AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Earth Surface

COMMENTARY
10.1029/2018JF004957

Key Points:
- Humans make deliberate, real-time interventions into geomorphic processes, especially during major storm events
- Existing morphodynamic models are not built to account for active, responsive human interventions
- Evolving model platforms may need to explicitly address active human interventions as morphodynamic processes unto themselves

Correspondence to:
E. D. Lazarus and E. B. Goldstein,
e.d.lazarus@soton.ac.uk;
@envidynxlab;
egoldste@uncg.edu; @ebgoldstein

Citation:
Lazarus, E. D., & Goldstein, E. B. (2019). Is there a bulldozer in your model?. *Journal of Geophysical Research: Earth Surface*, *124*. https://doi.org/10.1029/2018JF004957

Received 20 NOV 2018
Accepted 8 FEB 2019
Accepted article online 11 FEB 2019

Is There a Bulldozer in your Model?

Eli D. Lazarus[1] and Evan B. Goldstein[2]

[1]Environmental Dynamics Lab, School of Geography and Environmental Science, University of Southampton, Southampton, UK, [2]Department of Geography, Environment, and Sustainability, University of North Carolina at Greensboro, Greensboro, NC, USA

Abstract Deliberate, real-time human interventions into geomorphic processes are a phenomenon that no off-the-shelf numerical model of morphodynamics is built to capture. We suggest that active, responsive human processes that affect sediment transport during major storm events be included in evolving efforts to model geomorphic change.

During storm events, substantive real-time information now comes from crowd-sourced social media. This past year, we noticed moments of coverage, via Twitter, that captured something surprising: operators of heavy machinery intervening in storm-driven sediment transport in the midst of—not after—major storm events (Figure 1). We saw this for three separate events in 2018: twice along barrier islands of the North Carolina Outer Banks (USA), during Winter Storm Riley (March 2018) and Hurricane Florence (September 2018), and once in northern Italy, during a period of heavy rainfall and flash flooding (October 2018). In North Carolina, even as overwash flow surged past their tires, front-end loaders pushed sand into fresh gaps in the dune line that separates State Highway 12 from the Atlantic Ocean (Figures 1a–1d; Baldwin Video Productions, 2018; Flynn, 2018; Hampton, 2018; North Carolina Department of Transportation, 2018). In the Italian town of Cortina d'Ampezzo, an excavator drove into the flooded Boite River at Bigontina to remove cobbles and gravel from the channel under a narrow bridge crossing (Figure 1e) (severe-weather.eu, 2018).

World-leading platforms for numerically modeling morphodynamic systems are exceptionally powerful tools, capable of rendering complex, three-dimensional fluid flows, sediment transport, and mobile topography over a range of spatial and temporal scales. Broadly posed, the purpose of a "process-based" numerical morphodynamic model is to use the physics that governs flow and sediment transport to predict topographic change. Morphodynamic modeling suites now address myriad coastal, fluvial, and aeolian processes, including wave refraction, shoaling, and breaking; long-wave transformation; wave-induced setup and unsteady currents; breaching, overwash, and flood inundation; bedload and suspended-sediment transport; dune-face avalanching; bed updating; biogeomorphic effects of vegetation; and effects of dredging and hard structures. But these models lack any protocol for simulating an earth-moving machine as it plows sand into an active dune breach or digs out a river channel in peak flood.

From a geomorphic perspective, the observations from North Carolina and Cortina are intriguing because they record dynamic human interventions and storm-driven morphodynamic processes happening simultaneously. This kind of intervention is fundamentally different from a passive defensive structure such as a seawall, levee, or even an artificial dune, and likewise different from poststorm repair. Numerical models can account for passive defenses because, once emplaced, they function in the landscape as fixed elements: hydrodynamics at a seawall or levee can be calculated, and erosion of an existing dune can be predicted. But unlike seawalls and levees, a front-end loader functions as an active, responsive physical process of sediment transport unto itself. Equipment operators make responsive decisions based on the storm impacts happening around them, and those actions take time to execute. An operator scooping away the initial beds of a flood deposit even as deposition occurs is altering the evolving morphodynamics at that site and thus, in turn, is forcing a departure from whatever prediction of poststorm impact that a traditional morphodynamic model might have generated.

