



faDebrisFOAM: debris-flow modeling with coupled terrain evolution in OpenFOAM

Álvaro González¹, Alex Garcés², Aldo Tamburrino^{1,2}, and Santiago Montserrat²

¹Department of Civil Engineering, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Av. Blanco Encalada 2002, Santiago, Chile

²Advanced Mining Technology Center, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Av. Tupper 2007, Santiago, Chile

Correspondence: Alex Garcés (agarces@uchile.cl)

Abstract.

Debris-flow numerical models are widely used for hazard assessment and engineering design, yet many models still treat bed evolution in a simplified or uncoupled manner. This study presents *faDebrisFOAM*, an open-source depth-averaged solver developed in OpenFOAM® that couples debris-flow motion, entrainment, deposition, and terrain evolution within a finite-area framework. The model represents the mixture as an equivalent fluid of variable density and incorporates mass exchanges with an erodible bed layer through entrainment and deposition laws. The Terrain Modification Algorithm (TMA), developed in this work, updates the computational grid at each time step, allowing topographic changes to feed back directly into the governing equations and simulated flow dynamics. The model is evaluated through three applications: validation against large-scale US Geological Survey (USGS) flume experiments, testing in an idealized parabolic geometry, and application to the 2015 debris-flow event in the La Mesilla catchment in northern Chile. The solver reproduces the measured evolution of flow thickness in the USGS flume experiments with good agreement. The idealized application demonstrates that terrain evolution is not a passive output but an active control on run-out, velocity, flow depth, and volume redistribution. The La Mesilla case further shows that coupled terrain modification promotes surge self-generation, self-channelization, and channel-plug formation, which are absent or weakened when the TMA is disabled. These results indicate that coupled terrain evolution can modify flow confinement, stress distribution, and preferential routing throughout the simulation. *faDebrisFOAM* therefore provides an open-source framework for investigating morphodynamic feedbacks in debris-flow propagation.

1 Introduction

Numerical models are increasingly used to study debris-flow dynamics and estimate the magnitude of these events. Because they provide quantitative information on variables relevant to hazard assessment, they are useful for engineering design, risk reduction, and urban or territorial planning. However, assumptions and simplifications needed to describe such complex phenomena constrain their predictive capability and inevitably lead to discrepancies between simulations and reality. Over the last decades, there have been significant improvements in the understanding of entrainment and depositional processes in debris flows, mainly due to laboratory experiments and in situ field measurements collected around the world (Takahashi et al., 1992;



Major, 1997; Major and Iverson, 1999; Egashira et al., 2001; Rickenmann et al., 2003; Mangeney et al., 2010; McCoy et al., 2010; Iverson et al., 2011; Berger et al., 2011; Johnson et al., 2012; McCoy et al., 2012; De Haas et al., 2015; Hürlimann et al., 2019; Cabré et al., 2020; Aguilar et al., 2020). However, many aspects of this subject remain unclear, including identifying the processes involved in bed destabilization and the factors that determine erosion rate. This may explain why numerical models usually include them in a relatively simplified form (Bartelt et al., 2017; McDougall and Hungr, 2005; FLO-2D Software, Inc., 2009; D’Aniello et al., 2015; Uchida et al., 2013). Morphological changes in the bed layer caused by entrainment and deposition are also critical, but their evolution is commonly not coupled with flow simulation. Despite these limitations, modeling entrainment and deposition may have significant consequences for engineering structure design, hazard mapping, and the study of fluvial and alluvial dynamics.

Debris flows are mixtures of sediment and water that flow due to gravity. Frictional stresses within the fluid and solid phases, as well as between them, influence their dynamics (Iverson, 1997). Because these flows can reach considerable volumes and travel long distances, their adverse effects on humans and infrastructure are often substantial (Iverson, 2013). Moreover, debris-flow volume does not remain constant during propagation, as it may increase by an order of magnitude or more through entrainment of material along its path (Berger et al., 2011; McDougall and Hungr, 2005; Iverson, 2013). The entrained material, whose properties and composition may differ from those of the initial mixture, can modify the density, composition, and rheology of the flow (Iverson, 2013; McDougall and Hungr, 2004, 2005). In general, entrainment tends to dominate on steep slopes, whereas deposition prevails on gentler ones (Iverson, 2013; Hungr et al., 2005). Material deposition can affect flow dynamics by enhancing or reducing flow mobility, depending largely on the mixture’s heterogeneity and the characteristics of the deposited sediments (De Haas et al., 2015). Therefore, debris-flow numerical models should incorporate both processes and their consequences for the terrain to better represent flow trajectories and hazard assessment (Berger et al., 2011; McDougall and Hungr, 2005).

This work develops an open-source finite-area solver that integrates entrainment, deposition, and bed evolution into debris-flow modeling. The novelty of *faDebrisFOAM* lies in its coupled treatment of debris-flow motion, entrainment, deposition, and terrain evolution within a depth-averaged numerical framework. Unlike most existing debris-flow models, *faDebrisFOAM* modifies the computational domain during the simulation due to mass exchanges between the flow and the erodible bed. This coupling allows the topography to feed back into the governing equations, directly influencing flow dynamics, stress distributions, and routing over complex terrain. Building on this formulation, the present study addresses the following research question:

- How does coupled terrain modification influence debris-flow dynamics?

This paper is organized as follows. Section 2 presents the formulation of the governing equations, including a flow-like boundary condition and the Terrain Modification Algorithm (TMA), which enables dynamic grid evolution in response to entrainment and deposition. Section 3 presents three applications of the solver: validation against large-scale USGS flume experiments, testing in an idealized synthetic geometry, and testing in a real debris-flow event in northern Chile. The results and implications of these applications are discussed in Sect. 4, followed by the main conclusions in Sect. 5.



2 Modeling approach

The system of equations implemented in `faDebrisFOAM` describes the motion of shallow debris flows over a slightly curved three-dimensional surface. Under the shallow-flow assumption, one spatial dimension can be eliminated by depth-averaging the conservation equations. A special case of the Shallow Water Equations is the so-called Savage-Hutter model (Savage and Hutter, 1989, 1991), in which the depth-averaging procedure is formulated with respect to the local surface-normal direction, and the velocity vector is forced to be surface-tangential. The water–sediment mixture is represented as an equivalent single-phase fluid (Hungr, 1995), with constant density within each control volume, but it varies spatially and temporally due to water and sediment exchanges. The resulting governing equations are discretized and solved in OpenFOAM® using the finite-area method (Tuković, 2005; Tuković and Jasak, 2012).

The governing equations follow the approach of Rauter and Tuković (2018), who reformulated the Savage-Hutter model to express the equations in a global Cartesian coordinate system, with surface alignment enforced via normal and tangential projection operators. This allows the depth-averaged flow velocity to remain a three-dimensional vector. As a result, the governing equations can be written without explicit curvature terms, which are difficult to evaluate on unstructured grids typically used to represent complex natural topography (McDougall and Hungr, 2005; Bartelt et al., 2017). In this study, all vector quantities are denoted in bold italics.

OpenFOAM® is an open-source C++ library developed to solve a wide range of problems in computational fluid dynamics. OpenFOAM® users can use and/or modify the finite area library (FA) like other solvers and utilities. One of the primary benefits of this software is that the discretization of the computational domain, the discretization of the PDEs, and the methods used to solve the resulting matrix equations are independent. This offers excellent versatility, as different discretization methods can be used for each problem.

The OpenFOAM® solver `faSavageHutterFOAM` (Rauter et al., 2018) was used as the starting point in the development of `faDebrisFOAM`. However, some significant modifications were introduced: (1) variable density of the equivalent fluid; (2) the bottom surface of the control volume is defined as mobile; (3) the implementation of debris flow entrainment, deposition, and friction model equations; (4) the implementation of flow-like boundary conditions; and (5) the implementation of a Terrain Modification Algorithm (TMA). While the first three topics are explained in Sect. 2.1, the flow-like boundary condition and the TMA are introduced in Sects. 2.2 and 2.3, respectively.

In the literature, the term “deposition” often refers to two distinct processes. The first is the material loss from the flowing mixture as it moves into the bed layer. This process has been measured and observed in field events (Berger et al., 2011; Hungr et al., 2005; McCoy et al., 2012; Schürch et al., 2011) and in experimental setups (De Haas et al., 2015; Major, 1997; Egashira et al., 2001). The second process refers to the flow detention in zones with gentle slopes and/or loss of confinement (Hungr et al., 2005; VanDine, 1996). Numerical models include the first process as a deposition rate, analogous to a negative entrainment rate (Iverson, 2012). In contrast, the second process is dominated by a resistance law, typically including a yield stress or a Coulomb friction term. Some models additionally impose an explicit stopping criterion, based for example on a flow velocity or momentum threshold, to prevent unrealistic persistent low-velocity creeping.

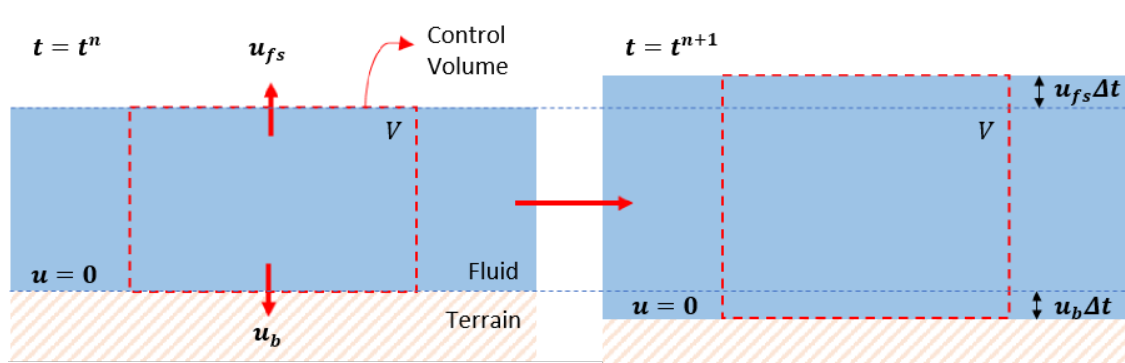


Figure 1. The control volume (red dotted line) changes as a function of the lower surface velocity u_b and the free surface velocity u_{fs} . $t^{n+1} = t^n + \Delta t$, with Δt the time step.

The entrainment and depositional processes are included in the equations of motion as mass exchanges between the flow and the erodible bottom layer. Beyond changing the flow volume, these processes modify the terrain geometry, thereby affecting flow dynamics.

95 We derive the system of equations using a control volume where the flow velocity u is zero at the lower surface, and the flow-free surface determines its upper limit (Fig. 1). As a result, the control volume encompasses the entire fluid column, simplifying the interface between the flow and the terrain. Thus, the mass and momentum fluxes into and out of the control volume are through the lateral faces. Figure 1 shows how the bed material is incorporated into the flow at time $t^{n+1} = t^n + \Delta t$ by moving down its lower surface. The incorporated volume, previously at rest, must be accelerated because it is now located
 100 above the $u = 0$ limit. Thus, control-volume modifications affect both the continuity and momentum equations.

2.1 Governing equations

The system of equations is derived from the conservative differential equations of mass and momentum on a grid element of basal surface S_B and normal vector n_b . The S_B element, of any arbitrary number of sides, is part of a curvilinear three-dimensional surface (Fig. 2).

