation on the flow hydrodynamics (flow speed and water height), and potental bed erosion (via surface shear stress).

2. METHOD

2.1. Computational domain setup and meshing

A two-dimensional (2D) computational domain was created to simulate the flow hydrodynamics through the vegetated area in a gully (Figure 1). The model gully morphology (i.e. the bottom of the domain) was created following the morphology of small classical gully located in the Fitzroy River basin approximately 2km west of Rockhampton, Queensland, Australia (Roberts, 2022). The gully morphology consisted of i) initial head (2.0 m high, 3.1 m long), ii) second step (0.4 m high, 0.4 m long), and iii) the channel. In the computational domain, the channel consisted of two parts including i) unvegetated area (7.3 m long, slope of 0.25), and ii) vegetated area (slope of 0.33). In the vegetated area, a porous media (Figure 1b) was created to simulate the effects of vegetated area on the flow. The vegetation type is long grass, following the field examination in Roberts (2022).

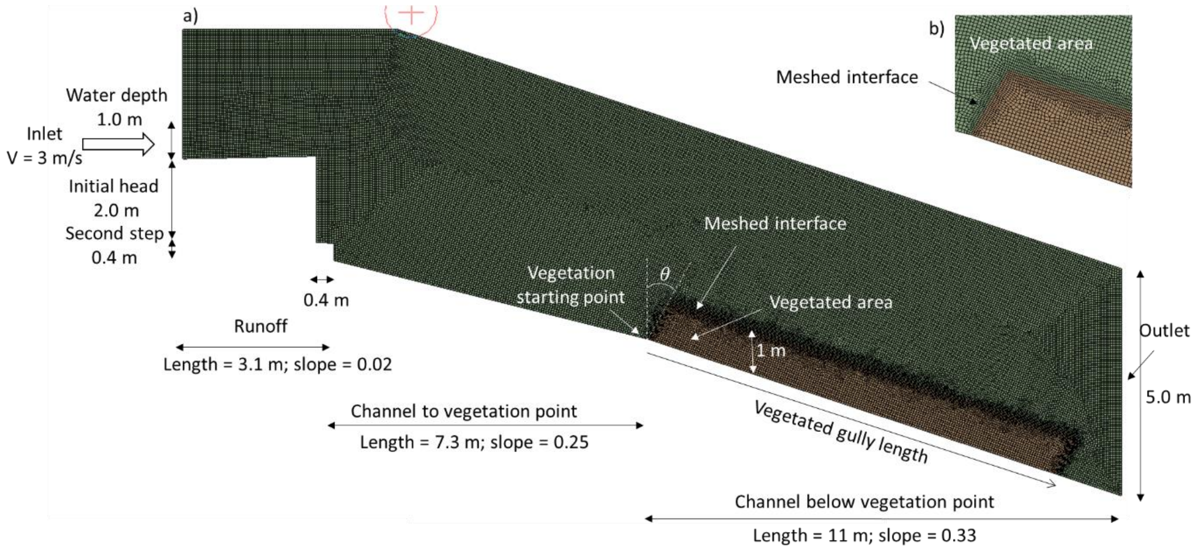

Figure 1: Computational domain setup and meshing: a) the morphology of gully (height, length and slope) and the location of vegetated area are indicated. The morphology of vegetated area is characterised by the length and angle (θ); (b) details of meshed interface of vegetated area.