Such ostensibly small changes from mechanized earth moving can have an outsized impact on how a morphological event plays out. On a coastal barrier, for example, the dune crest is a vertical threshold that storm-driven flow from the seaward side must breach to impact sites beyond the beach. Subtle but continuous modification of the dune—with heavy machinery—to maintain a threshold height might be

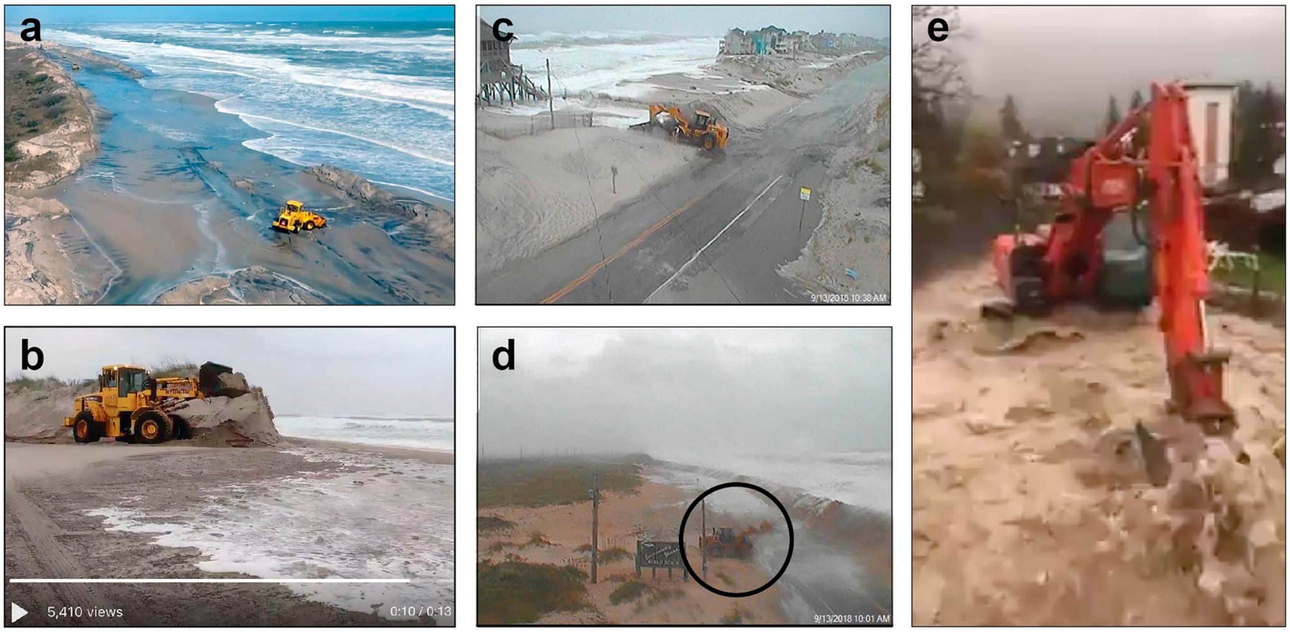

Figure 1. Examples, drawn from social media, of direct morphodynamic interventions by earth-moving equipment during extreme storm events in 2018. Panels (a)–(d) show active overwash on the North Carolina Outer Banks (USA) barrier islands from (a) Winter Storm Riley, in March 2018 (Baldwin Video Productions, 2018) and (b–d) Hurricane Florence, in September 2018. Panel (b) is a video frame (Hampton, 2018); panels (c) and (d) North Carolina Department of Transportation (NC DOT) traffic cameras (Flynn, 2018). Panel (e) is a video frame from Cortina, Italy, showing an excavator digging cobble and gravel from inside a flooded channel in October 2018 (severe-weatherEU, 2018).

enough to prevent overwash flooding. That prevention of flooding matters to infrastructure in the built environment and also to the geomorphic evolution of the barrier in the long term: overwash flow delivers sediment from the shoreface to the back barrier, serving as the mechanism by which a barrier can maintain its elevation and width with sea-level rise (e.g., Lorenzo-Trueba & Ashton, 2014). Paradoxically, cutting off the cross-shore sediment pathways of a barrier system can render the landscape more vulnerable to storm events in the short term and to eventual drowning in the long term (Rogers et al., 2015). A similar example may be extended to interventions along river systems, which have analogous morphological effects on both short-term flood hazard and long-term floodplain resilience (Criss & Shock, 2001; Baldassarre et al., 2013).