105 Equation (1) represents the mass continuity equation of the water–sediment mixture, accounting for temporal variations of flow depth and mass exchanges with the erodible bed. Equation (2) is the corresponding continuity equation for the water phase, which governs the evolution of the volumetric water concentration within the mixture. Equation (3) expresses the tangential projection of momentum conservation in Cartesian coordinates, projected through tangential operators. Equation (4) corresponds to the normal projection of the momentum conservation in Cartesian coordinates and is used to compute the basal
 110 pressure acting on the bed. Finally, Eq. (5) represents the sediment mass balance of the erodible bed layer, describing its temporal evolution due to entrainment and deposition.

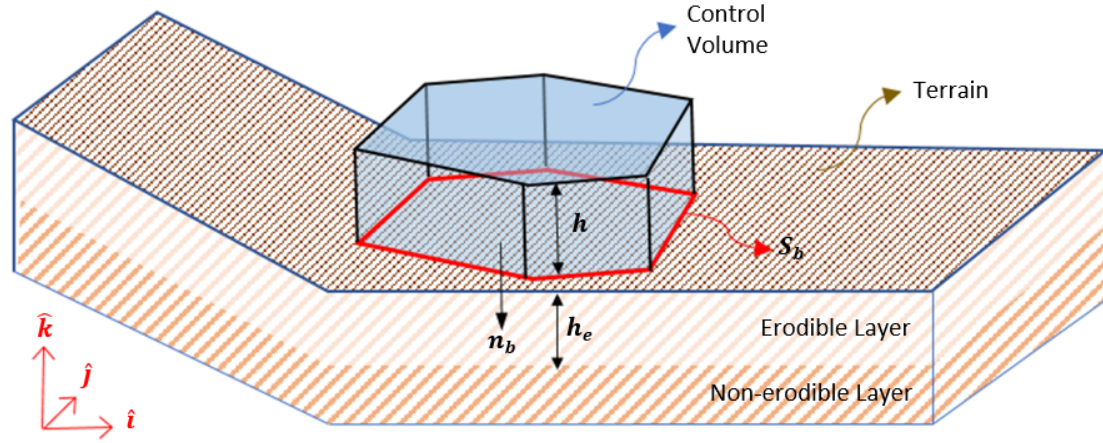


Figure 2. Example of a control volume used to deduce the system of equations.

$$\frac{\partial(\rho h S_B)}{\partial t} + \int_{S_b} \nabla \cdot (\rho h \bar{\mathbf{u}}) dS = \rho_b u_b S_B \quad (1)$$

$$\frac{\partial(C_w h S_B)}{\partial t} + \int_{S_b} \nabla \cdot (C_w h \bar{\mathbf{u}}) dS = C_{w,b} u_b S_B \quad (2)$$

$$\frac{\partial(\rho h \bar{\mathbf{u}} S_B)}{\partial t} + \int_{S_b} \chi \nabla_s \cdot (\rho h \bar{\mathbf{u}} \bar{\mathbf{u}}) dS = \rho h \mathbf{g}_s S_B - \tau_b S_B - \frac{1}{2} \int_{S_b} \nabla_s (p_b h) dS \quad (3)$$

$$115 \quad p_b = \mathbf{n}_b \left(\rho h \mathbf{g}_n - \frac{1}{S_B} \int_{S_b} \chi \nabla_n \cdot (\rho h \bar{\mathbf{u}} \bar{\mathbf{u}}) dS - \frac{1}{2 S_B} \int_{S_b} \nabla_n (p_b h) dS \right) \quad (4)$$

$$\frac{\partial(h_e S_B)}{\partial t} = -u_b S_B \quad (5)$$

The unknown flow fields, which are defined at the element centroids and are variable in time (t), are ρ , the mixture density; C_w , the volumetric concentration of water; h , the flow height measured normal to the surface; $\bar{\mathbf{u}}$, the depth-averaged flow velocity constrained to be tangent to the terrain surface; p_b , the basal pressure; and h_e , the erodible sediment layer thickness
 120 (defined as a non-negative value).

In these equations, S_b represents the boundary of the bottom surface S_B . ∇ is the differential operator, where $\nabla_s = (\mathbf{I} - \mathbf{n}_b \mathbf{n}_b) \cdot \nabla$ and $\nabla_n = (\mathbf{n}_b \mathbf{n}_b) \cdot \nabla$ are, respectively, the tangential and normal components to the surface, with $\mathbf{I}$ the identity



matrix. Analogously, the tangent and normal components of the gravitational acceleration vector are defined as $\mathbf{g}_s = (\mathbf{I} - \mathbf{n}_b \mathbf{n}_b) \cdot \mathbf{g}$ and $\mathbf{g}_n = (\mathbf{n}_b \cdot \mathbf{n}_b) \mathbf{g}$.

125 The volumetric concentration of water in the mixture is C_w , whereas $C_{w,b}$ denotes the water volumetric concentration of the erodible bed material; both are assumed uniform in the surface-normal direction. The coefficient χ is a shape factor accounting for the vertical velocity profile, defined through $\overline{u u} = \chi \overline{u} \overline{u}$ (Rauter and Tuković, 2018). $\boldsymbol{\tau}_b$ is the basal shear stress vector opposing the flow motion. The erodible sediment layer thickness is denoted by h_e , and its temporal evolution is governed by the normal velocity of the lower control-volume boundary, u_b , which represents the net effect of entrainment and deposition
130 processes.

C_w and ρ are related by Eq. (6), where ρ_w is the water density and ρ_s the sediment density, both constants. This equation also relates the bed density ρ_b and its volumetric water concentration $C_{w,b}$, both of which are constant.

$$\rho = C_w \rho_w + (1 - C_w) \rho_s \quad (6)$$

The entrainment and depositional processes are incorporated into the model by u_b , the velocity of the control volume lower
135 surface, defined in the direction of $\mathbf{n}_b$ (see Fig. 1). This velocity is calculated with Eq. (7), where $u_{b,E}$ is the entrainment rate and $u_{b,D}$ the deposition rate, both defined as non-negative. These rates come from experimental or field measurements (Berger et al., 2011; Iverson et al., 2011; McCoy et al., 2012; Fagents and Baloga, 2006). The basal shear stress $\boldsymbol{\tau}_b$ must be incorporated by assuming a resistance law (Salm, 1993; O'Brien et al., 1993).

$$u_b = u_{b,E} - u_{b,D} \quad (7)$$

140 The assumptions used in the deduction of Eqs. (1) to (5) are: (1) water-sediment mixture is represented as an equivalent fluid of variable density; (2) the equivalent fluid density does not change in the surface-normal direction; (3) the vertical velocity profile can be represented by the shape-factor χ ; (4) pressure is assumed as hydrostatic (McDougall and Hung, 2004); (5) the velocity vectors are tangent to the surface, this is enforced by the boundary condition $\overline{\mathbf{u}} \cdot \mathbf{n}_b = 0$; (6) mass fluxes between the flow and the terrain have density ρ_b ; (7) the equivalent fluid is a continuum and isothermal medium; (8) shear stresses in the
145 free surface are zero.

Since the deduced system of equations is non-linear and highly coupled, it must be solved sequentially and iteratively. First, the normal component of the momentum equation (Eq. (4)) is solved, followed by its tangential component (Eq. (3)), obtaining the values of p_b and $\overline{\mathbf{u}}$, respectively. Then, both continuity equations (Eqs. (1) and (2)) are solved simultaneously, using (ρh) and $(C_w h)$ as variables. The values of C_w , ρ and h are then calculated using Eqs. (6) and (8). This procedure must be repeated
150 until a convergence criterion is reached. Since the continuity equation of the erodible bed layer (Eq. (5)) is not coupled to the rest of the system, it can be solved once the other four equations have converged.

$$C_w = \frac{\rho_s}{(\rho h) / (C_w h) + (\rho_s - \rho_w)} \quad (8)$$



Although no inferior limit is imposed for C_w in Eq. (8), it is clear that $C_w = 1 - C_v$ and that the volumetric concentration of sediment, C_v , rarely surpasses values around 0.8 (Iverson, 1997; FLO-2D Software, Inc., 2009). When assigning $C_{w,b}$ values in the initial and boundary conditions, this limit must be considered.

2.1.1 Resistance laws

In the deduction of Eqs. (3) and (4), the total stress tensor is calculated as $\mathbf{T} = \boldsymbol{\tau} - p\mathbf{I}$, with $\boldsymbol{\tau}$ the deviatoric stress tensor and p the pressure. The scale analysis shown by González Bilbao (2021) demonstrates that the most important term in the deviatoric stress tensor is the basal shear stress τ_b , which acts in the opposite direction to the flow. Basal shear stress is usually represented using resistance laws, which merge all stresses in the mixture into a single term (Iverson, 2005). We introduce two commonly used resistance laws below.

The first resistance law is the Voellmy-Salm model, initially used for snow avalanche simulations. In Eq. (9), μ is related to the dry-Coulomb friction term, and ξ is associated with the turbulent stresses. Both parameters must be calibrated (Bartelt et al., 2017; Salm, 1993). Note that these parameters are independent of the mixture's sediment concentration.

$$\tau_b = \mu p_b \frac{\bar{u}}{|\bar{u}|} + \frac{\rho g}{\xi} |\bar{u}| \bar{u} \quad (9)$$

The quadratic model (Eq. (10)) was developed for debris flows, where the yield stress (τ_y) and dynamic viscosity (η) vary exponentially with sediment concentration. K and n are parameters that depend on the geometry and roughness of the channel (O'Brien et al., 1993).

$$\tau_b = \tau_y \frac{\bar{u}}{|\bar{u}|} + \frac{K\eta}{8h} \bar{u} + \frac{n^2 \rho g}{h^{1/3}} |\bar{u}| \bar{u} \quad (10)$$

2.1.2 Entrainment and deposition rates

The model incorporates entrainment and deposition rates, denoted as $u_{b,E}$ and $u_{b,D}$, respectively. As with basal shear stress, these rates are implemented using equations from the literature. For instance, *faDebrisFOAM* includes the entrainment model presented by McDougall and Hungr (2005) (Eq. 11), which requires the calibration of a parameter E . This model assumes a natural exponential growth with displacement and is therefore referred to as the Exponential model. *faDebrisFOAM* also incorporates entrainment model proposed by Frank et al. (2015) (Eqs. 12 and 13). We call it the RAMMS entrainment model because it was initially developed for the RAMMS software. This model determines the entrainment rate by a constant value E_R . Material is entrained only if the actual erosion depth e_t is smaller than the maximum potential erosion depth e_m . The maximum potential erosion depth is calculated using the critical shear stress τ_c and a potential erosion depth $dz/d\tau$, both constant parameters that the user can modify.

$$u_{b,E} = Eh|\bar{u}| \quad (11)$$



$$e_m = \begin{cases} 0, & \text{for } |\tau_b| < \tau_c, \\ \frac{dz}{d\tau} (|\tau_b| - \tau_c), & \text{for } |\tau_b| \geq \tau_c. \end{cases} \quad (12)$$

$$u_{b,E} = E_R \quad \text{for } e_t \leq e_m \quad (13)$$

Equation (14) was presented by Fagents and Baloga (2006) to calculate deposition rates applicable to debris flows initiated as lahars. In this equation, v_s is a characteristic settling velocity.

$$185 \quad u_{b,D} = v_s C_v \quad (14)$$

Here, we present only two entrainment models and one deposition model. The remaining models available in `faDebrisFOAM` (Cao et al., 2004; Egashira et al., 2001; Takahashi, 1991) can be reviewed in González Bilbao (2021).

