The Journal of Open Source Software

The Kestrel software for simulations of morphodynamic Earth-surface flows

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DOI: 10.21105/joss.06079

Software

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Editor: Chris Vernon

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Submitted: 09 August 2023
Published: 15 January 2024

Summary

Kestrel is a program for simulating flows composed of a mixture of fluid and sediment. It includes the facility to model material exchange with the topography over which the flow propagates, by incorporating sediment entrainment and deposition. These physical processes, which mutually couple the flow with its underlying bed, are sometimes collectively termed 'morphodynamics'. Simulations may be initiated either on simple surfaces or on more realistic terrains, via a user-specified digital elevation model (DEM). The latter option enables computations on topographies measured to approximate the Earth's surface, so that real world events may be reconstructed and potential future scenarios may be modelled. Kestrel has been primarily developed for Earth sciences research into natural hazards, including volcanic mudflows (lahars), flash floods and landslides. However, it may also be useful for modelling flows of interest to engineers, applied mathematicians, geophysicists and industry scientists, see e.g. Capart & Young (1998), Cao et al. (2004), Iverson & Ouyang (2015) and Langham et al. (2021). The versatility of the code is a deliberate design choice. As discussed below, many of the key physical processes are implemented in a modular way, allowing the user to choose between different options, depending on the problem. Furthermore, for expert users it should be relatively straightforward to extend the code to support alternative modelling terms that suit individual needs.

Kestrel is predominantly written in Fortran, with some C++ for handling geospatial data via external libraries. While expertise in the scientific background is required to set up simulations and correctly interpret their results, the program is otherwise intended to be straightforward to use for a broad range of scientists. It has relatively few dependencies (GDAL, PROJ and optionally, NetCDF), making it easy to build on modern Unix-like platforms. After installation, simulations are prepared by writing an input file specifying suitable parameter choices and run on the command line. During the simulation, resources are allocated dynamically, according to the inundated area at each time step, in order to handle large-scale flows efficiently. Solution fields are saved at regular intervals, together with spatial maps of their maximums over the whole simulation. Output is via text file or NetCDF (preferred). In the latter case, data is losslessly compressed, enabling efficient checkpointing for large simulations. Additionally, we provide an extension to the open-source QGIS software, which imports Kestrel solutions in NetCDF format at their georeferenced coordinates and prepares each of the data fields for visualisation. This provides a particularly convenient workflow for geoscientists. An example of this output is given in Figure 1.

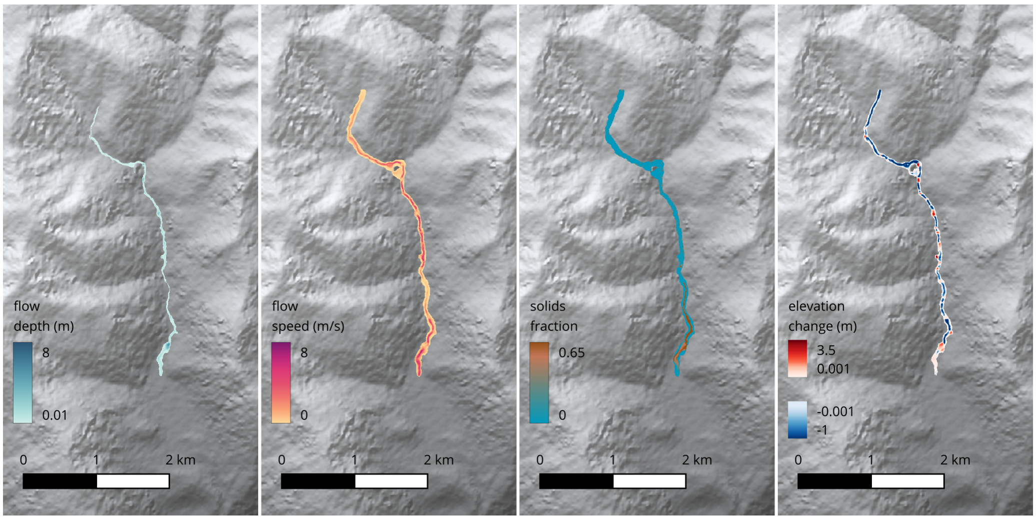

Figure 1: An example of `Kestrel` simulation output, postprocessed and georeferenced automatically in `QGIS`, using our bespoke plugin. (Labels and colour bars have been added separately in `QGIS`, for clarity.) The panels show (left-to-right) flow depth, flow speed, solids fraction, and topographic elevation change of a small volume flow released onto the slopes of a steep valley.