These modes of midstorm anthropogenic sediment flux all but defy measurement. Even the volume of sediment displaced in the course of post storm emergency response (e.g., Goldstein, 2018; Whitehead, 2018)—to say nothing of midstorm intervention—remains largely unquantified (Nordstrom, 1994, 2000). Coastal barrier overwash, for example, can deposit tens to hundreds of thousands of cubic meters of sediment per kilometer alongshore in a single event (Carruthers et al., 2013; Morton & Sallenger, 2003), even in built settings (Rogers et al., 2015). A handful of coastal geomorphologists have recognized the geomorphic importance of local public works that clear sand from roads and streets (e.g., Nordstrom, 1994), but hazard geomorphology has not comprehensively quantified the volumes moved by emergency crews. The consequence of this missing information may be inaccurate predictions from the process-based models upon which decision makers increasingly rely—and that further improvements to modeled formulations for "natural" flow and sediment transport will never remedy.

The answer may be to explicitly model active human interventions as morphodynamic processes, thereby making sediment transport driven by a bulldozer no less important than sediment transport driven by fluid flow. The "efficacy of humans as geomorphic agents" (Hooke, 1994) is now an established concept in geomorphology (Haff, 2002, 2003, 2010, 2014; Hooke et al., 2012; Tarolli et al., 2017; Wilkinson & McElroy, 2007), even if the dynamics of human geomorphic agency remain murky. Adding a "responsive intervention" capability to morphodynamic models would make them more complete and comprehensive, because deliberately intervening in a morphodynamic event may divert a system to a "final" morphological state markedly different from the one that would have manifested otherwise. Agent-based models of coupled human-landscape system dynamics exist, but they include post facto or passive hazard defenses like beach nourishment (Lazarus et al., 2011; McNamara & Werner, 2008; Williams et al., 2013), artificial dunes (Magliocca et al., 2011), and river levees (Werner & McNamara, 2007). Model agents engage after a storm event has passed, and completed defenses appear instantaneously in the modeled landscape (e.g., a fully widened beach, a fully rebuilt dune, a uniformly raised levee). None of these models tracks the movements of heavy equipment, especially during an extreme event.

The modeling approach that we propose is difficult but not intractable. For example, an agent-based model of a developed barrier island, by McNamara and Werner (2008), includes two separate operating time scales: one fast, for storm events, on the order of hours to days and one slow, for interstorm periods, on the order of years to decades. Such a two-time scale approach could be more widely adopted into morphodynamic models—coastal and fluvial—that aim to address storm and interstorm periods, with earth-moving machinery acting in the former. Models that include responsive intervention could be used to explore and address hazard-mitigation strategies for typical storm scenarios. On a coastal barrier, for example, is it more efficient and effective for earth movers to maintain dune height or dune width during a typical storm? For a given magnitude of storm event, what is the lowest dune height (and/or minimum dune volume) that can still protect island infrastructure from damage? How many front-end loaders are needed to maintain the minimum essential dune for a given storm event? Numerical experiments could test different system interventions and be used to guide operator decisions. A future in which these morphodynamic models run during storm events, informing earth-moving interventions by enabling operators (or autonomous vehicles) to receive orders and updates in real time, is perhaps not far away.