2.2 Hydrograph boundary condition

In `faDebrisFOAM`, debris flows can be generated from a static initial volume that accelerates due to gravity or from a variable
190 discharge hydrograph introduced as an inflow boundary condition. The first option was inherited from `faSavageHutterFOAM` (Rauter et al., 2018) and has been widely used in debris-flow and snow-avalanche models (McDougall and Hungr, 2005; Bartelt et al., 2017; Mergili et al., 2017). The second possibility was developed for `faDebrisFOAM` and corresponds to a hydrograph defining a second-order boundary condition. Just as FLO-2D (FLO-2D Software, Inc., 2009) and RAMMS (Bartelt et al., 2017), the hydrographs are lists of an unlimited number of (Q, C_v, t) values, with Q the debris-flow discharge and C_v the
195 volumetric concentration of sediments. Since Q is not present in the deduced system of equations, it must be incorporated into the model through h and $\bar{u}$. The ρ and C_w values in the boundary conditions are directly calculated from the C_v values in the hydrograph data.

At the inlet, which consists of N elements along the boundary of the numerical grid, the flow rate Q at any time t is calculated using Eq. (15). Here, h_j and v_j are the flow height and velocity at element j , respectively, while b_j and $\hat{e}_j$ denote the element
200 width and unit normal vector.

$$Q = \sum_{j=1}^N Q_j = \sum_{j=1}^N b_j h_j v_j \cdot \hat{e}_j \quad (15)$$

To calculate the h_j and v_j values in every boundary element, it is assumed that $h_j = \bar{h}$, with $\bar{h}$ an average height; and that v_j is calculated by Eq. (16), where $\bar{v}$ is an average velocity and $\hat{e}$ is the unit vector that points in the flow direction.

$$v_j = \frac{\bar{v}}{|\hat{e} \cdot \hat{e}_j|} \hat{e} \quad (16)$$



205 Replacing in Eq. (15), a relation between Q and the unknown variables $\bar{h}$ and $\bar{v}$ is obtained, with $B = \sum_j b_j$ the boundary total width.

$$Q = \sum_{j=1}^N b_j \bar{h} \left(\frac{\bar{v}}{|\hat{\mathbf{e}} \cdot \hat{\mathbf{e}}_j|} \hat{\mathbf{e}} \cdot \hat{\mathbf{e}}_j \right) = B \bar{h} \bar{v} \quad (17)$$

We impose the normal flow condition on the boundary to obtain the missing equation. This is equivalent to neglecting the spatial and temporal partial derivatives in Eq. (3). Thus, Eq. (18) relates $\bar{h}$ and $\bar{v}$ using the selected resistance law for the basal shear stress τ_b .

$$|\tau_b(\bar{h}, \bar{v})| = \rho \bar{h} |\mathbf{g}_s| \quad (18)$$

Although this approach of defining a flow-like boundary condition from a hydrograph is straightforward, the problem is that a constant $\bar{h}$ does not represent the free surface of the flow as a horizontal plane. To correct this problem, h_j is redefined as $h_j = z_{fs} - z_j$, with z_{fs} the altitude of the flow free surface and z_j the altitude of the centroid of any element j . By replacing this in Eq. (15), a single value for z_{fs} is obtained for all h_j values. This procedure results in boundary conditions for the discharge Q and the free-surface altitude z_{fs} .

$$z_{fs} = \frac{(Q/\bar{v}) + \sum_{j=1}^N b_j z_j}{B} \quad (19)$$

2.3 Terrain Modification Algorithm

Entrainment and depositional processes alter terrain geometry, thereby modifying flow routing, stress distributions, and run-out behavior. To account for this interaction, faDebrisFOAM incorporates a Terrain Modification Algorithm (TMA) that updates the basal surface geometry during the simulation, ensuring full coupling between flow dynamics and bed evolution.

The TMA operates on the basis of the erodible sediment layer mass continuity (Eq. 5). After convergence of the governing equations at a given time step, the normal velocity of the lower control-volume surface, u_b , is used to compute the change in erodible-layer thickness Δh_e within each grid element. This thickness change defines a corresponding volumetric variation ΔV_j for element j associated with entrainment or deposition during the time step.

The computational domain is discretized into non-overlapping convex polygonal elements defined by their vertices (Fig. 3). Terrain modification is achieved by updating the vertical position of the vertices such that the geometric volume change (ΔV_j^*) induced in each element matches the volume variation prescribed by ΔV_j . In this manner, local mass conservation in the erodible bed layer is enforced directly through geometry modification rather than through source terms or post-processing corrections. For time step t^n , the position vector of any vertex i is named $\mathbf{r}_i^n$. The TMA calculates a new set of vectors $\mathbf{r}_i^{n+1}$ in each time step that satisfies the equation $\Delta V_j = \Delta V_j^*$ across the entire grid.

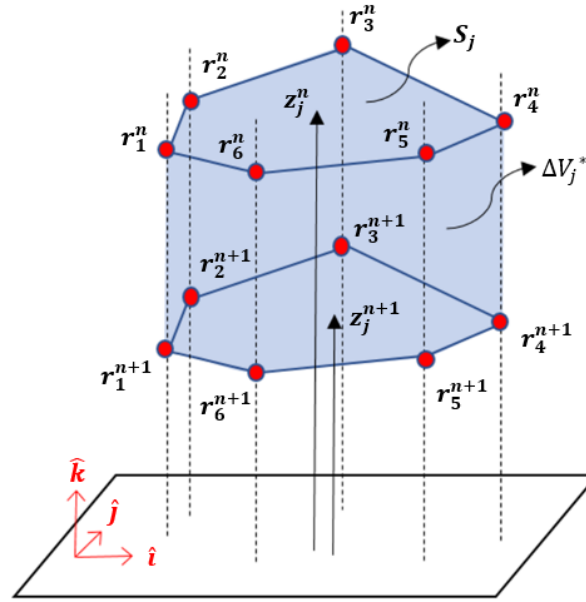


Figure 3. Vertical movement of grid vertices for a hexagonal element. The defined volume ΔV_j^* is shown in blue. z_j^n and z_j^{n+1} are the centroid altitudes of the surfaces defined in times t^n and t^{n+1} .

The updated vertex positions define a new basal surface geometry for the subsequent time step. As a consequence, geometric quantities entering the governing equations, including the basal surface normal vector $\mathbf{n}_b$, element area S_B , and the tangential and normal components of gravity ($\mathbf{g}_s$ and $\mathbf{g}_n$), are recalculated. This allows terrain evolution to feed back into the momentum
 235 balance and continuity equations, influencing flow acceleration, confinement, and routing. Appendix A provides the detailed implementation of the TMA.

2.4 Solver internal performance

The system of equations of `faDebrisFOAM` is solved over a three-dimensional curved surface generated from a raster file. Using the `pMesh` utility, a polyhedron formed by a finite number of three-dimensional elements is created (Juretić, 2015).
 240 Then, the `makeFaMesh` utility extracts the terrain topography, defining the curved three-dimensional surface that serves as the numerical grid in the finite area method.

As part of this work, we developed the OpenFOAM® utility `setInitialConditions`, using the utility `releaseAreaMapping` (Rauter et al., 2018) as a starting point. This utility implements the initial and boundary conditions required for any debris flow simulation. The OpenFOAM® library `faDebrisFlow` was also created to include some friction, entrainment, and deposition
 245 models found in the literature for debris flows. All the models in the library can be used in `faDebrisFOAM`.

The transient terms are discretized using the second-order, stable Adams–Moulton scheme (Moukalled et al., 2016). The gradient terms associated with the basal pressure in the PDEs are explicitly discretized using the Gauss method with linear



interpolation. Advective terms are also discretized using the Gauss method, although implicitly, while the selected interpolation scheme is the upwind scheme. The matrix equations deduced from Eqs. (1)–(3) are solved using the gradient method
250 PBiCGStab (Van der Vorst, 1992) preconditioned with the DILU method (Pommerell, 1992) and using implicit relaxation (Moukalled et al., 2016).

The PDEs are solved sequentially at each time step until convergence. Since Eq. (5) is solved in the last position and Eq. (4) is directly solved, only Eqs. (1)–(3) are relevant to define the stopping criterion of the iterative procedure. Before solving any of these equations, the initial residuals $r^{\bar{u}}$, $r^{\rho h}$, and $r^{C_w h}$ are calculated. The sequential iterative method converges when all
255 the r^ϕ values drop below a limit value $r_{\max}^\phi$. Once the system has converged, the grid is modified if the TMA is activated. Finally, the Courant number criterion calculates a new time step value Δt , and a new iteration starts at time $t^{n+1} = t^n + \Delta t$.

3 Applications

3.1 Solver validation: USGS flume experiment

The solver is validated by reproducing the large-scale debris-flow experiments conducted in the USGS flume (Iverson et al.,
260 2010). The USGS experimental setup consists of a straight, rectangular concrete channel measuring 95 m in length, 2 m in width, and 1.2 m in depth. The channel slope is $\theta = 31^\circ$ for the first 74 m, transitioning smoothly to $\theta = 2.4^\circ$ toward a nearly planar concrete run-out surface. In the experiments, approximately 10 m^3 of saturated, poorly sorted sand–gravel material was released behind a headgate. Flow thickness time series were measured at instrumented cross sections located at $x = 32 \text{ m}$, 66 m , and 90 m downstream of the gate.

265 The numerical setup reproduces the experimental geometry and initial released volume. Basal resistance is modeled using a Voellmy–Salm friction law (Salm, 1993; Bartelt et al., 2017). We conducted a series of simulations to calibrate the friction parameters needed to match the experimental results for the SGM rough-bed experiments. The calibrated values are $\mu = 0.05$ and $\xi = 1200 \text{ m s}^{-2}$ in the upper channel section, and $\mu = 0.10$ and $\xi = 200 \text{ m s}^{-2}$ in the deposition zone. We disable entrainment, deposition, and the TMA in this simulation to remain consistent with the rigid-bed experimental configuration.

270 We evaluate model performance using arrival time, peak flow thickness, and the overall shape of the stage-time graphs. The simulations reproduce the flow-front timing and the downstream attenuation of peak thickness between $x = 32 \text{ m}$ and 66 m with good agreement. At $x = 90 \text{ m}$, the model captures the general magnitude of flow thickness but does not reproduce the peak observed in the experiments, which may be associated with surge-like behavior.

Overall, the comparison in Fig. 4 shows that the solver is able to reproduce the main flow dynamics and evolution of
275 flow thickness observed in the USGS flume experiments. The discrepancy in the lowest section suggests a limitation of the simulation, probably associated with the formation of roll waves (Meng et al., 2025).

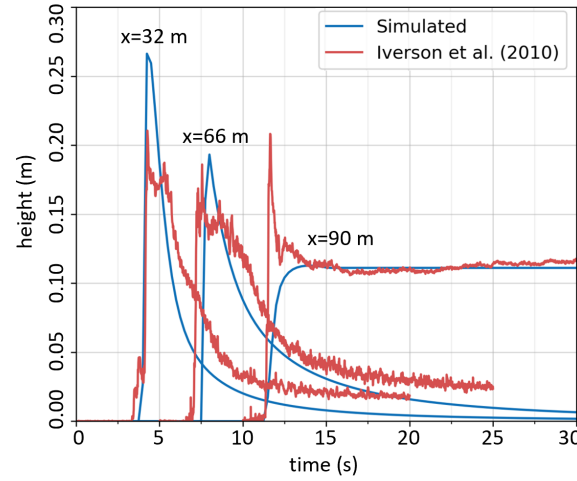


Figure 4. Comparison of flow heights simulated by *faDebrisFOAM* and measured in the USGS flume experiment at locations $x = 32$ m, 66 m, and 90 m.

