

stochastic sediment transport modeling

annotated bibliography

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This annotated bibliography is in preparation of a publication of a high resolution sediment transport dataset alongside a new sediment transport theory based upon Markov random process theory. As such the bibliography contains papers from three categories: (1) similar sediment transport experiments; (2) applied mathematics and computer vision papers relating to experiment analysis; and (3) papers on stochastic mathematics or sediment transport theory.

annotations:

- [1] S. Abbott and S. Francis, “Saltation and suspension trajectories of solid grains in a water stream,” *Royal Transactions of the Royal Society of London A.*, vol. 294, no. 1321, pp. 225–254, 1977.

This is the followup paper to Francis (1973) which is probably the earliest photography based experiment resolving sediment transport characteristics in a water stream. The authors take many thousands of photos to obtain positions, velocities, and accelerations of bed and wash load particles within a flume. They discriminate position and velocity components into modes of motion (as in rolling, sliding, suspended). Wide variation is noted, but the dataset is too small to access distributions of velocity or acceleration. This paper is significant, but much like Shields (1936) its significance has become entirely historical as its database contribution is completely overshadowed by modern datasets (see Heyman et al. (2016)).

- [2] C. Ancey, P. Bohorquez, and E. Bardou, “Sediment Transport in Mountain Rivers,” *ERCOFTAC Bulletin.*, vol. 100, pp. 37–52, 2014.

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- [3] C. Ancey, P. Bohorquez, and J. Heyman, “Stochastic interpretation of the advection-diffusion,” *Journal of Geophysical Research : Earth Surface*, vol. 120, pp. 325–345, 2015.

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- [4] C. Ancey, A. C. Davison, T. Böhm, M. Jodeau, and P. Frey, “Entrainment and motion of coarse particles in a shallow water stream down a steep slope,” *Journal of Fluid Mechanics*, vol. 595, no. 2008, pp. 83–114, 2008.

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- [5] C. Ancey and J. Heyman, “A microstructural approach to bed load transport: mean behaviour and fluctuations of particle transport rates,” *Journal of Fluid Mechanics*, vol. 744, no. 2014, pp. 129–168, 2014.

Ancey obtains a macroscopic exner equation from a birth death equation. This exner equation is a linear advection diffusion equation with a source term. This paper introduces linked birth-death processes between cells and takes the limit as the width of cells goes to zero to

obtain advection diffusion formulation of sediment transport. Number fluctuations in the i th cell are considered the result of four factors: (1) transport into the cell from its neighboring upstream cell; (2) individual or collective entrainment within the cell; (3) deposition within the cell; and (4) migration out of the cell to the neighboring cell downstream.

- [6] C. Ancey, “Stochastic modeling in sediment dynamics: Exner equation for planar bed incipient bed load transport conditions,” *Journal of Geophysical Research: Earth Surface*, vol. 115, no. F2, pp. n/a–n/a, 2010.

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- [7] C. Ancey, T. Böhm, M. Jodeau, and P. Frey, “Statistical description of sediment transport experiments,” *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, vol. 74, no. 1, pp. 1–14, 2006.

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- [8] Anderson P.W., “More is Different,” pp. 393–396, 1972.

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- [9] C. Arteta, V. Lempitsky, and A. Zisserman, “Interactive Object Counting,” *ECCV*, vol. 8691, 2014.

Authors pursue object counting through ridge regression. The target is a field of 2d Kronecker deltas at the point annotation of each object. The output is a 2d density map. There is no requirement of object segmentation: point annotations are sufficient. Integrals of the density map give object counts. This is a conventional algorithm which does not use neural learning.

- [10] F. Ballio, D. Pokrajac, A. Radice, and S. Hosseini Sadabadi, “Lagrangian and Eulerian Description of Bed Load Transport,” *Journal of Geophysical Research: Earth Surface*, pp. 384–408, 2018.

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- [11] F. Ballio, V. Nikora, and S. E. Coleman, “On the definition of solid discharge in hydro-environment research and applications,” *Journal of Hydraulic Research*, vol. 52, no. 2, pp. 173–184, 2014.

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- [12] T. Böhm, C. Ancey, P. Frey, J. L. Reboud, and C. Ducottet, “Fluctuations of the solid discharge of gravity-driven particle flows in a turbulent stream,” *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, vol. 69, no. 6 1, pp. 1–13, 2004.

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- [13] J. Campagnol, A. Radice, R. Nokes, V. Bulankina, A. Lescova, and F. Ballio, “Lagrangian analysis of bed-load sediment motion: Database contribution,” *Journal of Hydraulic Research*, vol. 51, no. 5, pp. 589–596, 2013.

