Building quantitative skills with a simplified physical model of coastal storm deposition

Eli D. Lazarus

Environmental Dynamics Lab, School of Geography & Environmental Science, University of Southampton, Southampton, SO17 1BJ, UK

correspondence to: E.D.Lazarus@soton.ac.uk

ORCiD: 0000-0003-2404-9661

Abstract

This article describes an exercise for a physical laboratory experiment designed to enable physical geography students to practice transferrable quantitative skills through inquiry-based learning. The exercise is a deliberately simplified physical model of storm-driven coastal overwash typical of low-lying coastal barrier systems. The experiment can be trialled in anything from a baking pan or plastic tub to a specialised flume; set-up requires an erodible barrier with a low height relative to its alongshore length. Flow across the barrier is called overwash, which leaves behind depositional features called washover. Students measure geometric characteristics, or morphometry, of the experimental washover and examine them with scaling relationships. Here I present a dataset of nearly 450 student measurements, along with a sample of my own, from six experimental trials to demonstrate that students with little or no preparatory training were able to successfully complete the exercise and collectively generate a dataset of washover morphometry that resembles scaling relationships from the published literature. Using inquiry-based observations of a physical process to steer morphometric measurements that in turn motivate methods for quantitative analysis may serve as an effective means of embedding quantitative training in a physical geography syllabus or programme curriculum.

Keywords

physical laboratory experiment; inquiry-based learning; stream table; flume; coastal processes; washover

Introduction

The importance of transferrable quantitative skills for geography graduates is well-documented among employers, educators, and students (Harris et al., 2013), and in the UK is benchmarked in quality-assurance standards for university degrees in geography (QAA, 2022). Nevertheless, enabling students to develop quantitative skillsets represents a persistent challenge in teaching geography (Keylock and Dorling, 2004; Harris et al., 2013, 2014). Part of the challenge is contextual: students in any given module likely reflect a split camp (Harris et al., 2013), where for every student who feels confident with quantitative exercises there is another who does not. Another part of the challenge is practical: regardless of the relative quantitative confidence in the room, an inclusive formative exercise – where a primary intended learning outcome is to practice a skill – should be something that every student can reasonably complete. Acknowledging the benefits of quantitative skills is easy; testing a quantitative skill-building activity in the crucible of a classroom is the stuff that keeps teachers awake at night.

I currently teach a module on coastal environments for second-year undergraduates. Not all who enrol are pursuing a degree in physical geography. The module must be able to accommodate upwards of 60 students, and at present does not include a field component. For several years I have run the module in a lecture format. To try embedding more quantitative training outside the palisades of a "standalone" skills module (Keylock and Dorling, 2004; Harris et al., 2013) – and to counteract an annual free-fall in late-semester attendance – I decided to integrate a constructivist element of inquiry-based learning (Spronken-Smith et al., 2008; Day, 2012; Seel, 2017). Specifically, I wanted to design a piece of activity-driven coursework that would address several aims relevant to preparing second-year undergraduates for requirements typical of their final year, including an independent research project (an undergraduate dissertation, in UK terminology). In the low-stakes setting of my coastal module, I wanted students to observe a dynamical physical process; take measurements motivated by their observations to create their own dataset; explore their data through visualisation (i.e., plotting variables); explain what their plots conveyed; and situate the concept of the exercise in a wider context by relating it to published literature. A dissertation, in microcosm.

I made the vehicle for this exercise in inquiry-based learning a physical laboratory experiment. A recent review by Seel (2017) surveys the theoretical basis for "model-based learning" as an effective method for galvanising understanding. Physical (and virtual) laboratory investigations "provide opportunities for students to interact directly with the material world using the tools, data collection techniques, models, and theories of science" (de Jong et al., 2013), and physical geography has a long tradition of engaging such approaches (Day, 2012). And there is a kind of infectious magic in physical experiments, particularly those involving sediment transport. Hooke (1968) remarked on the striking similarities that can emerge in laboratory models relative to their field counterparts. Paola et al. (2009), borrowing from Wigner (1960), unpacked Hooke's observation to explain and formalise what they termed "the 'unreasonable effectiveness' of stratigraphic and geomorphic experiments". Even a basic physical model can offer a different vantage of real-world landscape dynamics.

Here, I present the basic premise and reproducible design for a deliberately simplified physical laboratory experiment that generates sedimentary features analogous to coastal overwash morphology. The design draws on experiments trialled in tubs (Lazarus and Armstrong, 2015), tanks (Lazarus, 2016; Lazarus et al. 2020), and flumes (Lazarus et al., 2022). I offer this activity as a resource for other teachers because I am encouraged, and indeed surprised, by the robustness and consistency of its results, even among students with no prior knowledge of overwash processes and no shared baseline quantitative skillset. The experiment requires care but not exactitude in set-up and measurement, freeing students – and teachers – to focus on data interpretation and critical explanation.

Materials and methods

Coastal overwash morphology and morphometry

Overwash is a process of cross-shore sediment transport typically driven by coastal storms, and is a principal mechanism by which low-lying coastal barrier systems maintain their height and width relative to sea level (Donnelly et al., 2006; FitzGerald et al., 2008; Nienhuis and Lorenzo-Trueba, 2019). Overwash occurs when water on one side of the barrier becomes sufficiently superelevated – such as through a combination of high tide, wave set-up, and storm surge – to overtop or inundate the barrier crest (Sallenger, 2000; Donnelly et al., 2006). Overwash is the flow of water across the barrier; washover is the sedimentary deposit that overwash leaves behind (**Fig. 1a**). Overwash morphology refers to the various features formed by overwash flow, including erosional and distributary channels (*cf.* Sherwood et al., 2023; Lazarus, 2023).