Statement of need

All fluid flows that propagate over the Earth's surface transport sediment to some degree. The presence of sediment at sufficiently high concentrations substantially complicates the physics of these flows, by modifying their density, rheology and their ability to entrain or deposit further volumes of sediment (Iverson, 1997; Iverson & Ouyang, 2015). In many regions of the world, local conditions can trigger destructive flowing fluid–sediment mixtures that travel over distances of up to tens of kilometres (Jakob & Hungr, 2005; Pierson et al., 1990; Scott et al., 2005). Driven by the need to understand their fundamental physics and ultimately to create predictive tools that can mitigate hazards, the development of mathematical models for these flows is an active research area and there is a corresponding need for flexible research codes that can numerically solve these models.

There are many existing codes available for simulating these systems. The programs most closely related to ours are the open source codes `D-CLAW` (George & Barnhart, 2023; George & Iverson, 2014; Iverson & George, 2014), `TITAN2D` (Patra et al., 2005, 2020; Simakov et al., 2019), `r.avaflow` (Mergili & Pudasaini, 2023; Pudasaini & Mergili, 2019), `IMEX_SfloW2D` (de'Michieli Vitturi, Costa, et al., 2023; de'Michieli Vitturi, Ongaro, et al., 2023; de'Michieli Vitturi & Lari, 2023) and the debris flow components of the proprietary software packages `RAMMS` (Christen et al., 2010; Meyrat et al., 2022) and `Flo-2D` (*Flo-2D*, 2023). Each of these codes uses a slightly different description of the flow physics and underlying mathematical framework. The diversity of approaches reflects differences in the level of detail included in physical descriptions, as well as genuine uncertainties present in current understanding of Earth surface flow physics. Our code implements a newly derived modelling framework and accompanying numerical scheme detailed in Langham et al. (2023), which is designed to be adjusted to accommodate a wide range of flow types by specifying particular physical closures at runtime. The model and its implementation also resolve some important technical issues that affect morphodynamic simulations on complex terrains. Its essential features are briefly described below.

Like all the above software, `Kestrel` numerically approximates solutions to an underlying system of partial differential equations for the flow, whose derivation uses the fact that the flow's lateral extent typically greatly exceeds its thickness, to reduce the spatial dimension

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by 1, thereby rendering simulations computationally tractable at geophysical scales. Kestrel supports simulations in either one or two orthogonal coordinate directions, perpendicular to gravity. It keeps track of the following observables, which depend on space and time coordinates $\mathbf{x}$ and t: the flow thickness $H(\mathbf{x}, t)$, in-plane velocity $\bar{\mathbf{u}}(\mathbf{x}, t)$, volumetric solids concentration $\bar{\psi}(\mathbf{x}, t)$, and the bed elevation $b(\mathbf{x}, t)$. A diagram of an example flow is shown in Figure 2.

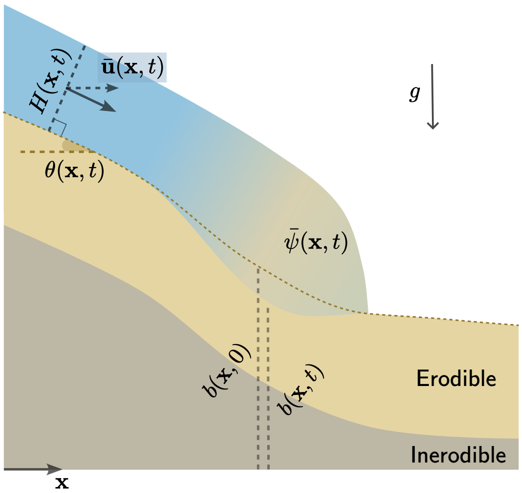

Figure 2: Schematic cross-section of the model setup showing the primary variables H, $\bar{\mathbf{u}}$, $\bar{\psi}$ and b. Note that Kestrel solves for the component of flow velocity perpendicular to gravity (dashed arrow). The total velocity is determined by the assumption that it lies parallel with the local slope. In the depicted flow, a portion of the erodible part of the bed towards the front has been eroded (as indicated by the dotted line), leading to an increase in the solids concentration.