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- [14] E. Candès and J. Romberg, “Practical Signal Recovery from Random Projections,” *IS&T/SPIE’s 17th Annual Symposium on Electronic Imaging*, vol. 2291, no. 626, p. 18, 2005.

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- [15] F. Charru, H. Moulleron, and O. Eiff, “Erosion and deposition of particles on a bed sheared by a viscous flow,” *Journal of Fluid Mechanics*, vol. 519, no. 2004, pp. 55–80, 2004.

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- [16] J. Crocker and D. Grier, “Methods of Digital Video Microscopy for Colloidal Studies,” *Journal of Colloid and Interface Science*, vol. 179, no. 1, pp. 298–310, 1996.

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- [17] T. G. Drake, R. L. Shreve, W. E. Dietrich, P. J. Whiting, and L. B. Leopold, “Bedload transport of fine gravel observed by motion-picture photography,” *Journal of Fluid Mechanics*, vol. 192, no. 1988, p. 193, 1988.

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- [18] H. A. Einstein, “Bedload transport as a probability problem,” Ph.D. dissertation, Wasserbau Eidg. Tech. , Hoschs, Zurich, 1937.

Einstein seeded tracer particles into an artificial flume and observed their movement characteristics. He interpreted particle transport as a switching process between two phases: the first is a resting phase, and the second is a movement phase. The parameter relevant to the resting phase is the time spent there, the resting time. The parameter relevant to the movement phase is the distance covered within it, the particle hop length. Time spent in motion was considered irrelevant, since the time spent in motion is very short relative to resting time. Within this formulation, the travel distance of a tracer particle in a time interval emerges from considering the phase to phase switching, in which one accounts for the total of all hop distances and the total of all resting times through the switching which occurred in the time interval.

- [19] R. Ettema and C. F. Mutel, “Hans Albert Einstein: Innovation and Compromise in Formulating Sediment Transport by Rivers,” *Journal of Hydraulic Engineering*, vol. 130, no. 6, pp. 477–487, 2004.

need to write the annotate 4 dis

- [20] S. Fathel, D. Furbish, and M. Schmeeckle, “Parsing anomalous versus normal diffusive behavior of bedload sediment particles,” *Earth Surface Processes and Landforms*, vol. 41, no. 12, pp. 1797–1803, 2016.

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- [21] S. L. Fathel, D. J. Furbish, and M. W. Schmeeckle, “Experimental evidence of statistical ensemble behavior in bed load sediment transport,” *Journal of Geophysical Research F: Earth Surface*, vol. 120, no. 11, pp. 2298–2317, 2015.

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- [22] D. J. Furbish, A. E. Ball, and M. W. Schmeeckle, “A probabilistic description of the bed load sediment flux: 4. Fickian diffusion at low transport rates,” *Journal of Geophysical Research: Earth Surface*, vol. 117, no. 3, pp. 1–13, 2012.

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- [23] D. J. Furbish, S. L. Fathel, and M. W. Schmeeckle, “Particle Motions and Bed Load Theory : The Entrainment Forms of the Flux and the Exner Equation,” in *Gravel-Bed Rivers: Processes and Distasters*, 1st ed., D. Tsutsumi and J. B. Laronne, Eds. John Wiley & Sons Ltd., 2017, ch. 4, pp. 97–120.

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- [24] D. J. Furbish, S. L. Fathel, M. W. Schmeeckle, D. J. Jerolmack, and R. Schumer, “The elements and richness of particle diffusion during sediment transport at small timescales,” *Earth Surface Processes and Landforms*, vol. 42, no. 1, pp. 214–237, 2017.

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- [25] D. J. Furbish, P. K. Haff, J. C. Roseberry, and M. W. Schmeeckle, “A probabilistic description of the bed load sediment flux: 1. Theory,” *Journal of Geophysical Research: Earth Surface*, vol. 117, no. 3, 2012.

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- [26] D. J. Furbish, J. C. Roseberry, and M. W. Schmeeckle, “A probabilistic description of the bed load sediment flux: 3. the particle velocity distribution and the diffusive flux,” *Journal of Geophysical Research: Earth Surface*, vol. 117, no. 3, 2012.

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- [27] D. J. Furbish and M. W. Schmeeckle, “A probabilistic derivation of the exponential-like distribution of bed load particle velocities,” *Water Resources Research*, vol. 49, no. 3, pp. 1537–1551, 2013.

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- [28] D. J. Furbish, M. W. Schmeeckle, R. Schumer, and S. L. Fathel, “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*, vol. 121, no. 7, pp. 1373–1390, 2016.

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- [29] M. A. Hassan and D. N. Bradley, “Geomorphic controls on tracer particle dispersion in gravel bed rivers,” *Gravel-Bed Rivers* 8, vol. 30, no. September, pp. 3–9, 2015.