The characteristics of the porous media were adjusted to examine their effects on the flow. Firstly, the length and angle of vegetated area was fixed at 2 m and 0º (i.e. vertically), respectively, while the flow resistance coefficient varied from 2 to 10 (m^{-1}) (2 m^{-1} intervals) (see details of porous media simulations and flow resistance coefficients in Nguyen et al., 2025b, 2025a). These simulation cases (cases 2 to 6) were undertaken to examine the effects of vegetation density, which is represented by the flow resistance coefficients on the flow. Secondly, the flow resistance coefficient and the angle of vegetated area was fixed at 2 m^{-1} and 0º, respectively, while the length of vegetated area varied from 4 to 10 m (2 m intervals) downstream from the vegetation point. These simulation cases (cases 7 to 10) were undertaken to examine the length of vegetated area on the flow. Thirdly, the flow resistance coefficient and length of vegetated area were fixed at 2 m^{-1} and 10 m, respectively, while the angle of vegetation were 30º and 60º relative to the vertical axis. These simulation cases (cases 11 and 12) were used to examine the effects of the angle of vegetation on the flow. All simulation cases (2 to 12) were compared with the reference case (case 1) in which no vegetation occurred in the gully. For all simulations, the height of vegetated area was 1 m. The water depth was set at 1 m and water velocity was 3 m/s at the domain inlet to replicate high flow conditions (Roberts, 2022). The computational domain was meshed with a cell size of 50 mm. The interface of vegetated area was meshed with a cell size of 25 mm. There were approximately 45,000 cells in the domain.

2.2. Model setup

The current study employed the Volume of Fluid (VOF) model to simulate flow hydrodynamics through a gully using ANSYS Fluent. ANSYS Fluent is a commercial CFD software known for its integrated graphical user interface (GUI) and comprehensive features for simulation and post-processing (Fluent, 2013). The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain (Fluent, 2013). Water and air were selected as fluids in the current study, with sediment in the water not considered. As an initial condition, the volume fraction of water at the domain inlet was 1 (i.e. 100% water) while the volume fraction of air in the entire domain was 1 (i.e. 100% air). The time-step was 0.001 s and the modelled results were saved every 500 time steps (i.e. every 0.5 s). Turbulence was modelled using $k-\epsilon$ RNG theory model. The $k-\epsilon$ RNG model turbulence model is derived from the instantaneous Navier-Stokes equations, using a mathematical technique called "renormalization group" (RNG) methods (Fluent, 2013). The temporal variation of water velocity at the domain outlet was examined to determine the steady state, which was achieved at 120 s. The results presented in the current study were at steady state conditions.