In two spatial dimensions, the governing equations that Kestrel solves are

$$\frac{\partial H}{\partial t} + \nabla \cdot (H\bar{\mathbf{u}}) = \mathcal{E} - \mathcal{D} + \mathcal{Q}_H, \tag{1}$$

$$\frac{\partial}{\partial t}(H\bar{\psi}) + \nabla \cdot (H\bar{\mathbf{u}}\bar{\psi}) = \psi_b(\mathcal{E} - \mathcal{D}) + \mathcal{Q}_H \mathcal{Q}_\psi, \tag{2}$$

$$\frac{\partial}{\partial t}(\bar{\rho}H\bar{\mathbf{u}}) + \nabla \cdot (\rho H\bar{\mathbf{u}} \otimes \bar{\mathbf{u}}) + \frac{g}{2\cos\theta}\nabla_s\left(\bar{\rho}H^2\cos^2\theta\right) = -\bar{\rho}gH\nabla_s b - \mathcal{T} + \nabla \cdot (\nu\bar{\rho}H\nabla\bar{\mathbf{u}}), \tag{3}$$

$$\frac{\partial b}{\partial t} = \frac{\mathcal{D} - \mathcal{E}}{\cos\theta}, \tag{4}$$

where $\bar{\rho} = \bar{\psi}\rho_s + (1 - \bar{\psi})\rho_f$ is the flow density, ρ_s, ρ_f, ψ_b, g and ν are user-defined modelling parameters, $\theta(\mathbf{x}, t)$ is the local slope angle between the bed normal and gravity, and $\nabla_s = \nabla - \mathbf{s}(\mathbf{s} \cdot \nabla)$, with $\mathbf{s} \equiv \cos(\theta)\nabla b$.

While most of the terms in these equations are fixed by the underlying depth-averaged flow physics (and shall not be discussed further), some parts of the right-hand sides are user-settable. The terms $\mathcal{T}$, $\mathcal{E}$ and $\mathcal{D}$ denote the basal drag, erosion rate and deposition rate respectively. These are modelling closures, assumed to be functions of the flow fields H, $\bar{\mathbf{u}}$ and $\bar{\psi}$. In each case, the user may choose from different options, depending on the problem at hand. For example, the drag $\mathcal{T}$ may be set either to a function appropriate for turbulent fluids, to various models of purely granular flows, or to a combined law that depends on the solids concentration. This provides the flexibility to simulate many different kinds of flow. Furthermore, it is worth noting that in many cases, the question of which closures most faithfully capture the flow physics is an open problem that cannot easily be addressed experimentally. Using numerical simulations to investigate the effects of different modelling choices is one way to approach this.

The remaining source terms $\mathcal{Q}_H$ and $\mathcal{Q}_\psi$ are time-dependent functions that provide one way for a modeller to control fluxes of material input into the simulation by specifying their form via time series data and identifying regions over which these fluxes apply. The flux values may be informed by geophysical measurements, expert judgement, or chosen according to some other consideration. Simulations may also be initiated by constructing an initial flow state which is evolved forward in time. `Kestrel` accepts arbitrary initial conditions given in the same format as its result files, or simple initial volumes of material (such as cubes and cylinders) can be specified via an input file.

