The Journal of Open Source Software

pySBeLT: A Python software for stochastic sediment transport under rarefied conditions

Sarah Zwiep[*1] **and Shawn M. Chartrand**[†1,2]

1 School of Environmental Science, Simon Fraser University **2** Department of Earth Sciences, Simon Fraser University

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Katy Barnhart

Reviewers:

- @pfeiffea
- @tdoane

Submitted: 21 January 2022
Published: unpublished

Summary

Granular sediment of various sizes moves downstream along river beds when water flow is capable of entraining particles from the bed surface. This process is known as bed load sediment transport because the particles travel close to the boundary. It is common to treat the transport process as a predictive problem in which the mean transport rate past a stationary observation point is a function of local water flow conditions (Christophe Ancey, 2020; Parker, 2008; **Wainwright:2014?**). A predictive approach introduces challenges to understanding bed load transport, however, because the stochastic nature of transport due to the movements of individual particles is neglected (Einstein, 1937; D. J. Furbish & Doane, 2021). Here, we present an open-source Python model, pySBeLT, which simulates the kinematics of rarefied particle transport (low rates) as a stochastic process along a riverbed profile. The primary aim of pySBeLT is to examine connections between individual particle motions and local transport rates, or the flux.

Statement of need

Research at the intersection of geomorphology, geophysics and hydraulics is increasingly focused on building a theoretical foundation for the treatment of bedload transport as a stochastic phenomenon (Christophe Ancey, 2020; D. J. Furbish & Doane, 2021). Associated theories are commonly tested against laboratory data from "rarefied" transport conditions (David Jon Furbish et al., 2016), where transport rates are low to moderate, interactions between two or more moving particles are rare, and a relatively small fraction of particles on the bed surface participate in transport (Christophe Ancey, 2010; Fathel et al., 2015; Roseberry et al., 2012; **Wu:2019?**). For example, laboratory experiments using a downstream light table counting device and conducted at roughly twice the threshold for particle motion involve the transport of less than approximately 12% of particles on the upstream bed surface (Chartrand, 2017). This result highlights that the flux measured across a boundary or within an area of bed surface is directly linked to the motions of individual particles arriving from upstream locations (David Jon Furbish et al., 2012).

Because particle motions are controlled by fluid turbulence, the irregular bed surface, and collective effects (Christophe Ancey et al., 2006; C. Ancey et al., 2008; Lee & Jerolmack, 2018), the connection between particle movements and the bedload transport rate has been difficult to formulate mathematically. pySBeLT provides an extensible framework within Python to numerically examine correlations between upstream particle entrainment rates and travel distances, with downstream flux. pySBeLT was motivated by a birth-death, immigration-emigration Markov model for bedload transport. Here, the movements of individual particles

*co-first author
†co-first author

are represented by stochastic entrainment, motion, and deposition processes, and sediment flux is represented as a counting phenomenon where the number of particles in motion above the bed surface is a random variable (C. Ancey et al., 2008). The model supports ensemble simulations so that repeat numerical experiments can be conducted efficiently, or the problem can be probed across a range of input parameter values (discussed below).

pySBeLT is run forward in time according to default or user specified parameter values. After initialization, pySBeLT first constructs a bed of fixed particles of set_diam in both the downstream and cross-stream dimensions (one particle wide in the present build), and over a downstream domain length **'bed_length'**. Bed surface particles of **'particle_diam'** are then randomly placed at vertices between fixed bed particles until the **'particle_pack_frac'** is met. Vertices are defined by a contact point between two adjacent particles. The bed of surface particles is then separated into **'num_subregions'**, and at this point the forward simulations are ready to commence. The subregion boundaries are located by: (1) the user specifies the **'num_subregions'**, and (2) the subregion boundaries occur at domain locations set by a distance = **'bed_length'** / **'num_subregions'**.

Simulation iterations involve three steps (Fig. 1): (1) the number of particle entrainment events per **'num_subregions'** are drawn from a Poisson pmf, and this is done randomly for each numerical step up to **'iterations'**; (2) surface particles from each subregion are randomly selected for entrainment, and if there are insufficient surface particles available for entrainment, then all available particles are moved; (3) each entrained particle moves a distance according to a randomly sampled value from either the normal or lognormal distribution (see THEORY.md for more details), and is placed at the nearest vertex between two particles that is available for placement. Placed particles are permitted to stack up to the **'level_limit'** in height. Particles are not permitted to travel to the same available vertex. To stop this from occuring the entrained particles are moved in random order and once a particle is placed on a vertex, that vertex is no longer considered available for any subsequent particle entrainments for that iteration. Travel distances of particles that exceed **'bed_length'** are returned and queued at the upstream boundary, and are introduced back into the domain at the next numerical step according to travel distance sampling described above. This overall process repeats for the specified **'iterations'**.