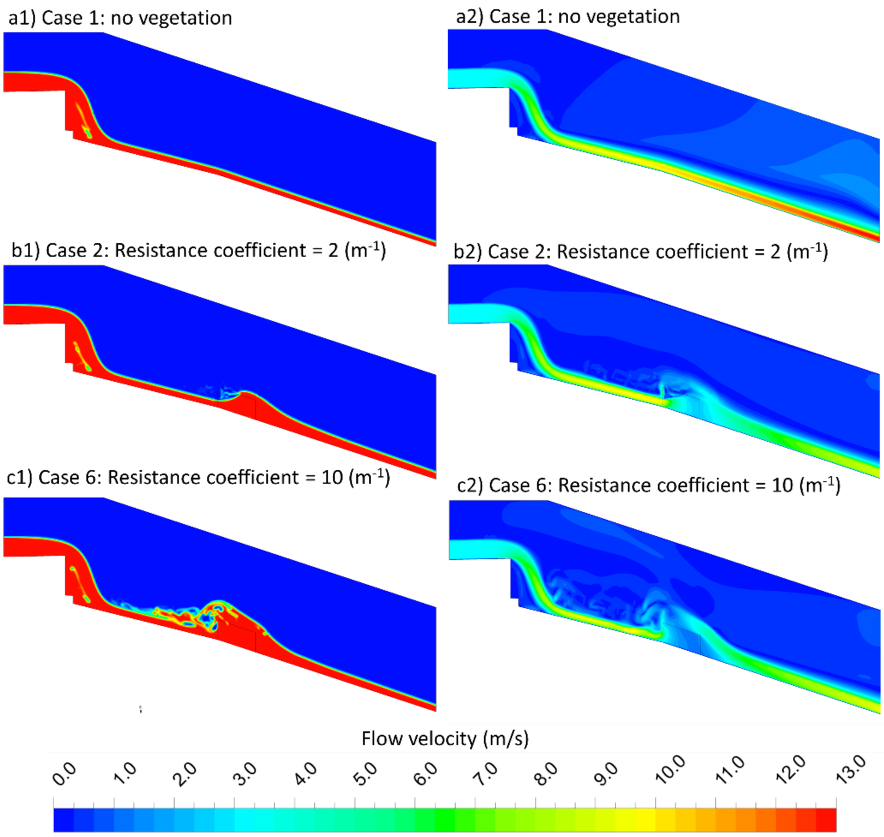

Figure 2. Water (red) and air (blue) fraction in (a1) – (c1) and flow velocity in (a2) - (c2) when the flow resistance coefficient varies from 0 to 10 m^{-1}. Note the legend is applicable for only (a2) to (c2).

3. RESULTS

3.1. Effects of vegetation density (resistance coefficient) on the flow hydrodynamics

The vegetation density, modelled using the flow resistance coefficient, strongly influences the water level (Figure 2a1 – 2c1) and flow velocity (Figure 2a2 – 2c2) in a gully. Water level in the gully increases from approximately 0.2 m to 1 m (i.e. similar to the vegetation height) when the flow resistance coefficient increases from 0 to 2 m^{-1} (Figure 2a1 to 2b1, respectively), and up to 2 m when the coefficient increases to 10 m^{-1}. Increasing the flow resistance coefficient also increases the turbulence upstream of the vegetation, which is indicated by the mixture of water/air fraction (Figure 2b1 vs. 2c1). The flow velocity inside the vegetation decreases from 3 to 1 m/s when the coefficient increases from 2 to 10 m^{-1} (Figure 2b2 and 2c2). When vegetation occurs in a gully, the flow velocity downstream decreases significantly. For example, the flow velocity at the outlet of the computational domain decreases from approximately 13 m/s to 10 m/s when a flow resistance coefficient of 2 m^{-1} is applied (Figure 2a2 vs. 2b2). However, increasing the flow resistance coefficient does not result in a significant change to the flow velocity downstream of the vegetation. For example, the flow velocity at the outlet is still 10 m/s when a coefficient of 10 m^{-1} is applied (Figure 2c2).

3.2. Effects of vegetation length on the flow hydrodynamics

The length of vegetated area in a gully strongly influences the flow hydrodynamic patterns (Figure 3). Increasing the vegetated region results in an increase of the extent that elevated water occurs in a gully. For example, the extent of elevated water level (~ 1 m) increases from 4 to 10 m when the vegetated length increases from 4 to 10 m (Figure 3a1 – 3b1, respectively). Increasing the vegetated length also results in an increase of the extent of reduced flow velocity in a gully. For example, the reduced flow velocity (< 3 m/s) increases from 4 to 10 m when the vegetated length increases from 4 to 10 m (Figure 3a2 – 3b2, respectively). Increasing the vegetated length, however, does not result in a significant change in the hydrodynamics upstream of the vegetated area.