Incorporating mechanized earth moving into morphodynamic models will require that we better understand and quantify the processes and effects of earth-moving interventions and operator decision making during storm events. We are currently unaware of any existing data to tackle this problem. For example, we recently wrote to the North Carolina Department of Transportation, which maintains the nearly 240-km length of State Highway 12 along the barrier islands of the Outer Banks, to ask if their equipment, like the machinery pictured in Figures 1a–1d, have GPS transmitters that record their positions during a given deployment. A department official confirmed that they do not. Nevertheless, it is reasonable to expect that in a future "internet of things" more heavy machinery will have this capacity (e.g., Fu et al., 2017). Many morphodynamic models are free, open-source software that evolve with the needs of the user communities. In that context, a "bulldozer module" appears within reach, whereby empirical data from actual equipment-operator behavior could be included in experiments with numerical morphodynamic models.

Acknowledgments
The authors gratefully acknowledge financial support from NERC BLUECoast (EDL; NE/N015665/2), DOD DARPA (EBG; R0011836623/HR001118200064), and The Leverhulme Trust (EDL & EBG; RPG-2018-282). We thank Peter Haff, an anonymous reviewer, and Giovanni Coco for providing insightful and constructive reviews. There are no data to declare; all social media sources are cited with URLs.

References

Baldassarre, G. D., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., & Blöschl, G. (2013). Socio-hydrology: Conceptualising human-flood interactions. *Hydrology and Earth System Sciences*, *17*(8), 3295–3303. https://doi.org/10.5194/hess-17-3295-2013

Baldwin Video Productions (2018). Winter Storm Riley damage to Rt. 12 [Facebook status update, 2018, March 5], Retrieved from https://www.facebook.com/baldwinvideo/videos/972235979599654/

Carruthers, E. A., Lane, D. P., Evans, R. L., Donnelly, J. P., & Ashton, A. D. (2013). Quantifying overwash flux in barrier systems: An example from Martha's Vineyard, Massachusetts, USA. *Marine Geology*, *343*, 15–28. https://doi.org/10.1016/j.margeo.2013.05.013

Criss, R. E., & Shock, E. L. (2001). Flood enhancement through flood control. *Geology*, *29*(10), 875–878. https://doi.org/10.1130/0091-7613(2001)029<0875:FETFC>2.0.CO;2

Flynn, M. (RippleEnviro) (2018). "Storm surge has begun to overwash the dunes during the last hour on the incoming tide. Sending well wishes to that brave operator working to hold the line. #Florence #NC12 #OBX." [Tweet] https://twitter.com/RippleEnviro/status/104025398586794803.13 Sep 2018, 15:00 UTC.

Fu, J., Jenelius, E., & Koutsopoulos, H. N. (2017). Identification of workstations in earthwork operations from vehicle GPS data. *Automation in Construction*, *83*, 237–246. https://doi.org/10.1016/j.autcon.2017.08.023

Goldstein, E. (ebgoldstein) (2018). "Very interesting photos coming out of Surf City NC. they seem to be scraped back up the washover to build back the dune." [Tweet] https://twitter.com/ebgoldstein/status/1041502488585756674, 17 Sep 2018, 01:41 UTC.

Haff, P. K. (2002). Neogeomorphology. *Eos, Transactions American Geophysical Union*, *83*(29), 310–317. https://doi.org/10.1029/2002EO000223

Haff, P. K. (2003). Neogeomorphology, prediction, and the anthropic landscape. In P. R. Wilcock & R. M. Iverson (Eds.), *Prediction in Geomorphology Geophysical Monograph Series* (Vol. 135, pp. 15–26). Washington, DC: American Geophysical Union.

Haff, P. K. (2010). Hillslopes, rivers, plows, and trucks: Mass transport on Earth's surface by natural and technological processes. *Earth Surface Processes and Landforms*, *35*(10), 1157–1166. https://doi.org/10.1002/esp.1902

Haff, P. K. (2014). Technology as a geological phenomenon: Implications for human well-being. *Geological Society, London, Special Publications*, *395*(1), 301–309. https://doi.org/10.1144/SP395.4

Hampton, J. (jeffhampton56) (2018). Road grader pushes sand Friday morning from NC 12 near Hatteras Village where surf broke through 8 foot dunes during high tide Thursday. [Tweet] https://twitter.com/jeffhampton56/status/1040575254555373570, 14 Sep 2018, 12:17 UTC.