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- [30] M. A. Hassan, M. Church, and A. P. Schick, “Distance of movement of coarse particles in gravel bed streams,” *Water Resources Research*, vol. 27, no. 4, pp. 503–511, 1991.

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- [31] J. Heyman, P. Bohórquez, and C. Ancey, “Exploring the physics of sediment transport in non-uniform super-critical flows through a large dataset of particle trajectories,” *J. Geophys. Res:Earth Surf.*, vol. submitted, 2015.

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- [32] J. Heyman, P. Bohorquez, and C. Ancey, “Entrainment, motion, and deposition of coarse particles transported by water over a sloping mobile bed,” *Journal of Geophysical Research: Earth Surface*, vol. 121, no. 10, pp. 1931–1952, 2016.

There is a very nice outline here of the way different approaches to stochastic sediment transport theories have arrived at the same advection diffusion formulation (as in Parker or Ancey et al 2014). This is used to introduce an overarching problem termed ‘lack of closure’ to stochastic models. Closure is the relationship between the parameters required by advection diffusion formulations of sediment transport rate to measurable channel parameters. In this paper Heyman presents an experiment where particle motion was tracked from the

side. Median background subtraction was employed to get particle velocity and acceleration distributions. There are a few unique contributions such as average particle velocity as a function of particle elevation. Two methods are described for calculating particle diffusivity. Analysis of particle properties seems to follow something similar to Ballio et al 2018, involving Gaussian smoothing kernels.

- [33] J. Heyman, H. B. Ma, F. Mettra, and C. Ancey, “Spatial correlations in bed load transport: Evidence, importance, and modeling,” *Journal of Geophysical Research: Earth Surface*, vol. 119, no. 8, pp. 1751–1767, 2014. [Online]. Available: <http://doi.wiley.com/10.1002/2013JF003003>

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- [34] —, “Spatial correlations in bed load transport : Evidence , importance , and modeling,” *Journal of Geophysical Research : Earth Surface*, pp. 1751–1767, 2014.

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- [35] J. Heyman, F. Mettra, H. B. Ma, and C. Ancey, “Statistics of bedload transport over steep slopes: Separation of time scales and collective motion,” *Geophysical Research Letters*, vol. 40, no. 1, pp. 128–133, 2013.

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- [36] T. B. Hoey, “Temporal variations in bedload transport in rates and sediment storage,” *Progress in Physical Geography*, vol. 16, no. 3, pp. 319–338, 1992.

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- [37] A. A. Kalinske, “Movement of sediment as bed load in rivers,” *Eos, Transactions American Geophysical Union*, vol. 28, no. 4, pp. 615–620, 1947.

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- [38] H. Kuhn, “The Hungarian Method for the Assignment Problem,” *Naval Research Logistics Quarterly*, vol. 2, no. 1, pp. 83–97, 1955.

This is the classic paper introducing the Hungarian method for the assignment problem. The assignment problem is the cheapest way to assign workers to jobs provided each worker has a specific cost to compete a specific job.

- [39] E. Lajeunesse, L. Malverti, and F. Charru, “Bed load transport in turbulent flow at the grain scale: Experiments and modeling,” *Journal of Geophysical Research: Earth Surface*, vol. 115, no. 4, 2010.

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- [40] E. Lajeunesse, O. Devauchelle, and F. James, “Advection and dispersion of bedload tracers,” no. November, pp. 1–19, 2017.

This is a nice physics-like paper. They take the Charru 2004 model for advection of bedload tracers and solve it both numerically and exactly in asymptotic regimes. They note super-super diffusion (to use G Parker’s term) at short timescales and Brownian diffusion (I think) at long timescales. They analyze scaling behavior of mean tracer position, variance of tracer position, and skew of tracer position, and find two scaling regimes in each. These analyses all applied for steady transport conditions. They extended their analysis to unsteady flow conditions as one finds in nature by incorporating an intermittency factor which rescales time using the fraction of above-threshold flows. They also eliminate time from the

scaling equations on variance and skew, expressing variance as a function of travel distance. "According to this model, it should be possible to estimate the particle flight length and the average bed load transport rate from the evolution of the variance and the skewness of a plume of tracers in a river."

- [41] H. Ma, J. Heyman, X. Fu, F. Mettra, C. Ancey, and G. Parker, "Bed load transport over a broad range of timescales: Determination of three regimes of fluctuations," *Journal of Geophysical Research: Earth Surface*, vol. 119, no. 12, 2014.

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- [42] P. A. Nelson, D. Bellugi, and W. E. Dietrich, "Delineation of river bed-surface patches by clustering high-resolution spatial grain size data," *Geomorphology*, vol. 205, pp. 102–119, 2014.