3.2 Simple parabolic-shaped geometry

faDebrisFOAM was tested using a simple parabolic-shaped geometry that represents an idealized channel with a longitudinal profile composed of two constant slope sections, $\alpha_1 = 10^\circ$ and $\alpha_2 = 20^\circ$, connected by a smooth parabolic curve. The cross-section starts upstream as a concave curve that gradually flattens downstream. Equation (20) defines the topography over the domain $[x, y] \in [0, L_x] \times [0, L_y]$, where $L_y = 1500$ m, $L_x = 150$ m, $L_m = 500$ m, and $A_1 = 50$ m. The resulting geometry is shown in Fig. 5.

$$z(x, y) = \begin{cases} \tan(\alpha_1)y - A_1 \sin\left(\frac{x\pi}{L_x}\right) \sin\left(\frac{y\pi}{2L_y}\right), & \text{for } y \leq L_m, \\ \frac{\tan(\alpha_2) - \tan(\alpha_1)}{2(L_y - L_m)}(y - L_m)^2 + \tan(\alpha_1)y - A_1 \sin\left(\frac{x\pi}{L_x}\right) \sin\left(\frac{y\pi}{2L_y}\right), & \text{for } y > L_m. \end{cases} \quad (20)$$

Three scenarios—R1, R2, and R3—were designed to evaluate the effects of different friction and entrainment model parameters and the implementation of the TMA. The objective of this application is not to perform parameter calibration but to investigate how these model features influence flow behavior. All simulations use the Exponential entrainment model (McDougall and Hungr, 2005), the Fagents–Baloga deposition model (Fagents and Baloga, 2006), and the Voellmy–Salm friction model (Salm, 1993; Bartelt et al., 2017). Table 1 summarizes parameter values based on those reported by other studies (Bartelt et al., 2017; McDougall and Hungr, 2005; Fagents and Baloga, 2006; Cascini et al., 2014). The TMA is activated in scenarios R1 and R3 with default parameters. Scenarios R2 and R3 share identical parameters; however, the TMA is only activated in R3. We omitted a simulation without TMA using the same parameters as R1 because the results are nearly identical. The inflow boundary condition is a four-point hydrograph with a peak discharge of $80 \text{ m}^3 \text{ s}^{-1}$ (Fig. 6). The simulation duration is 1400 s,

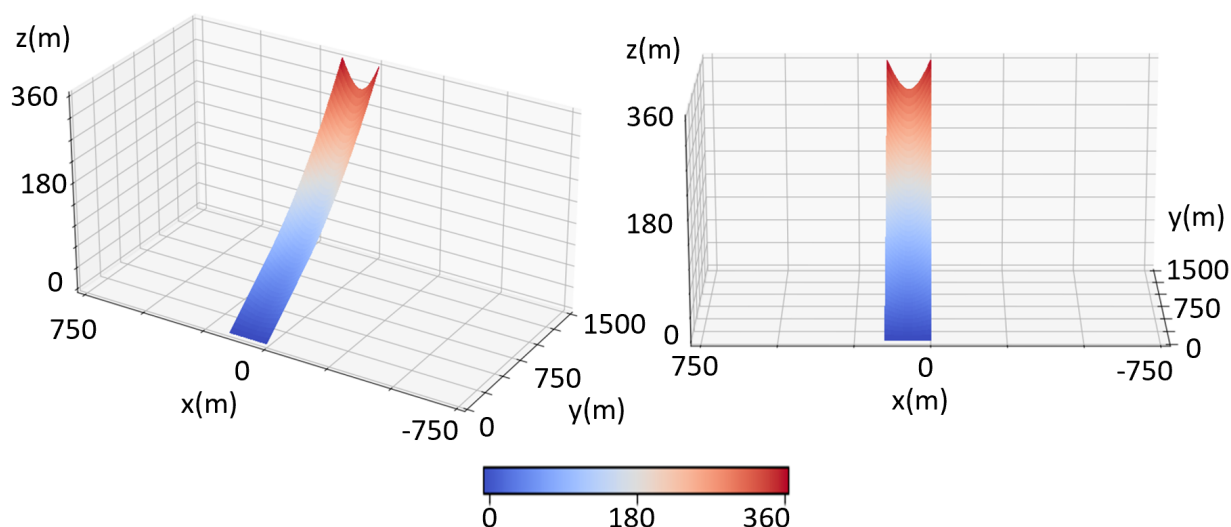


Figure 5. Simple parabolic-shaped geometry.

Table 1. Model coefficients for scenarios R1, R2 and R3.

	Friction (Voellmy–Salm)		Entrainment (Exponential)		Deposition (Fagents–Baloga)	
	μ (-)	ξ (m s^{-2})	E (m^{-1})	τ_c (kPa)	v_s (m s^{-1})	TMA
R1	0.20	200	0.002	1.0	0.01	on
R2	0.15	400	0.005	1.0	0.01	off
R3	0.15	400	0.005	1.0	0.01	on

with flow input restricted to the first 200 s, allowing the model to simulate flow detention. The initial erodible sediment layer thickness h_e was set uniformly to 2 m across the whole domain.

295 Typical outputs of debris flow models include maps of flow height and velocity, which are essential for hazard assessment (Hürlimann et al., 2008). These maps are also useful for back-analysis, calibration, and reproducing past debris-flow events (Zegers et al., 2020; Garcés et al., 2022). Maximum flow height h and velocity $|\bar{u}|$ for scenarios R1–R3 are shown in Fig. 7. All cases yield symmetric flow patterns, and the flow stops before reaching the downstream boundary, forming a depositional lobe. Scenario R1 yields the lowest values of $h_{\max}$, $|\bar{u}|_{\max}$, run-out distance δ_y , and relative volume change ΔV , compared to
 300 R2 and R3 (Table 2). Volumetric change is expressed relative to the inflow volume V_{in} as $\Delta V = V_{\max}/V_{\text{in}}$. Run-out distance δ_y is the maximum downstream distance reached by the center of mass.

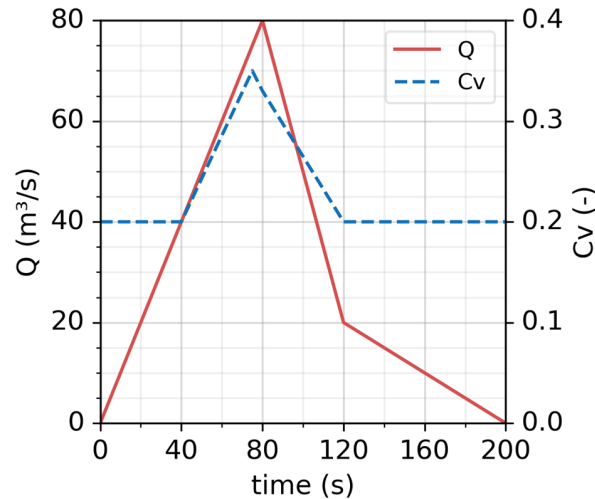


Figure 6. Four-point hydrograph defined at the inlet boundary.

Table 2. Results for scenarios R1, R2, and R3.

	$h_{\max}$ (m)	$ \bar{u} _{\max}$ (m s ⁻¹)	δ_y (m)	ΔV (-)	Δh_e (m)	Δz (m)
R1	2.0	5.7	675	1.4	–	[–0.85, 1.46]
R2	5.5	8.6	985	10.7	[–1.97, 3.28]	–
R3	6.2	9.2	945	8.7	–	[–2.05, 4.10]

The bottom row of Fig. 7 shows the topographic change at the end of the simulation ($t = 1400$ s). In cases R1 and R3, these changes are real terrain changes (Δz) since the TMA was active. For R2 (TMA off), it represents the calculated entrained and deposited thickness (Δh_e), which does not affect the terrain topography throughout the simulation. Differences between R2 (TMA off) and R3 (TMA on) show the self-channelization in R3, where erosion concentrates at the center (Fig. 7), increasing both flow height and velocity. Toward the sides, flow height and velocity decrease, reducing $|\tau_b|$ below its critical threshold, deactivating entrainment and initiating deposition. Downstream, the TMA forms a depositional lobe in R3, forcing the flow to divert around the deposit and promoting erosion along the lobe margins.

Figure 8 shows the evolution of flow, topography, and basal shear stress $|\tau_b|$ across cross-section $y = 500$ m for scenario R3 at four time steps: 180s, 240s, 720s, and 1400s. At 180s, the front reaches the cross-section with $|\bar{u}| = 4.5$ – 5.0 m s⁻¹ and minor erosion begins. By 240s, $\Delta z = -1.5$ m at the center, flow height rises to 5m, and velocity drops to around 0.5 m s⁻¹. Deposition initiates at the center while the flanks remain more mobile, creating lateral erosion paths. By 720s, deposition dominates the center, while erosion continues at the flanks, with velocities of 1.5 – 2.0 m s⁻¹. At 1400s, the flow has ceased and material has stopped.

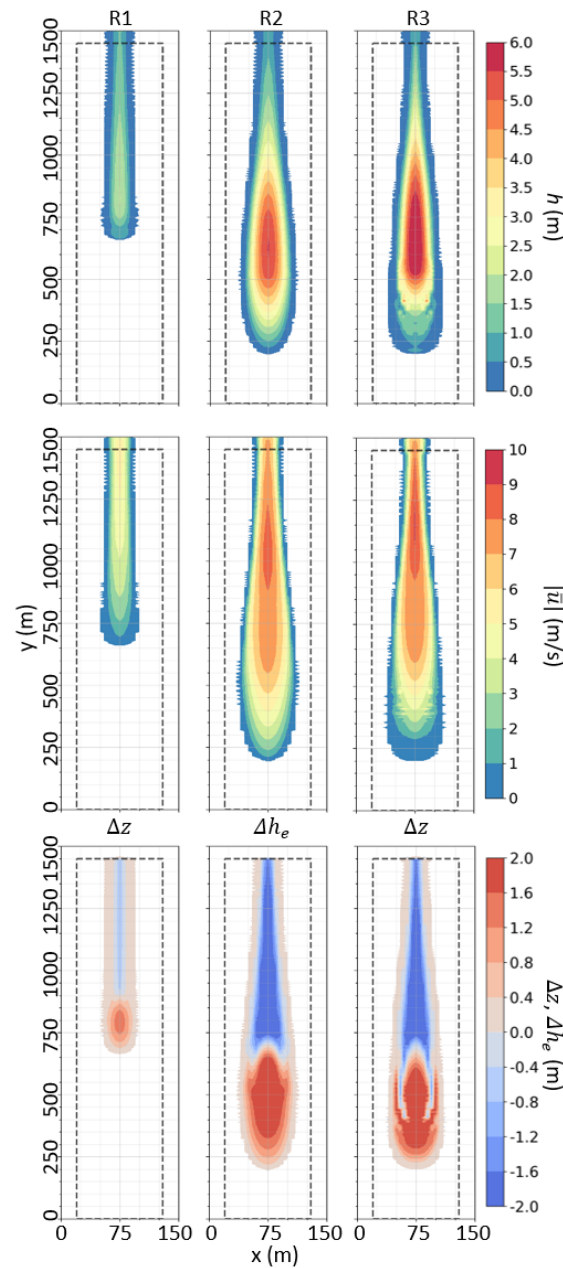


Figure 7. Simulation results for R1 (left), R2 (center), and R3 (right). Top row: max flow height (h). Middle row: max velocity ($|\bar{u}|$). Bottom row: terrain change Δz for R1 and R3, and entrainment/deposition thickness Δh_e for R2. Positive values represent deposition; negative values represent erosion for R1 and R3, and entrainment for R2. The black dashed rectangle denotes the active zone for entrainment/deposition.

