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A preliminary erosion model for gullies with complex geometries

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Abstract:

INTRODUCTION AND RATIONALE

Alluvial gully erosion constitutes a significant proportion of the sediment load transported through the Great Barrier Reef catchment annually. Post-European land usage practices such as mining, deforestation and grazing have increased erosion rates (Bartley et al., 2018). There has recently been a focus on the development of process-based models for simulating single events in linear gullies in the form of MERGE (Roberts, 2020), in addition to classical models used for predicting large-scale landscape evolution on a decadal scale, e.g. Willgoose et al. (1991). However, the transformation of amphitheatre gullies and other complexes over single events remains largely unexplored (Roberts et al., 2022). Understanding these processes is essential for informing short-term management projects as well as supporting the validity of long-term approximations.

Amphitheatre gullies can be contrasted against their linear counterparts by two main features: (i) their geometry changes at comparable rates in both the x- and y-direction over a two-dimensional plane, and (ii) flow direction within the gully is primarily determined by their irregular boundary and internal obstructive features. We introduce a new modelling approach to capture erosion dynamics in these large systems. For this, the Saint-Venant's equations for shallow water flow are coupled with a modified two-dimensional version of MERGE.

FRAMEWORK AND METHODS

The MERGE equations are based on a differentiable conservation of mass framework, where the available erosion energy is a proportion of the potential energy lost as water moves downhill (Roberts, 2020). The resulting stream power equation $\Omega = |\mathbf{u}|\rho g S_{\mathbf{u}}$ [$\mathrm{W\,m^{-2}}$] has been adapted for the two-dimensional model, where ρ [$\mathrm{kg\,m^3}$] is the water density, g [$\mathrm{m\,s^{-2}}$] is gravitational acceleration and $S_{\mathbf{u}} = \left|\frac{(\nabla a \cdot \mathbf{u})\mathbf{u}}{|\mathbf{u}|^2}\right|$ [unitless] is the magnitude of the parallel component of the steepest slope ∇a [unitless] resolved onto the water flux vector $\mathbf{u}$ [$\mathrm{m^2\,s^{-1}}$]. Stream power, Ω, is nonzero only when water is moving downhill. This was used to determine

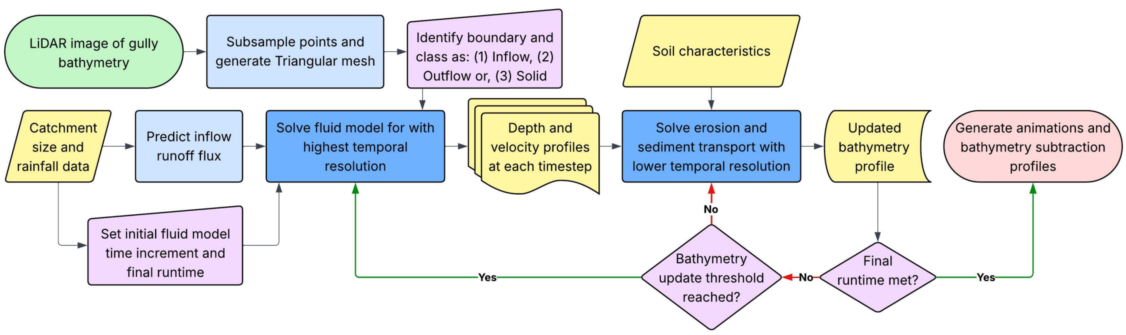

Figure 1. Workflow for modelling gully erosion as used in the Rosewood Gully case study.

the rate of sediment entrainment from the gully floor η_{ef} [kg m^{-2} s^{-1}] and, along with the soil bulk density σ [kg m^{-3}], the decrease in bathymetry height a [m] with time t, $\frac{\partial a}{\partial t} = -\frac{\eta_{ef}}{\sigma}$.

The resulting set of differential equations is coupled and solved numerically in a self-consistent manner. LiDAR bathymetry data is transformed into a triangular mesh for the fluid simulation. An HLLC Riemann solver described by Hou et al. (2015) and implemented in a public code repository has been adapted to incorporate a clean boundary influx and local outflux. This approach was selected for its capability to simulate the wetting and drying of the irregular terrain (Song et al., 2011) – a necessary feature for accurately representing the pedestals common in amphitheatre gullies. The sediment transport equations are solved by finite volume to compute sediment concentration in the water column, net displacement and transport. As the geometry of the gully changes with erosion, the profile is recursively updated for the fluid solver with the changing bathymetry (see Figure 1).

DISCUSSION AND CASE STUDY: ROSEWOOD GULLY

The model was trialled on a one-hectare gully at Duaringa, in Queensland's Central Highlands Region. The results allowed for the identification of regions of net erosion and deposition within a single gully over a simulated event cycle. This framework was designed to incorporate intervention strategies to develop tailored approaches for mitigating gully erosion. Solving the resulting optimisation problem will allow for localised minimum-cost remediation plans for stabilising whole gully networks and/or critical subsets.

Often, existing modelling strategies do not differentiate between the primary features – heads, walls and floors – whereas MERGE fits the erosion equations to match the characteristics of the feature being eroded. At the head, conditions are considered too energetic for deposition to occur. Along the walls, stream power is shared with the floor across a transect of the wetted perimeter (Roberts, 2020). This approach is not suited to two-dimensional modelling, as the stream power varies across a transect and the choice of transect position is inherently arbitrary. There is scope to develop a shear-based strategy to capture erosion when water is moving parallel to the steepest slope, where the stream power evaluates to zero W m^{-2}. We also plan to incorporate automatic identification of gully heads using characteristics such as sudden slope changes, and to explore mechanisms for head-cut retreat in later versions of the model.

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