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- [43] M. Pietikäinen, M. Turk, L. Wang, G. Zhao, and L. Cheng, "Machine learning in motion analysis: New advances," *Image and Vision Computing*, vol. 31, no. 6-7, pp. 419–420, 2013.

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- [44] A. Radice, S. Malavasi, and F. Bailio, "Solid transport measurements through image processing," *Experiments in Fluids*, vol. 41, no. 5, pp. 721–734, 2006.

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- [45] A. Radice, F. Ballio, and V. Nikora, "On statistical properties of bed load sediment concentration," *Water Resources Research*, vol. 45, no. 6, pp. 1–8, 2009.

This is a long duration video observation of bedload transport. A nice quote from the introduction: many empirical and phenomenological formulations for predicting solid discharge in open channels have been proposed. However, the estimates of the solid transport rate using these conventional equations proved to be highly uncertain [e.g., Gomez and Church, 1989; Martin, 2003], leading to increased attention to the small-scale details of sediment transport, which could help in advancing the existing relationships." They also note several observations that bedload velocity is only weakly dependent on shear stress conditions at the bed, meaning activity or concentration fluctuations drive sediment transport fluctuations. This is in agreement with Ancey 2008. They measure water flow in 1D with ADV. They find an inertial range with $-5/3$ exponent. They find scaling behavior in sediment concentration fluctuations: exponent $-5/3$ was obtained characteristic of the fluid and concentration profiles. The experiment observed dyed tracer grains from above at low transport stages with no sediment recirculation.

- [46] J. C. Roseberry, M. W. Schmeeckle, and D. J. Furbish, "A probabilistic description of the bed load sediment flux: 2. Particle activity and motions," *Journal of Geophysical Research: Earth Surface*, vol. 117, no. 3, 2012.

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- [47] M. Saletti, P. Molnar, A. E. Zimmermann, M. A. Hassan, and M. Church, "Temporal variability and memory in sediment transport in an experimental step-pool channel," *Water Resour. Res.*, vol. 51, pp. 1649–1670, 2015.

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- [48] W. Sayre and D. Hubbell, “Transport and Dispersion of Labeled Bed Material North Loup River , Nebraska,” *Transport of Radionuclides by Streams*, 1965.

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- [49] M. W. Schmeeckle, J. M. Nelson, and R. L. Shreve, “Forces on stationary particles in near-bed turbulent flows,” *Journal of Geophysical Research: Earth Surface*, vol. 112, no. 2, pp. 1–21, 2007.

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- [50] J. Schmidhuber, “Deep Learning in neural networks: An overview,” *Neural Networks*, vol. 61, pp. 85–117, 2015.

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- [51] G. Seizilles, E. Lajeunesse, O. Devauchelle, and M. Bak, “Cross-stream diffusion in bedload transport,” *Physics of Fluids*, vol. 26, no. 1, 2014.

need to write the annotate 4 dis

- [52] A. Singh, K. Fienberg, D. J. Jerolmack, J. Marr, and E. Foufoula-Georgiou, “Experimental evidence for statistical scaling and intermittency in sediment transport rates,” *Journal of Geophysical Research: Earth Surface*, vol. 114, no. 1, pp. 1–16, 2009.

This is one of two papers I know of which measure a time series of bed elevations within a location in a flume experiment.

- [53] B. M. Sumer, L. H. C. Chua, N.-S. Cheng, and J. Fredsøe, “Influence of Turbulence on Bed Load Sediment Transport,” *Journal of Hydraulic Engineering*, vol. 129, no. 8, pp. 585–596, 2003.

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- [54] J. G. Venditti, P. A. Nelson, R. W. Bradley, D. Haught, and A. B. Gitto, “Bedforms, Structures, Patches, and Sediment Supply in Gravel-Bed Rivers,” *Gravel-Bed Rivers*, pp. 439–466, 2017.

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- [55] H. Voepel, R. Schumer, and M. A. Hassan, “Sediment residence time distributions: Theory and application from bed elevation measurements,” *Journal of Geophysical Research: Earth Surface*, vol. 118, no. 4, pp. 2557–2567, 2013.

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- [56] Y. Xue, N. Ray, J. Hugh, and G. Bigras, “A novel framework to integrate convolutional neural network with compressed sensing for cell detection,” *IEEE Transactions on Image Processing*, pp. 2319–2323, 2017.

The authors use a convolutional neural network which takes in an image containing objects and gives out a vector. This vector is a compressed representation of the pixel level positions of objects within the image. The vector is formed by multiplying the sparse array encoding pixel level positions by a Gaussian random matrix. Compressed sensing theory provides a way to recover the encoded signal with high accuracy using L1 optimization.