pySBeLT tracks a number of different parameters through a simulation: the vertical and horizontal positions of every particle center, the randomly sampled number of entrainment events, the number of particles actually entrained, the actual particle travel distance, the particle 'age', or the number of numerical steps since last entrainment for every particle, and the number of particles which cross all boundaries, i.e. sub-region and downstream at x_max. All values, or the values needed to derive this information, are stored in HDF5 data files using the h5py package (Collette, 2013).

pySBeLT produces a time varying signal of particle flux counted at the downstream domain (as well as internal subregion domains), with a particle bed that changes through particle stacking and pile removal, and downstream motions of travel distance (Fig. 2). An implication of particle stacking within the context of the pySBeLT stochastic framework is a time varying signal of the average "particle age", as well as the average "particle age range", defined as the difference of the maximum and minimum particle ages. The model can be readily modified to simulate kinematics using different probability distributions (see THEORY.md for more details), or examining particle age dynamics for deeper beds of particles available for transport. The relatively simple parameterization of pySBeLT execution also makes it suitable for use as a teaching tool within advanced undergraduate and graduate courses emphasizing bed load sediment transport.

Figures

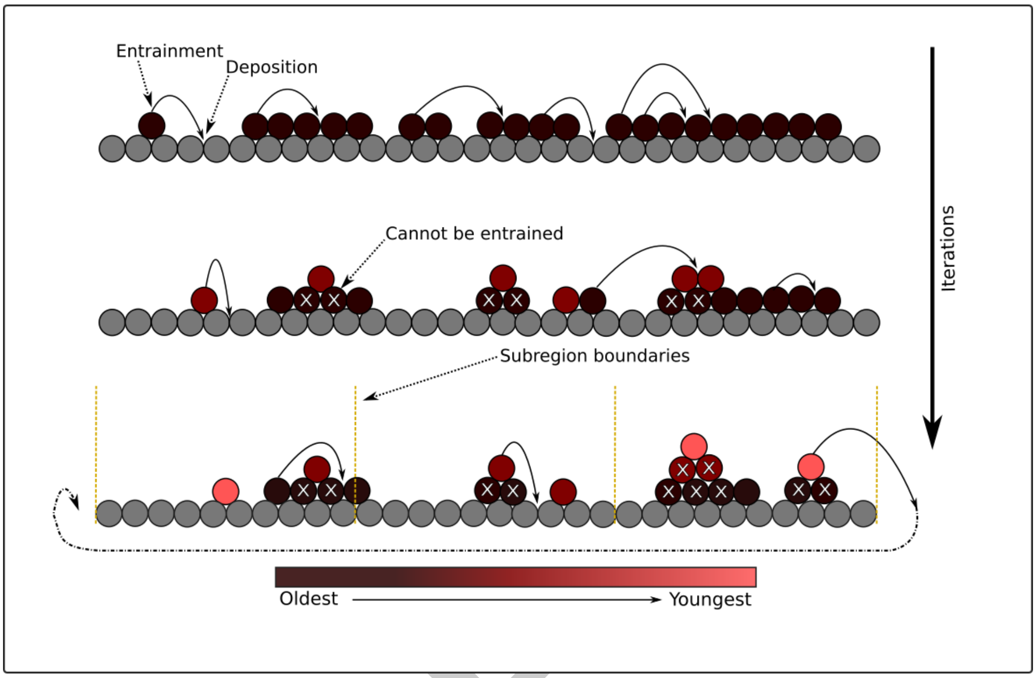

Figure 1. *Graphic illustrating the three steps of particle transport modelling by py_SBeLT. The **'level_limit'** in height is set to 3 in the graphic.*