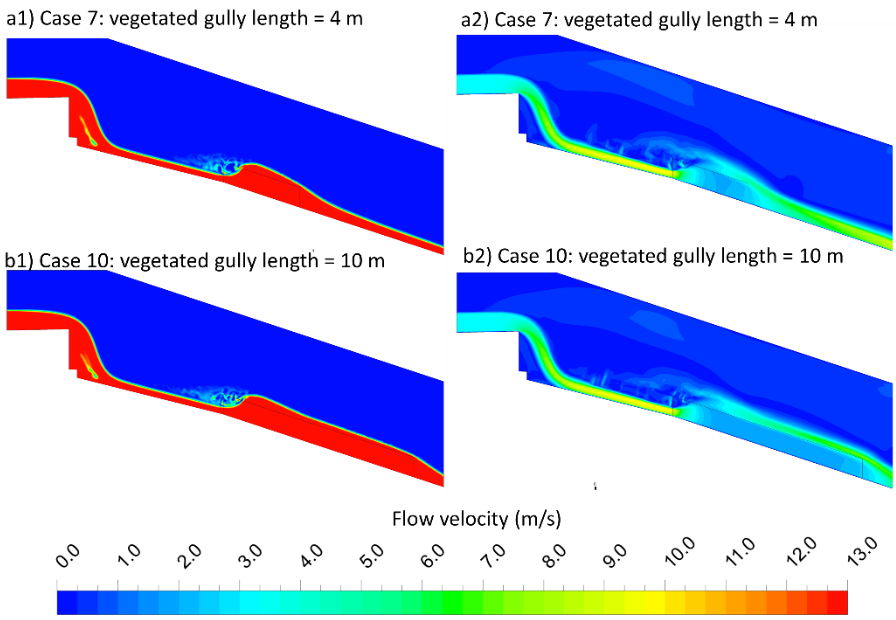

Figure 3. Water (red) and air (blue) fraction in (a1) – (b1) and flow velocity in (a2) - (b2) when the vegetation length increases from 4 to 10 m. Note the legend is applicable for only (a2) to (b2).

3.3. Effects of vegetation angle on the flow hydrodynamics

Vegetation angle influences the patterns of flow hydrodynamics upstream of the vegetation (Figure 4). When the vegetation angle was 30^{o} relative to the vertical axis, the turbulence flow occurs at the upstream of the vegetated area (Figure 4a1). When the vegetation angle was 60^{o}, however, the turbulence flow does not occur at the upstream of the vegetated area (Figure 4b1). The vegetation angle does not significantly influence the water level and flow velocity in the gully (Figure 4a2 and 4b2).

3.4. Effects of vegetation on the surface shear stress

The surface shear stress on the gully bed was derived from CFD modelling to examine the effects of vegetation on the potential bed erosion (Figure 5). For all simulation cases, applying vegetation in a gully results in a significant decrease of surface shear stress, from approximately 100 to 10 Pa in the vegetated area, which then increases progressively downstream of the vegetated area. The rate of the increase of surface shear stress downstream of the vegetation is not significantly influenced by the vegetation characteristics. For example, surface shear stress downstream of the vegetation is relatively similar when the vegetation increases (Figure 5a) and the vegetation angle increases (Figure 5c). The increasing rate of surface shear stress downstream of the vegetation is also relatively similar when the vegetated area increases (Figure 5b). Noticeably, surface shear stress downstream of the vegetation increases but is still consistently lower than the surface shear stress in which no vegetation occurs in a gully (i.e. reference case).