Hooke, R. L. B. (1994). On the efficacy of humans as geomorphic agents. *GSA Today*, *4*(9), 224–225.
Hooke, R. L., Martín-Duque, J. F., & Pedraza, J. (2012). Land transformation by humans: A review. *GSA Today*, *22*(12), 4–10.
Lazarus, E. D., Mcnamara, D. E., Smith, M. D., Gopalakrishnan, S., & Murray, A. B. (2011). Emergent behavior in a coupled economic and coastline model for beach nourishment. *Nonlinear Processes in Geophysics*, *18*(6), 989–999. https://doi.org/10.5194/npg-18-989-2011
Lorenzo-Trueba, J., & Ashton, A. D. (2014). Rollover, drowning, and discontinuous retreat: Distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. *Journal of Geophysical Research: Earth Surface*, *119*, 779–801. https://doi.org/10.1002/2013JF002941
Magliocca, N. R., McNamara, D. E., & Murray, A. B. (2011). Long-term, large-scale morphodynamic effects of artificial dune construction along a barrier island coastline. *Journal of Coastal Research*, *27*(5), 918–930.
McNamara, D. E., & Werner, B. T. (2008). Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. *Journal of Geophysical Research*, *113*, F01016. https://doi.org/10.1029/2007JF000840
Morton, R. A., & Sallenger, A. H. Jr. (2003). Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research*, *19*(3), 560–573.
North Carolina Department of Transportation (2018). "Today, just south of the Bonner Bridge area, DOT staff are working to clear the overwash from the recent tides. With the high tides tonight and tomorrow morning, NC-12 is now expected to reopen around tomorrow evening (March 6) and: http://bit.ly/2D4WY5i" [Tweet] https://twitter.com/NCDOT_NC12/status/970774304613953536, 05 Mar 2018, 21:33 UTC.
Nordstrom, K. F. (1994). Beaches and dunes of human-altered coasts. *Progress in Physical Geography*, *18*(4), 497–516. https://doi.org/10.1177/030913339401800402
Nordstrom, K. F. (2000). *Beaches and dunes of developed coasts*. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9780511549519
Rogers, L. J., Moore, L. J., Goldstein, E. B., Hein, C. J., Lorenzo-Trueba, J., & Ashton, A. D. (2015). Anthropogenic controls on overwash deposition: Evidence and consequences. *Journal of Geophysical Research: Earth Surface*, *120*, 2609–2624. https://doi.org/10.1002/2015JF003634
severe-weatherEU (severeweatherEU). (2018). "Today in north Italy. Would you dare do this? Is this a smart thing to do? Video: Marco Bellodis" [Tweet] https://twitter.com/severeweatherEU/status/1056639867663327240, 28 Oct 2018, 20:12 UTC.
Tarolli, P., Sofia, G., & Ellis, E. (2017). Mapping the topographic fingerprints of humanity across Earth. *Eos*, *98*, 13–15.
Werner, B. T., & Mcnamara, D. E. (2007). Dynamics of coupled human-landscape systems. *Geomorphology*, *91*(3–4), 393–407. https://doi.org/10.1016/j.geomorph.2007.04.020
Whitehead, J. (JCWclimate) (2018). "@ebgoldstein Probably. These commonly happen in bad nor'easters too. Locals call them dune pushes. Sand has to get out of the road and go somewhere so it goes back to a dune." [Tweet] https://twitter.com/JCWclimate/status/1041503920022085633, 17 Sep 2018, 01:47 UTC.
Wilkinson, B. H., & McElroy, B. J. (2007). The impact of humans on continental erosion and sedimentation. *Geological Society of America Bulletin*, *119*(1–2), 140–156. https://doi.org/10.1130/B25899.1
Williams, Z. C., McNamara, D. E., Smith, M. D., Murray, A. B., & Gopalakrishnan, S. (2013). Coupled economic-coastline modeling with suckers and free riders. *Journal of Geophysical Research: Earth Surface*, *118*, 887–899. https://doi.org/10.1002/jgrf.20066