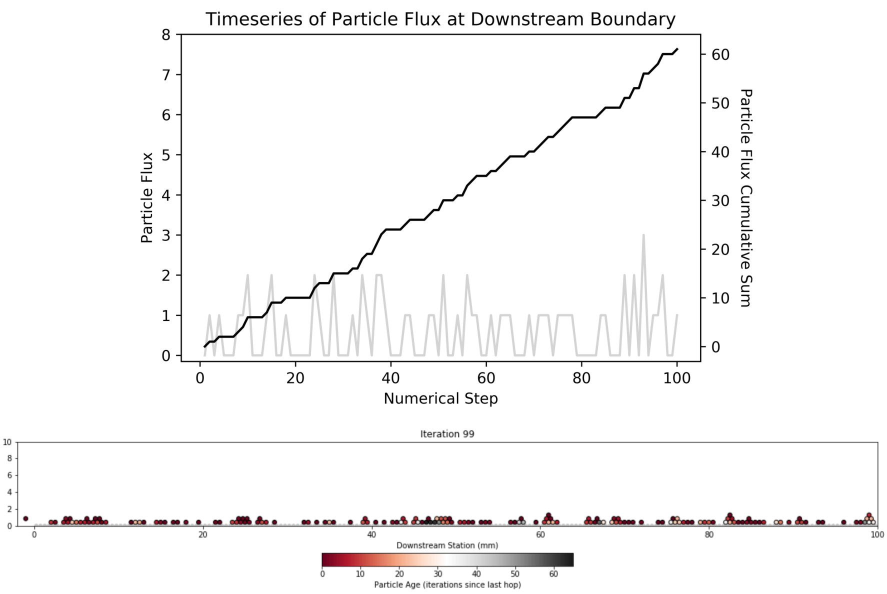

Figure 2. *Example py_SBeLT output of particle flux at downstream boundary and particle bed configuration at numerical step 100*

Acknowledgements

S. Zwiep was funded in part through an Undergraduate Student Research Award from the National Science and Engineering Research Council of Canada (NSERC). S.M. Chartrand was funded through a Postdoctoral Fellowship awarded by NSERC, and through internal research funding provided by Simon Fraser University. The model was inspired by discussions with D.J. Furbish, who also provided useful input and critical feedback at various stages of model development and testing. K. Pierce also provided helpful feedback during model development. G. Baker provided insightful mentorship for S. Zwiep during improvements to the model.

References

Ancey, Christophe. (2020). Bedload transport: A walk between randomness and determinism. Part 1. The state of the art. *Journal of Hydraulic Research*, *58*(1), 1–17. https://doi.org/10.1080/00221686.2019.1702594

Ancey, Christophe. (2010). Stochastic modeling in sediment dynamics: Exner equation for planar bed incipient bed load transport conditions. *Journal of Geophysical Research: Earth Surface*, *115*(F2). https://doi.org/10.1029/2009JF001260

Ancey, Christophe, Böhm, T., Jodeau, M., & Frey, P. (2006). Statistical description of sediment transport experiments. *Physical Review E*, *74*(1), 11302–11302. https://doi.org/10.1103/PhysRevE.74.011302

Ancey, C., Davison, A. C., Böhm, T., Jodeau, M., & Frey, P. (2008). Entrainment and motion of coarse particles in a shallow water stream down a steep slope. *Journal of Fluid Mechanics*, *595*, 83–114. https://doi.org/10.1017/S0022112007008774

Chartrand, S. M. (2017). *Pool-riffle dynamics in mountain streams : Implications for maintenance, formation and equilibrium* [PhD thesis, University of British Columbia]. https://doi.org/10.14288/1.0349138

Collette, A. (2013). *Python and HDF5*. O'Reilly.

Einstein, H. A. (1937). *Bedload transport as a probability problem* [PhD thesis].

Fathel, S. L., Furbish, D. J., & Schmeeckle, M. W. (2015). Experimental evidence of statistical ensemble behavior in bed load sediment transport. *Journal of Geophysical Research: Earth Surface*, *120*(11), 2298–2317. https://doi.org/10.1002/2015JF003552

Furbish, D. J., & Doane, T. H. (2021). Rarefied particle motions on hillslopes – Part 4: Philosophy. *Earth Surface Dynamics*, *9*(3), 629–664. https://doi.org/10.5194/esurf-9-629-2021

Furbish, David Jon, Haff, P. K., Roseberry, J. C., & Schmeeckle, M. W. (2012). A probabilistic description of the bed load sediment flux: 1. Theory. *Journal of Geophysical Research: Earth Surface*, *117*(F3), F03031–F03031. https://doi.org/10.1029/2012JF002352

Furbish, David Jon, Schmeeckle, M. W., Schumer, R., & Fathel, S. L. (2016). Probability distributions of bed load particle velocities, accelerations, hop distances, and travel times informed by Jaynes's principle of maximum entropy. *Journal of Geophysical Research: Earth Surface*, *121*(7), 1373–1390. https://doi.org/10.1002/2016JF003833

Lee, D. B., & Jerolmack, D. (2018). Determining the scales of collective entrainment in collision-driven bed load. *Earth Surface Dynamics*, *6*(4), 1089–1099. https://doi.org/10.5194/esurf-6-1089-2018

Parker, G. (2008). Transport of gravel and sediment mixtures. In M. Garcia (Ed.), *Sedimentation engineering: Theory, measurements, modeling and practice (ASCE manuals and reports on engineering practice no. 110)* (pp. 165–251). ASCE. https://doi.org/10.1061/9780784408148.ch03

Roseberry, J. C., Schmeeckle, M. W., & Furbish, D. J. (2012). A probabilistic description of the bed load sediment flux: 2. Particle activity and motions. *Journal of Geophysical Research: Earth Surface*, *117*(F3), F03032–F03032. https://doi.org/10.1029/2012JF002353