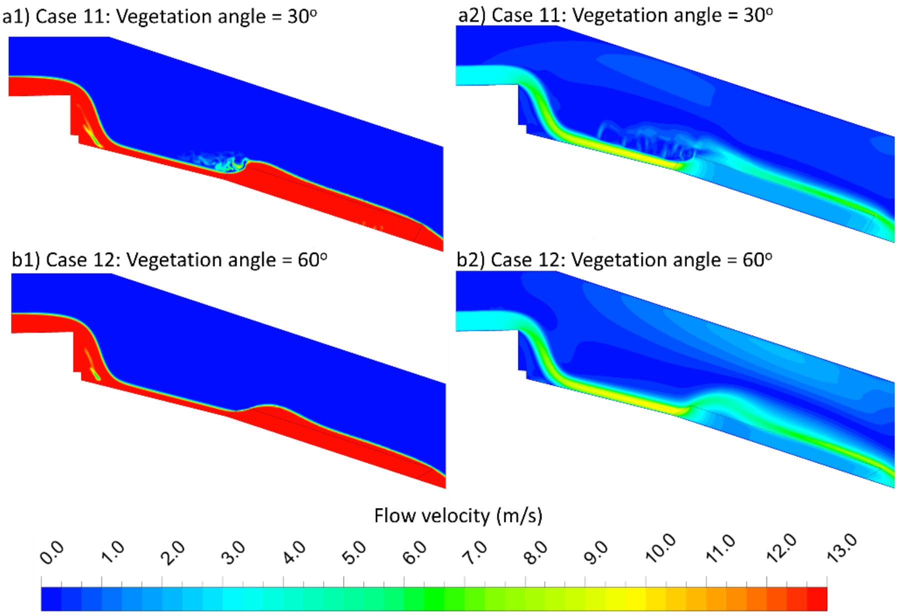

Figure 4. Water (red) and air (blue) fraction in (a1) – (b1) and flow velocity in (a2) - (b2) when the vegetation angle increases from 30° to 60°. Note the legend is applicable for only (a2) to (b2).

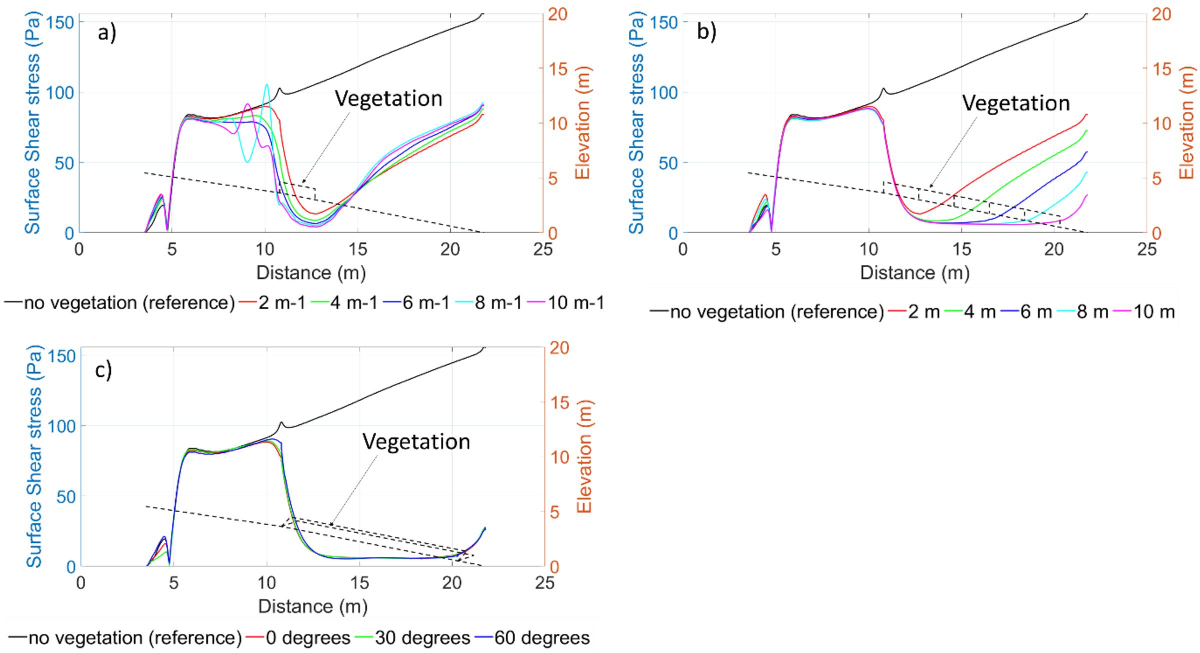

Figure 5: Surface shear stress on the gully's bed (solid lines) when the flow resistance coefficient increases from 2 to 10 m^{-1} (a), the length of vegetated area increases from 2 to 10 m (b), and the vegetation angle increases from 0° to 60° relative to the vertical axis (c). Surface shear stress on the gully's bed (solid line) when no vegetation occurs (reference case) is also presented. The elevation of gully bed (dashed line) and vegetated area with various length (b) and angle (c) is indicated.