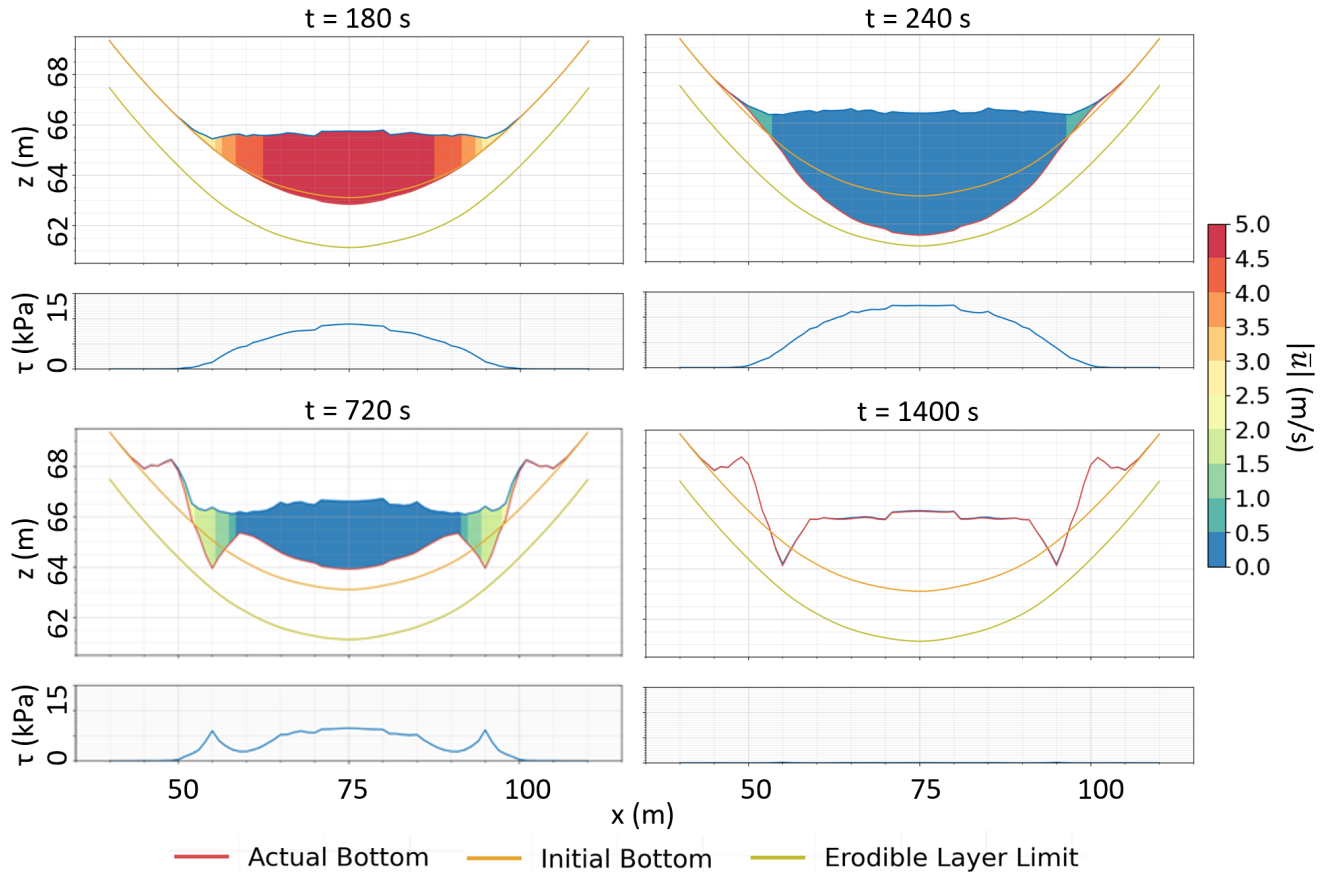


Figure 8. Flow and topographic development for scenario R3 at cross-section $y = 500$ m. Panels depict results at different time steps. $|\tau_b|$ variation is shown in the bottom row. The horizontal-to-vertical ratio is 4 : 1 for better visualization.

Figure 9 shows the time evolution of entrained, deposited, and net volume changes in scenario R3. Values are integrated over the entire domain. Inflows are negative, and outflows are positive. The peak discharge at the inflow boundary condition occurs at 80s, and flow stops at 200s (see Fig. 6). The total volume increases until 220s, after which deposition dominates. Peak entrainment occurs at 150s, with a second phase between 600s and 850s, corresponding to the flow diversion around the downstream depositional lobe and consequent erosion along the lobe margins. Notably, total entrained volume exceeds the hydrograph inflow volume by an order of magnitude, as in real cases (King, 1996). At 1300s, volume exchange ceases, consistent with the final deposition state in Fig. 8. Volume balance error remains below 0.02%, confirming model conservation. Simulation times were 2.8h for R1, 3.6h for R2, and 5.5h for R3, executed in parallel using four processors on an Intel Core i7-4770 @ 3.40GHz with 6GB DDR3 RAM @ 3.2GHz.

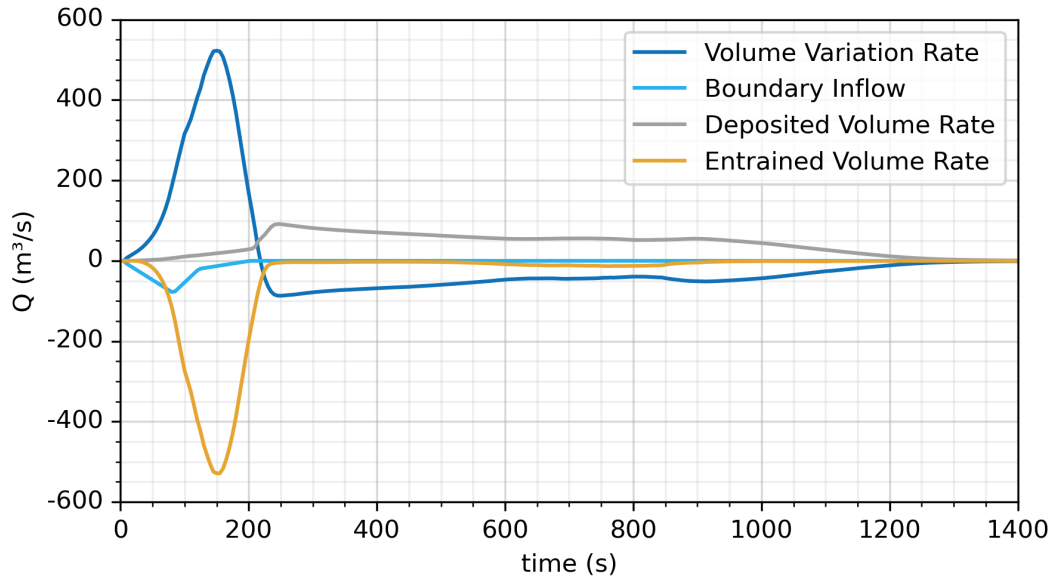


Figure 9. Volume fluxes for scenario R3. Values are domain-integrated for each time step. Inflows are negative, outflows positive.

3.3 La Mesilla catchment, Chile

325 The third application is an ephemeral creek known as La Mesilla, located in the southernmost part of the Atacama Desert (28.835° S, 70.435° W). In March 2015, an extreme precipitation event triggered debris flows, which Zegers et al. (2020) studied extensively. The triangular hydrograph used as the inlet boundary condition is shown in Fig. 10 and reproduces the peak discharge estimated by Zegers et al. (2020).

A LiDAR scan with a horizontal resolution of 1 m × 1 m was conducted after the 2015 event. The channel was removed
 330 from the post-event topography to reconstruct the pre-event surface of the alluvial fan (Zegers et al., 2020). The black dotted polygons in the M2 and M3 columns of Fig. 11 indicate the zone where entrainment and deposition processes are activated during the simulations. This zone is situated downstream of the inlet boundary to avoid numerical instabilities induced by the TMA and upstream of the El Carmen River, since the applied debris-flow entrainment and deposition models are not valid for the river.

335 We simulated three scenarios on the La Mesilla alluvial fan. All cases employed the RAMMS entrainment model (Frank et al., 2015) with parameters $E_R = 0.05 \text{ m s}^{-1}$, $\tau_c = 0.5 \text{ kPa}$, and $dz/d\tau = 0.1 \text{ m kPa}^{-1}$, along with the Fagents–Baloga deposition model (Fagents and Baloga, 2006) with $v_s = 0.001 \text{ m s}^{-1}$. Because previous studies used FLO-2D, we adopted the quadratic rheological model with parameters from Zegers et al. (2020). The values are $n = 0.05 \text{ m}^{-1/3} \text{ s}$, $K = 1166$, $\alpha_1 = 7.5 \times 10^{-4} \text{ kg m}^{-1} \text{ s}^{-1}$, $\alpha_2 = 1.52 \times 10^{-2} \text{ kg m}^{-1} \text{ s}^{-2}$, $\beta_1 = 14.39$, and $\beta_2 = 18.7$. Simulation runtimes were 14.9 h for
 340 M1, 20.1 h for M2, and 42.9 h for M3, all executed on the same computer as the previous test.

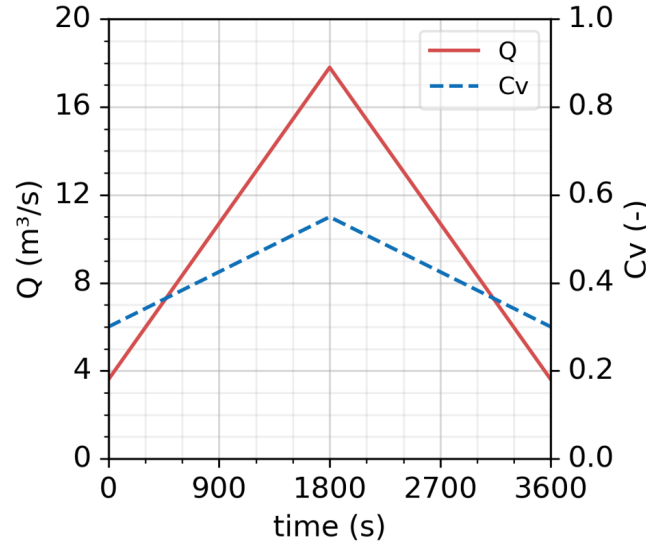


Figure 10. Flow hydrograph and sediment concentration curve for La Mesilla simulations.

The first scenario (M1) excludes entrainment and deposition (as in Zegers et al. (2020)), while M2 and M3 include both. The only difference between M2 and M3 is TMA activation in M3. Figure 11 shows the maximum flow field values (h , $|\bar{u}|$, C_v , and $|\tau_b|$), the final calculated entrained/deposited thickness (Δh_e) for M2, and the topographic change (Δz) for M3.

In the upper part of the La Mesilla alluvial fan, the debris flow behaves as a single body. In the lower part, however, the gentler slope and loss of confinement promote channel formation and flow divergence. The most evident difference among the three simulations is the extent and shape of the flooded area. In M1, the flow discharges widely into the river, while M2 and M3 produce a branched flow pattern with four distinct channels, three of which appear in both simulations. The lack of entrainment and deposition in M1 limits the volume and sediment concentration to the hydrograph-defined maximum ($C_{v,max} = 0.55$), resulting in a non-channelized flow with relatively low heights ($h_{max} = 1.1$ m) and velocities ($|\bar{u}|_{max} = 2.2$ m s⁻¹), covering about 74% of the inundated area reported by Zegers et al. (2020). In contrast, M2 and M3 exhibit higher sediment concentrations up to $C_{v,max} = 0.7$, corresponding to the sediment concentration in the bed layer ($C_{v,b}$).