In deriving Eqs. (1)–(4), some physical assumptions are made that reduce the complexity of our model compared to some of the similar codes cited above, such as the neglect of interstitial pressure between sediment particles and the assumption that the sediment is composed of particles that are all roughly the same size. Conversely, we include the effects of morphodynamics, which not all codes support. The reasoning for these choices is twofold: (1) to simplify the problem for modellers wishing to conduct simulations efficiently, without compromising the most essential flow physics and (2) in order to focus on making some important technical advances for morphodynamic models, which are particular to our code and detailed by Langham et al. (2023). These advances include improvements to standard numerical schemes, a careful treatment of the effects of the basal geometry and a regularisation that ensures the model is well-posed as an initial value problem.

Even in the most straightforward cases, morphodynamic simulations involve many free parameters, which are not all directly measurable for real world scenarios. Proper calibration and an appreciation of the uncertainties present at each stage of the modelling process is essential to obtain reliable results from `Kestrel`. Examples and guidance for getting started may be found in our documentation, which includes details of the currently available model closures and their associated parameters. Results from `Kestrel` simulations have thus far been used in the following scientific publications: (Jenkins et al., 2023; Langham et al., 2023). `Kestrel` also forms the backend for the `LaharFlow` volcanic hazard model (Woodhouse, 2023).

Acknowledgements

The development of this software spanned research grants from the the Newton Fund (NE/S00274X/1), EPSRC Impact Acceleration Account (EP/X525674/1) and a NERC Knowledge Exchange Fellowship (NE/R003890/1). We thank our colleagues Andrew J. Hogg, Luke T. Jenkins and Jeremy C. Phillips, who worked on the foundational mathematical and geological ideas that underpin the code. We also thank users who supported the development of `Kestrel`, especially Felipe Flores (SERNAGEOMIN, Chile), Francisco Vásconez (IG-EPN, Ecuador), Selwyn Cabaluna (PHIVOLCS, Phillipines) and other geological collaborators at SERNAGEOMIN, IG-EPN, PHIVOLCS, INGEMMET (Perú), as well as all current and past `Kestrel` users.

References

Cao, Z., Pender, G., Wallis, S., & Carling, P. (2004). Computational dam-break hydraulics over erodible sediment bed. *J. Hydraul. Eng.*, *130*(7). https://doi.org/10.1061/(ASCE)0733-9429(2004)130:7(689)

Capart, H., & Young, D. L. (1998). Formation of a jump by the dam-break wave over a granular bed. *J. Fluid Mech.*, *372*, 165–187. https://doi.org/10.1017/s0022112098002250

Christen, M., Kowalski, J., & Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Reg. Sci. Technol.*, *63*(1-2), 1–14. https://doi.org/10.1016/j.coldregions.2010.04.005

de'Michieli Vitturi, M., Costa, A., Di Vito, M. A., Sandri, L., & Doronzo, D. M. (2023). Lahar events in the last 2,000 years from Vesuvius eruptions. Part 2: Formulation and validation of a computational model based on a shallow layer approach. *EGUsphere*, *2023*, 1–31. https://doi.org/10.5194/egusphere-2023-1301

de'Michieli Vitturi, M., & Lari, G. (2023). IMEX_SfloW2D. In *GitHub repository* (Version 1.0.0). GitHub. https://demichie.github.io/IMEX_SfloW2D/

de'Michieli Vitturi, M., Ongaro, T. E., & Engwell, S. (2023). IMEX_SfloW2D v2: A depth-averaged numerical flow model for volcanic gas-particle flows over complex topographies and water. *Geosci. Model Dev.*, *2023*, 1–42. https://doi.org/10.5194/gmd-2023-80

Flo-2D. (2023). https://flo-2d.com/

George, D. L., & Barnhart, K. (2023). D-Claw: Software for granular-fluid flows. In *GitHub repository*. GitHub. https://github.com/geoflows/D-Claw

George, D. L., & Iverson, R. M. (2014). A depth-averaged debris-flow model that includes the effects of evolving dilatancy. II. Numerical predictions and experimental tests. *P. Roy. Soc. A-Math. Phy.*, *470*(2170), 20130820. https://doi.org/10.1098/rspa.2013.0820

Iverson, R. M. (1997). The physics of debris flows. *Rev. Geophys.*, *35*(3), 245–296. https://doi.org/10.1029/97RG00426