4. DISCUSSION

The current study demonstrated the feasibility of using CFD to model the flow hydrodynamics in a gully. Firstly, representing vegetation as porous media could be an effective approach to model the effects of vegetation in the flow hydrodynamics. We found that increasing vegetation density (which was modelled using flow resistance coefficient of porous media) results in a decrease of flow velocity (Figure 2b2 – 2c2). This is consistent with field observations in other field-based experimental studies (e.g. Neumeier, 2007; Rezaei et al., 2024). Further work, however, is required to investigate the relationship between the vegetation density and flow resistance coefficient. While the key benefit of our approach is lower computational cost by simplifying the complex geometry of vegetation to be a porous media area, the interactions between vegetation and flow, which might result in the variation of vegetation's shape such as bending and inclination angle and thus drag coefficient (Meng et al., 2024), have not been accounted for.

Secondly, the VOF model could be an effective approach to examine the variation of water depth in a gully. For example, it is well understood that as the frictional resistance and the complex flow patterns on the vegetated surface reduce flow speeds, water surface slopes develop over the vegetated surface (Möller and Christie, 2019; Young et al., 2016). The change of water level, in turn, might influence the flow velocity and vegetation response. The VOF approach, which models both the flow velocity in water phase and water level in the interface between the air-water phase, could resolve the complex relationship between a gully's characteristics, flow conditions and water level. This study does indicate that the approach of modifying flow velocity via Manning's Equation while maintaining a constant water depth, as applied in the MERGE-focussed studies, may be overly simplistic. Coupling of the CFD model with MERGE would provide a better understanding of the variation in modelled erosion reduction due to vegetation from these different approaches.

Thirly, using the surface shear stress from the CFD results could assist in determining sections in a gully that are more vulnerable to erosion. A number of other studies have found the relationship between water movement induced shear stress and bed erosion (e.g. Mehta et al., 2015). CFD could produce the shear stress across the entire gully bed – sections where the shear stress is greater than the erosion threshold could indicate sections where interventions are likely to be more effective in reducing total erosion.

Finally, the current study provides a number of implications for using vegetation as an intervention for mitigating gully erosion. We found that flow velocity and surface shear stress decrease through the vegetation, however, both begin to recover downstream of the vegetation, and this recovery is not significantly influenced when the vegetation density increases. In contrast, extending the vegetated area, even with low vegetation density, results in the extent of low flow velocity and surface shear stress downstream in the gully. This implies that using vegetation as an intervention for gully erosion should focus on extending the vegetated area along the entire gully rather than increasing vegetation density in a specific area.

5. CONCLUSION

The current study presents a novel approach to model the effects of vegetation on mitigation of gully erosion, using Computational Fluid Dynamics (CFD). The vegetation area with various densities was modelled using porous media with various flow resistance coefficients (from 2 to 10 m^{-1}, 2 m^{-1} intervals). The vegetation length in a gully varied from 2 to 10 m (2 m intervals). The vegetation angle included 0^o, 30^o and 60^o, relative to the vertical axis. Volume of Fluid (VOF) model was employed to examine the variations in the water level (i.e. the interface between water/air phase) in a gully. A reference simulation case (i.e. gully without vegetation) was also undertaken. We found that vegetation changes significantly affected the hydrodynamics in a gully, including an increase of water level, decrease of flow velocity, and decrease of surface shear stress. Increasing vegetation density does not change significantly the water level in a gully but does increase the turbulence upstream of the vegetation. Flow velocity through the vegetation also decreases when the vegetation density increases. Changing the vegetation angle only reduces the turbulence upstream of the vegetation but does not change significantly the flow velocity and water level in the gully. Noticeably, we found that downstream of the vegetated area, the flow velocity and surface shear stress increase progressively. This implies that increasing the vegetated area in a gully is an important intervention to reduce the gully erosion. The results in the current study also emphasise that CFD could be an effective method to model the flow hydrodynamics and assist in the study of interventions for the mitigation of gully erosion.

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