Scenario M2 results in $h_{max} = 2.4$ m and $|\bar{u}|_{max} = 3.0$ m s⁻¹, while scenario M3 results in $h_{max} = 2.5$ m and $|\bar{u}|_{max} = 3.2$ m s⁻¹. These maximum values occur in the active entrainment and deposition region. They are consistent with field observations reported by Zegers et al. (2020) ($h_{max} \sim 2.0$ m, $|\bar{u}|_{max} \sim 3.5$ m s⁻¹).

Because TMA is active in M3, the flow alters the terrain, self-channelizing and reducing lateral dispersion. This explains the differences in h_{max} and $|\bar{u}|_{max}$ between M2 and M3 (Fig. 11). Furthermore, TMA activation allows the flow to either follow previously formed channels or create new paths when channel plugs occur. These two processes are not possible in M2 since the TMA is off.

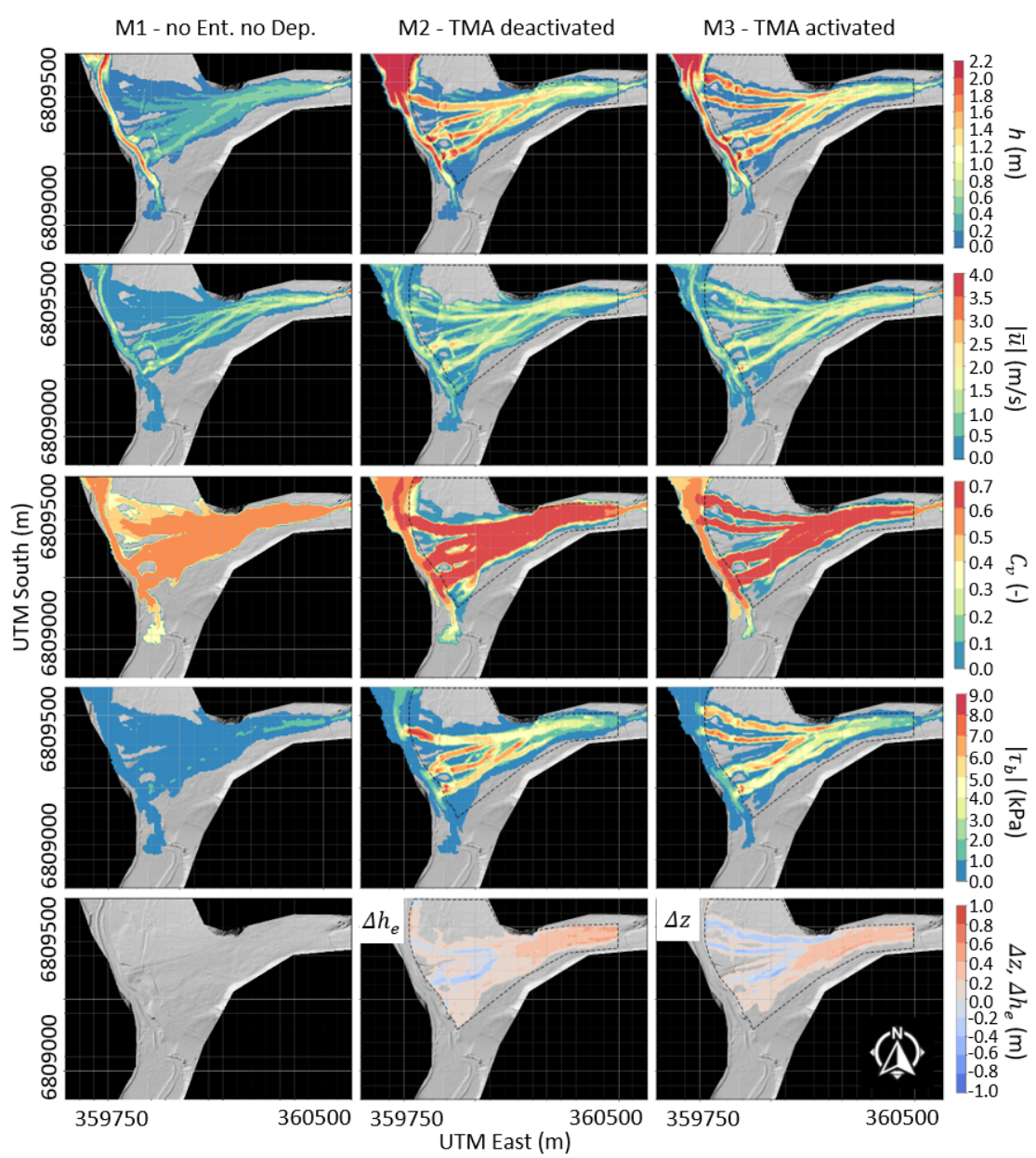


Figure 11. Simulation results for M1 (left), M2 (center), and M3 (right). Panels show maximum flow height (h), velocity ($|\vec{u}|$), sediment concentration (C_v), basal shear stress ($|\tau_b|$), and either entrained/deposited thickness (Δh_e for M2) or topographic change (Δz for M3). Positive values indicate deposition; negative values indicate entrainment. The black dotted polygon indicates the activation zone for entrainment and deposition.



Self-channelization, plug formation, and flow branching also cause differences between M2 and M3. Although maximum
360 $|\tau_b|$ values in M2 and M3 occur in different fan regions, they are comparable: $|\tau_b|_{\max} = 9.4 \text{ kPa}$ in M2 and 8.9 kPa in M3. The range of entrained thicknesses is $\Delta h_e \in [-0.47, 0.71] \text{ m}$ for M2 and $\Delta z \in [-0.50, 0.95] \text{ m}$ for M3. While the maximum entrained thickness is slightly greater in M3, total entrained and deposited volumes in M2 are 15 % and 7 % higher, respectively. Figure 11 shows where entrainment ($\Delta z, \Delta h_e < 0$) and deposition ($\Delta z, \Delta h_e > 0$) occur.

Because M3 is the only simulation with entrainment, deposition, and TMA active, we analyze it in more detail. Figure 12
365 presents the evolution of h , C_v , and Δz at four time steps. Points P1 (○), P2 (□), P3 (△), and P4 (◇) are used in Fig. 13 to illustrate temporal variation of flow variables.

The critical shear stress τ_c is set to 0.5 kPa . Below this threshold, entrainment does not occur, and only deposition takes place. As Q and C_v values increase according to the hydrograph, flow depth h , sediment concentration C_v , and consequently the basal stress $|\tau_b|$ also increase. Before $t = 525 \text{ s}$, only deposition occurs. Afterward, $|\tau_b|$ exceeds τ_c , triggering entrainment.
370 At $t = 560 \text{ s}$, the first row in Fig. 12 shows entrainment occurring at the top of the fan, forming a surge with higher h and C_v at its front, located between P1 and P2. This surge is further analyzed in Fig. 13.

The second row of Fig. 12 ($t = 875 \text{ s}$) captures the movement of this first surge and the formation of three subsequent surges. At $t = 2300 \text{ s}$, five surges are present in different development stages. The fronts of the northernmost and southernmost surges have already reached the river, but their tails remain visible. Two other surges travel through the central channel and eventually
375 merge before discharging into the river. A fifth surge is visible at $t = 2300 \text{ s}$, north of P3. As it approaches the river, it leaves the previous channels and incises a new flow path ($t = 2900 \text{ s}$). Owing to their high h , C_v , and $|\bar{u}|$, this surge possesses enough momentum to maintain a relatively straight course. In contrast, less energetic flows are more sensitive to terrain and deviate more easily.

Once generated, surges entrain material at the front, while their bodies and tails—with lower h and C_v —tend to deposit
380 sediment in the channel center. For example, the southernmost channel experiences net erosion at $t = 875 \text{ s}$ and net deposition at $t = 2900 \text{ s}$. This transition also appears in other branches. In all cases, entrainment occurs at the flow center, whereas deposition prevails along the flanks. As the flow declines, fewer surges form, and deposition becomes dominant. At $t = 2900 \text{ s}$, the southern channel on the alluvial fan has experienced net deposition, whereas the rest of the channels have experienced erosion.

Figure 13 presents the temporal variation of key flow fields at points P1 to P4 over a 200 s window. Included variables are h ,
385 C_v , Δz , $\bar{u}$, τ_b , $\rho h g_s$, and $\nabla_s(p_b h/2)$. The latter two terms are relevant in the momentum equation (Eq. 3). Variables h , $|\bar{u}|$, and Δz are normalized as $h^* = h/h_+$, $|\bar{u}|^* = |\bar{u}|/u_+$, and $\Delta z^* = \Delta z/\Delta z_+$. Momentum equation terms are normalized by τ_c (for P1 and P2) and $4\tau_c$ (for P3 and P4). $h_+ = 2.0 \text{ m}$, $u_+ = 4.0 \text{ m s}^{-1}$, and $\Delta z_+ = 0.5 \text{ m}$ are arbitrary values chosen for clarity. All vectors are projected along the flow direction.

P1 in Fig. 13 shows the arrival of the first two surges. Their arrival is evident from sudden increases in h^* and C_v . The
390 surges pass P1 at $t = 525 \text{ s}$ and $t = 585 \text{ s}$, and then reach P2 at $t = 570 \text{ s}$ and $t = 620 \text{ s}$. Each surge briefly increases $|\tau_b|$, triggering entrainment. Perturbations at P1 travel downstream and cause significant erosion at P2 (up to 0.2 m in about 10 s). Surge development shows a short reduction of velocity $|\bar{u}|^*$ during peak h^* and C_v , followed by a rapid increase of velocity $|\bar{u}|^*$. This behavior is replicated in P3 and P4.