Iverson, R. M., & George, D. L. (2014). A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. Physical basis. *P. Roy. Soc. A-Math. Phy.*, *470*(2170). https://doi.org/10.1098/rspa.2013.0819

Iverson, R. M., & Ouyang, C. (2015). Entrainment of bed materials by Earth-surface mass flows: Review and reformulation of depth-integrated theory. *Rev. Geophys.*, *53*. https://doi.org/10.1002/2013RG000447

Jakob, M., & Hungr, O. (2005). *Debris-flow hazards and related phenomena* (Vol. 739). Springer. https://doi.org/10.1007/b138657

Jenkins, L. T., Creed, M. J., Tarbali, K., Muthusamy, M., Trogrlić, R. Š., Phillips, J. C., Watson, C. S., Sinclair, H. D., Galasso, C., & McCloskey, J. (2023). Physics-based simulations of multiple natural hazards for risk-sensitive planning and decision making in expanding urban regions. *Int. J. Disast. Risk Re.*, *84*, 103338. https://doi.org/10.1016/j.ijdrr.2022.103338

Langham, J., Woodhouse, M. J., Hogg, A. J., Jenkins, L. T., & Phillips, J. C. (2023). *Simulating shallow morphodynamic flows on evolving topographies*. https://arxiv.org/abs/2306.16185

Langham, J., Woodhouse, M. J., Hogg, A. J., & Phillips, J. C. (2021). Linear stability of shallow morphodynamic flows. *J. Fluid Mech.*, *916*. https://doi.org/10.1017/jfm.2021.235

Mergili, M., & Pudasaini, S. P. (2023). *R.avaflow – the mass flow simulation tool* (Version 3). https://www.avaflow.org

Meyrat, G., McArdell, B., Ivanova, K., Müller, C., & Bartelt, P. (2022). A dilatant, two-layer debris flow model validated by flow density measurements at the Swiss Illgraben test site. *Landslides*, *19*(2), 265–276. https://doi.org/10.1007/s10346-021-01733-2

Patra, A. K., Bauer, A. C., Nichita, C. C., Pitman, E. B., Sheridan, M. F., Bursik, M., Rupp, B., Webber, A., Stinton, A. J., Namikawa, L. M., & Renschler, C. S. (2005). Parallel adaptive numerical simulation of dry avalanches over natural terrain. *J. Volcanol. Geoth. Res.*, *139*(1-2), 1–21. https://doi.org/10.1016/j.jvolgeores.2004.06.014

Patra, A. K., Bevilacqua, A., Akhavan-Safaei, A., Pitman, E. B., Bursik, M., & Hyman, D. (2020). Comparative analysis of the structures and outcomes of geophysical flow models and modeling assumptions using uncertainty quantification. *Front. Earth Sci.*, *8*, 275. https://doi.org/10.3389/feart.2020.00275

Pierson, T. C., Janda, R. J., Thouret, J.-C., & Borrero, C. A. (1990). Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *J. Volcanol. Geotherm. Res.*, *41*(1), 17–66. https://doi.org/10.1016/0377-0273(90)90082-Q

Pudasaini, S. P., & Mergili, M. (2019). A multi-phase mass flow model. *J. Geophys. Res.-Earth*, *124*(12), 2920–2942. https://doi.org/10.1029/2019JF005204

Scott, K. M., Vallance, J. W., Kerle, N., Macías, J. L., Strauch, W., & Devoli, G. (2005). Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: Occurrence, bulking and transformation. *Earth Surf. Proc. Land.*, *30*(1), 59–79. https://doi.org/10.1002/esp.1127

Simakov, N. A., Jones-Ivey, R. L., Akhavan-Safaei, A., Aghakhani, H., Jones, M. D., & Patra, A. K. (2019). Modernizing Titan2D, a parallel AMR geophysical flow code to support multiple rheologies and extendability. *Int. C. High Perform.*, 101–112. https://doi.org/10.1007/978-3-030-34356-9_10

Woodhouse, M. J. (2023). *LaharFlow: The Bristol model of lahars on evolving topography*. https://laharflow.bris.ac.uk/