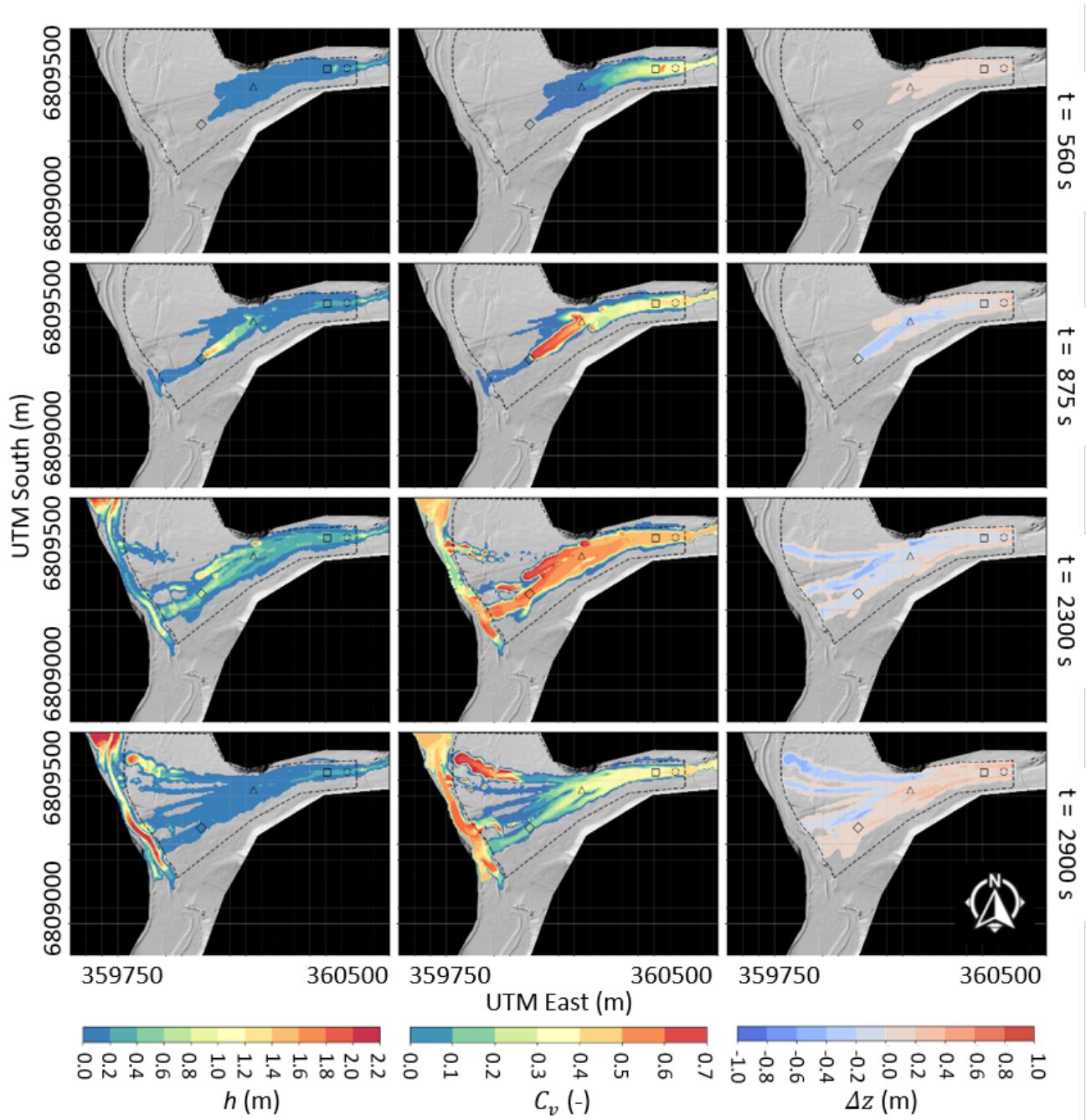


Figure 12. Flow fields h , C_v , and Δz at selected times for scenario M3. Marked points: P1 (○), P2 (□), P3 (△), P4 (◇).

At surge arrival, the momentum balance is dominated by the resistive term τ_b and the lateral pressure gradient $\nabla_s(p_b h/2)$.
 395 Later, gravity $\rho h g_s$ becomes the prevailing term. Notably, P1 exhibits two entrainment episodes, whereas the other points

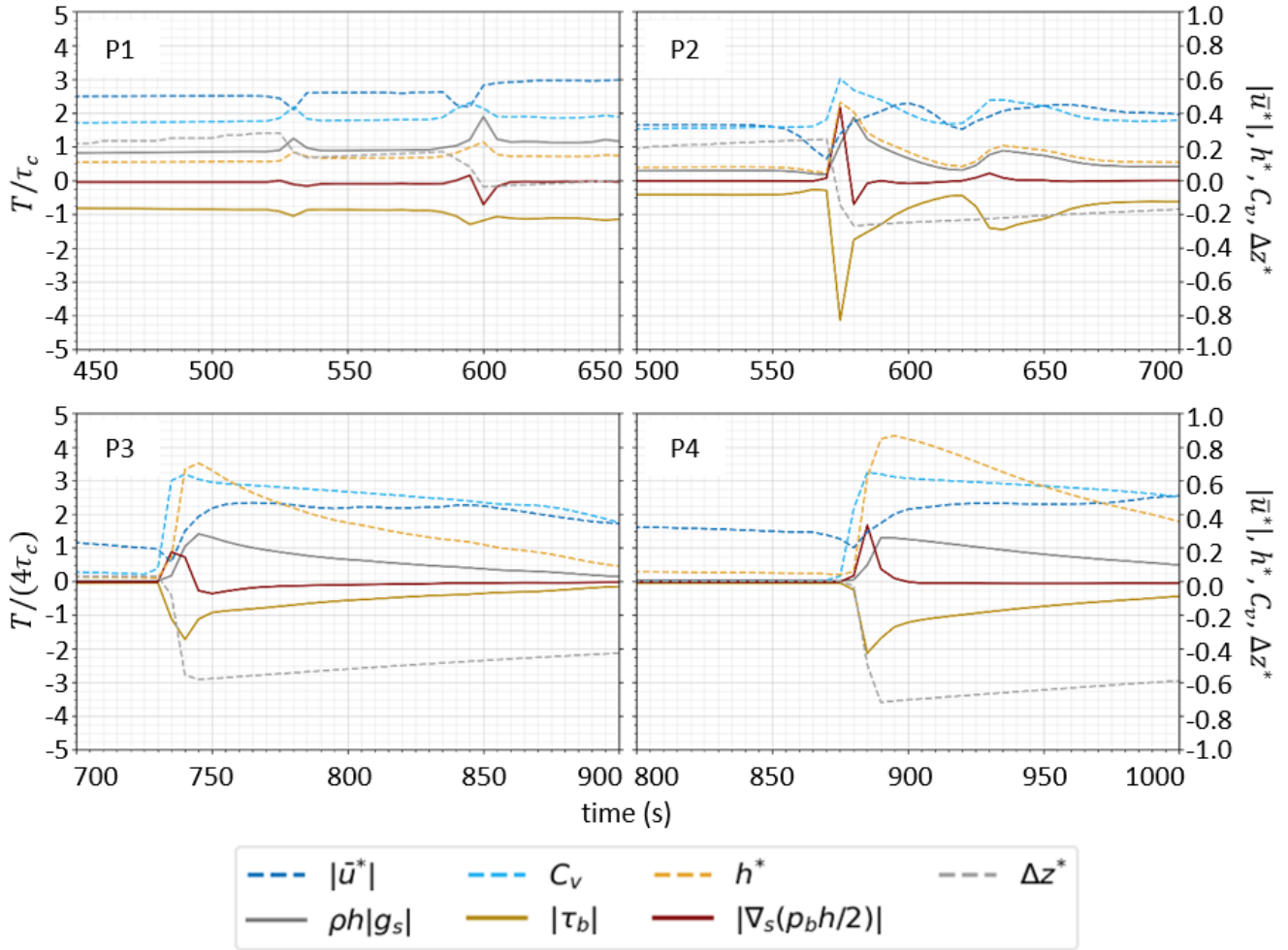


Figure 13. Flow field values over time at P1–P4. Fields h , $|\bar{u}|$, and Δz are normalized using $h_+ = 2.0$ m, $u_+ = 4.0$ m s⁻¹, and $\Delta z_+ = 0.5$ m, respectively. Momentum equation terms are normalized by 0.5 kPa (P1 and P2) and 2.0 kPa (P3 and P4).

exhibit only one. This is linked to the limit imposed by e_m (Eq. 13) and the thickness of material entrained by the first surge. Changes in Δz^* show that the surge front produces sudden erosion of the bed layer, while the body and tail produce slow but sustained increases of Δz^* , indicating deposition. This is consistent with field evidence indicating that entrainment primarily occurs at the flow front (Berger et al., 2011; McCoy et al., 2012; Iverson et al., 2011).

400 4 Discussion

The results of previous applications underscore three relevant processes: (1) surge self-generation, (2) flow self-channelization, and (3) formation of channel plugs. The first process is associated with entrainment and deposition, while the latter two occur



due to topographic changes; i.e., only when the Terrain Modification Algorithm (TMA) is activated. These results underscore the relevance of incorporating a coupled algorithm that accounts for terrain evolution during the simulation.

405 The surge self-generation process was observed in the La Mesilla simulations M2 and M3, but was analyzed in greater detail for M3 in Fig. 13. The surges originate as small perturbations, but then, as more material is incorporated, these perturbations grow and evolve into surges. In the surges depicted in Fig. 13, the primary forces in the flow direction are the gravitational term ($\rho h g_s$), the pressure gradient ($\nabla_s(p_b h/2)$), and basal shear stress (τ_b), as described in Eq. (3). At the surge front, the pressure term dominates; in the body and tail, gravity becomes the controlling factor. This distribution is consistent with field
410 measurements presented by various authors (McCoy et al., 2010; Berger et al., 2011; Major and Iverson, 1999). In the La Mesilla M3 scenario, surge growth is associated with longitudinal gradients of h and C_v . Because entrainment dominates at the surge front, bed material, characterized by a sediment volumetric concentration $C_{v,b}$, is incorporated into the flow, thereby increasing the mixture concentration C_v . In contrast, the surge body and tail exhibit lower h and C_v values, a configuration commonly reported in the literature (Davies, 1986; Ancy, 2001; Hung et al., 2005; Berger et al., 2011).

415 Self-channelization occurs only when the TMA is active, as topography must change to confine the flow. In the studied cases, the topographic change is characterized by erosion at the cross-section center and deposition at the sides. This pattern results from the interaction between the entrainment/deposition models and the cross-sectional profiles of h , $\bar{u}$, and, especially, $|\tau_b|$. For both entrainment models used, $u_{b,E} > u_{b,D}$, so when both processes are enabled, entrainment dominates. As a consequence, entrainment and deposition zones are controlled by the condition $|\tau_b| > \tau_c$, which activates entrainment. Since
420 $|\tau_b|$ is maximal at the center and gradually decreases toward the sides, $|\tau_b|$ eventually falls below τ_c , deactivating entrainment and resulting in deposition at the flanks. This deepens the channel bed at the center and raises the bottom surface at the sides of the debris flow.

The final relevant process is the generation of channel plugs and their consequences for flow behavior. In the parabolic-geometry application, deposition forms a lobe that the TMA incorporates into the bed, forcing subsequent flow to divert around
425 it. A similar mechanism operates in La Mesilla: depositional phases within surge bodies and tails progressively infill previously used channels, locally reducing slope and, in some cases, partially blocking them. These obstructions redistribute discharge across adjacent paths on the fan, making the routing sensitive to differences in local slope and channel geometry (e.g., widening, curvature, or reduced confinement). Once diversion occurs, surge fronts provide the erosive capacity to establish alternative flow paths.

430 5 Conclusions

This study presented the conceptual framework, numerical implementation, and application of faDebrisFOAM, an open-source finite-area solver for debris-flow modeling in which entrainment, deposition, and terrain evolution are treated as coupled processes. Debris flows are represented as an equivalent fluid of variable density, while entrainment and deposition are incorporated as mass exchanges between the flow and an erodible bed layer. The Terrain Modification Algorithm (TMA), which



435 updates the computational grid at each time step in response to these mass exchanges, allows topographic changes to feed back directly into the governing equations and, therefore, into the simulated flow dynamics.

We used a USGS flume test from Iverson et al. (2010) to validate the model. The simulations reproduced the main flow dynamics and the evolution of flow thickness with good agreement, supporting the numerical consistency of the solver under controlled, rigid-bed conditions. However, the additional behaviors that motivate this work do not emerge in that rigid-bed
 440 case. In the present model, surge development is associated with entrainment and deposition, whereas self-channelization and channel-plug formation require terrain evolution through the TMA. Results from the other two applications show that coupled terrain modification influences debris-flow dynamics. First, the simple parabolic-shaped geometry provides the clearest evidence of the role of the TMA, since flow patterns are easier to identify on idealized topography. In this case, topographic changes modify maximum flow height, velocity, run-out distance, and volume evolution, demonstrating that terrain evolution is
 445 not a secondary output, but an active control on debris-flow behavior. Second, the La Mesilla application confirms these effects over complex natural topography. The comparison between M2 and M3 isolates the effect of the TMA, since both simulations include the same entrainment and deposition parameters, but only M3 allows the terrain to evolve. Under these conditions, coupled terrain modification reduces lateral dispersion, promotes self-channelization, and enables channel plugs. As a result, the flow can reuse previously formed channels or incise new ones when local obstructions occur. These behaviors are absent
 450 when the terrain is held fixed, indicating that the TMA affects not only the final depositional pattern but also the flow dynamics throughout the event.

The ability to reproduce surges is a strength of `faDebrisFOAM`. Debris-flow fronts may reach flow heights and velocities up to three times their mean values, making it critical to understand surge development (Zanuttigh and Lamberti, 2007; Kean et al., 2013). Moreover, surge peak discharge is often used to estimate travel distances and impact forces, key parameters for
 455 hazard assessment and the design of mitigation works (Hung et al., 1984; Rickenmann, 1999).

Taken together, the results indicate that coupled terrain modification influences debris-flow dynamics by altering the local geometry through which the flow propagates, thereby affecting confinement and stress distribution. In the present applications, this coupling reproduces behaviors reported in real debris flows. From a practical perspective, the results also suggest that model interpretation and calibration remain sensitive to the imposed inflow conditions, the selected friction, entrainment, and
 460 deposition formulations, their parameters, and the thickness of the erodible sediment layer, as in other debris-flow numerical models (Garcés et al., 2022). For this reason, simple and well-constrained model formulations are preferable when the objective is to isolate morphodynamic effects and reduce uncertainty and equifinality (Zegers et al., 2020).

At its current stage of development, `faDebrisFOAM` provides an efficient depth-averaged framework for representing morphodynamic feedbacks. Future work should focus on improving the numerical efficiency and robustness of the TMA,
 465 particularly in parallel implementations.

Code and data availability. The source code of the numerical model and the data used for the three applications are available from the corresponding author upon reasonable request.



Appendix A: Terrain Modification Algorithm

The Terrain Modification Algorithm (TMA) was developed to modify the grid system based on how much material is entrained and deposited at each time step and in each grid element. A finite number of non-overlapping convex polygons form the numerical grid. Thus, to modify the position of a grid element, the position of its vertices must be changed. In the actual TMA implementation, only vertical vertex displacements are performed. This prevents any possible modification of the grid topology.

After solving Eqs. (1)–(5), it is possible to calculate in every grid element the entrained/deposited thickness (Δh_j) and volume (ΔV_j) between times t^n and t^{n+1} (Eqs. A1 and A2), where S_j is the area of any element j .

$$\Delta h_j = h_{e,j}^{n+1} - h_{e,j}^n \quad (\text{A1})$$

$$\Delta V_j = S_j \Delta h_j \quad (\text{A2})$$

Since Δh_j is measured normal to the surface of element j , its vertical equivalent Δh_j^* associated to the volume ΔV_j is calculated with Eq. (A3).

$$\Delta h_j^* = \frac{\Delta h_j}{\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}_j} \quad (\text{A3})$$

The position vector $\mathbf{r}_i^n$ of any vertex i of the grid is recalculated using Δh^* . A surface-weighted average is performed using the M elements ($k = 1, \dots, M$) to which the vertex i belongs.

$$\mathbf{r}_i^{n+1} = \mathbf{r}_i^n + \frac{\sum_k S_k \Delta h_k^*}{\sum_k S_k} \hat{\mathbf{k}} \quad (\text{A4})$$

The vertical movement of the vertices of any j -element defines two surfaces. The volume of the polyhedron defined by those surfaces and by the lateral vertical surfaces can be easily calculated (more details in González Bilbao (2021)) and will be named ΔV_j^* (see Fig. 3). Then, it is evident that to fulfill the conservation equation in the erodible sediment layer, the $\mathbf{r}_i^{n+1}$ values must ensure that $\Delta V_j = \Delta V_j^*$ for every j element. Although the procedure is simple at this point, it is not possible to find a solution in the simplest case: entrainment (or deposition) in only one grid element. To address this problem, we designed a second algorithm called Smoother.

The central idea of the Smoother algorithm is that the heterogeneous distribution of entrained/deposited volumes, where elements with and without entrained/deposited volumes can alternate, is unrealistic and just the consequence of using a grid formed by discrete elements and solving the equations in discrete time steps. Thus, the Smoother is designed to distribute part of the entrained/deposited volume of any element j with its neighboring elements. The result is a set of vectors $\mathbf{r}_i^{n+1}$ that fulfill the equation $\Delta V_j = \Delta V_j^*$ in the whole grid.



495 First, $\overline{\Delta h^*}$ and σ are calculated, which represent the average and dispersion of the Δh^* values among any element j and its N neighbors.

$$\overline{\Delta h_j^*} = \frac{1}{N+1} \left(\Delta h_j^* + \sum_{i=1}^N \Delta h_i^* \right) \quad (\text{A5})$$

$$\Delta h_j^{*,\max} = \max(\Delta h_j^*, \Delta h_1^*, \dots, \Delta h_N^*) \quad (\text{A6})$$

$$\Delta h_j^{*,\min} = \min(\Delta h_j^*, \Delta h_1^*, \dots, \Delta h_N^*) \quad (\text{A7})$$

500 $\sigma_j = \Delta h_j^{*,\max} - \Delta h_j^{*,\min}$ (A8)

The aim of the next step of the algorithm is to attenuate the maximum and minimum Δh_j^* values by redistributing the entrained/deposited volume ΔV_j with its neighboring elements. For this, Γ_j is calculated using Eq. (A9), with $\alpha_\Gamma \in (0, 1)$.

$$\Gamma_j = \begin{cases} 1, & \text{for } |\Delta h_j^* - \overline{\Delta h_j^*}| > \alpha_\Gamma \sigma_j, \\ 0, & \text{for } |\Delta h_j^* - \overline{\Delta h_j^*}| \leq \alpha_\Gamma \sigma_j. \end{cases} \quad (\text{A9})$$

Then, the maximum volume $\Delta V_j^{\max}$ of any element j that can be redistributed with its neighbors is calculated using
505 Eq. (A10), with $\beta_\Gamma \in (0, 1)$.

$$\Delta V_j^{\max} = \beta_\Gamma (\Delta h_j^* - \overline{\Delta h_j^*}) \Gamma_j S_j (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}_j) \quad (\text{A10})$$

Since it makes no sense for an element to send part of its volume to another with a bigger entrainment/deposition thickness, α_{ji} is introduced (Eq. A11). The α_{ji} values are calculated for any element j and its N neighbor elements ($i = 1, \dots, N$).

$$\alpha_{ji} = \begin{cases} 1, & \text{for } \Gamma_j = 1 \wedge \Delta h_j^* > \overline{\Delta h_j^*} \wedge \Delta h_j^* > \Delta h_i^*, \\ 1, & \text{for } \Gamma_j = 1 \wedge \Delta h_j^* < \overline{\Delta h_j^*} \wedge \Delta h_j^* < \Delta h_i^*, \\ 0, & \text{in any other case.} \end{cases} \quad (\text{A11})$$

510 $\Delta V_j^{\max}$ and α_{ji} are used in Eq. (A12) to recalculate the entrained or deposited volume in any element j . Since the volume lost by an element equals the volume gained by its neighbors, the continuity equation in the erodible sediment layer is globally



fulfilled. The summations in Eq. (A12) are performed over the grid elements that belong to $\text{nb}(C_j)$ and $\text{nb}(C_i)$, which are the sets of neighbor elements to j and i , respectively.

$$\begin{aligned} \Delta V_j = & \Delta V_j - \sum_{i \in \text{nb}(C_j)} \alpha_{ji} \left(\frac{S_i}{\sum_{k \in \text{nb}(C_j)} S_k} \right) \Delta V_j^{\max} \\ & + \sum_{i \in \text{nb}(C_j)} \alpha_{ij} \left(\frac{S_j}{\sum_{k \in \text{nb}(C_i)} S_k} \right) \Delta V_i^{\max}. \end{aligned} \quad (\text{A12})$$

515 Finally, Δh_j^* is recalculated with Eqs. (A2) and (A3), obtaining a smoother distribution of Δh^* .

The complete calculation sequence of the TMA is shown below, where the coefficient $\alpha_r \in (0, 1)$ is included in Eq. (A4) to prevent sudden changes in the r^{n+1} values. Since this is an iterative procedure, Eq. (A1) is modified to include the remnant Δh value from the previous iteration or time step. The closure condition of the algorithm is controlled by the $\Delta h_{\min}$ thickness and by the maximum number of iterations per time step $n_{\text{iter}}^{\text{TMA}}$.

520 1. Calculate h_e^{n+1} , $\Delta h = \Delta h + (h_e^{n+1} - h_e^n)$, and $\Delta h^* = \Delta h / (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}})$.

2. Calculate $\Delta V = S \Delta h$.

3. Use the Smoother.

(a) Calculate $\overline{\Delta h^*}$ and σ .

(b) Calculate Γ and the α_{ij} values.

525 (c) Calculate $\Delta V^{\max}$.

(d) Recalculate ΔV and then Δh^* .

4. Calculate the new coordinates of all vertices using

$$\mathbf{r}^{n+1} = \mathbf{r}^n + \alpha_r \frac{\sum_k S_k \Delta h_k^* \hat{\mathbf{k}}}{\sum_k S_k}.$$

5. Calculate the ΔV^* volumes defined by the movement of the vertices.

530 6. Recalculate Δh using $\Delta h = (\Delta V + \Delta V^*)/S$, and then Δh^* .

7. If $\Delta h_{\min} < \max(\Delta h^*)$ or $\Delta h_{\min} < -\min(\Delta h^*)$, return to step 2; otherwise, advance to step 8.

8. Recalculate $\hat{\mathbf{n}}$, $\mathbf{g}_n$, $\mathbf{g}_s$, and S .

Because the TMA is computationally expensive, we introduce extra conditions to prevent its activation when its effects on the flow dynamics are negligible. The first condition is that the Smoother is only used if $\Delta h_{\min} \alpha_s < \max(\Delta h^*)$ or $-\Delta h_{\min} \alpha_s >$
535 $\min(\Delta h^*)$, with $\alpha_s \in (0, 1)$. This condition prevents overusing the Smoother, since at least one element of the domain must



have an entrained/deposited thickness greater than $|\Delta h_{\min} \alpha_s|$. Analogously, the TMA is activated only if $\Delta h_{\min} < \max(\Delta h^*)$ or $-\Delta h_{\min} > \min(\Delta h^*)$. This condition is stricter than the previous one and ensures that the TMA is not used excessively. Additionally, the position vector of any vertex i , $\mathbf{r}_i^{n+1}$, is recalculated only if

$$\frac{\sum_k S_k h_k}{\sum_k S_k} > h_{\min}^{\text{TMA}},$$

540 where S_k and h_k are, respectively, the area and flow height of the M elements ($k = 1, \dots, M$) to which the vertex i belongs. The last condition aims to prevent the propagation of $\Delta h^* \neq 0$ values to zones where the flow height is lower than $h_{\min}^{\text{TMA}}$, which may be an undesired consequence of using the Smoother. The default parameter values set in `faDebrisFOAM` are: $\alpha_r = 0.85$, $\alpha_s = 0.70$, $\alpha_\Gamma = 0.20$, $\beta_\Gamma = 0.60$, $\Delta h_{\min} = 0.01$ m, $h_{\min}^{\text{TMA}} = 0.001$ m, and $n_{\text{iter}}^{\text{TMA}} = 5$.

Author contributions. AGon and AT: Conceptualization. AGon: Data curation and Software. AGon and AGar: Investigation and Visualiza-
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