Recent work has shown that washover, in the field and laboratory, reflects morphometric scaling relationships (Lazarus, 2016; Lazarus et al., 2020, 2021, 2022). Morphometric scaling means that the a geometric characteristic changes in a systematic way relative to another (Dodds and Rothman, 2000). In physical landforms, the archetypal example of morphometric scaling derives from the planform shape of river catchments, where catchment length and area are related by a power function (Hack, 1957). Washover exhibits a scaling relationship between perimeter and area that is useful for examining controls on washover expression by floodplain elements such as topography, vegetation, or buildings (Lazarus et al., 2021, 2022). For students, morphometric analysis may serve as an accessible point of entry into quantitative physical geography because they can rapidly create a novel – and, depending on their patience, potentially large – dataset by digitising landscape features from aerial photos, remotely sensed imagery, or digital terrain maps.

Laboratory investigations of overwash dynamics tend to consider a coastal barrier in cross-shore profile (Donnelly et al., 2006; Williams et al., 2012). By contrast, this exercise produces a spatially extended pattern of washover deposits alongshore (Lazarus and Armstrong, 2015; Lazarus, 2016; Lazarus et al., 2022). Allowing formation of an alongshore array of washover creates opportunities for dynamic interactions between neighbouring deposits, emergence of a self-organised spacing between deposits, and for deposits to develop complete three-dimensional geometry. In practical terms of classroom efficiency, an array of washover also means more features for students to measure per experimental trial.

Essential design components and running the experiment

The essential element of this experimental design is that the barrier aspect ratio is stretched in the alongshore dimension, such that barrier height is low relative to the alongshore length. For example, a barrier 600 mm long and 10 mm high may yield ~7–10 washover deposits (Lazarus and Armstrong, 2015); a barrier twice as high may yield half as many washovers. The experiment is comparatively less sensitive to barrier width. A wide barrier renders the experiment flow-limited: there is as much sediment available in the barrier as overwash is able to entrain. A narrow barrier will be sediment-limited, but will still produce washover deposits.

The basic set-up requires a shallow rectangular tray or tank, ideally with a drain tapped at one end (**Fig. 1b**). The barrier, which can be made with fine to coarse sand, is built across the tank in a way that establishes an "ocean" (reservoir) side and a "back-barrier" side. Shaping the barrier with a removable mold or rigid screed ensures that the barrier top is essentially flat (Lazarus and Armstrong, 2015; Lazarus, 2016; Lazarus et al., 2022). The absence of any topographic features is a key initial condition for a trial intended to demonstrate self-organisation. Topographic controls in the barrier itself may be a comparative condition that students wish to impose. With a hose and water at very low flow (the rate will vary with tank size), the "ocean" reservoir gets filled slowly. (A powerful or splashy inflow may require baffling, such as with a mesh bag of pea gravel.) As water permeates the sand, some water will leak under the barrier. Eventually, when the reservoir is full, a lens of water will propagate across the barrier surface and over the back-barrier edge, initiating washover in a regime akin to inundation (Sallenger, 2000). With the inflow running, and the "back-barrier" side of the tank allowed to drain, washover deposits will develop over the course of a few minutes (**Fig. 1c**). Note that even subtle irregularities in the initial barrier topography may be sufficient to steer the overwash flow toward a single site, inhibiting the initiation of any others. If this happens, perturbing the reservoir with a "wavemaker" (a wooden block, a large sponge, a flat hand) can drive overwash across more of the barrier surface. Such an intervention will not ruin the trial: again, the purpose of this experiment is to produce washover morphometry, not to resolve the forcing hydrodynamics of overwash flow. The experimental trial is over when sand grains are no longer visibly moving across the back-barrier transition; inflow can be turned off and the tank drained, so that washover morphometry can be measured. The barrier can be rebuilt and trials repeated successfully with wet sand.

Observations and measurements

The physics of forces of flow and sediment transport in this experiment do not scale with overwash in the field. But in their morphometry, the experimental washover deposits will share geometric and kinematic similarity with full-scale washover. Paola et al. (2009) refer to this as external similarity, and emphasise that a lack of dynamic similarity should not *a priori* discourage experimentation: "Informally, we might say that systems showing geometric similarity look like one another, those showing kinematic similarity act like one another, and those showing complete dynamic similarity are mechanistically like one another."

Here, the progress of the experiment may be recorded with an overhead camera, and students may draw schematic diagrams of what they observe happening. If the equipment is available, the initial and final configurations of the tank may be surveyed with a terrestrial laser scanner to generate high-resolution digital elevation models (DEMs) of the pre- and post-overwash barriers

(Lazarus, 2016; Lazarus et al., 2022). Students can measure washover morphometry in other ways, without a laser scanner. With an overhead camera, if the camera mount is approximately orthogonal and a length scale (e.g., ruler) is within the field of view, then students can digitise the washover deposits in open GIS software and, with some unit conversion, calculate two-dimensional geometric characteristics (e.g., length, width, perimeter, area, spacing). Alternatively, students can measure deposit length, width, perimeter, and spacing with string and a ruler or metre stick, and measure area by tracing the approximate outline of each deposit on graph paper.

Results

To demonstrate the general insensitivity of this exercise to imprecision among participants, I present 449 independent observations of washover deposits by 19 students, along with 35 independent observations of my own, taken from six experimental trials.

We conducted the exercise using an Armfield S12-MKII-50 Advanced Environmental Hydrology System, which has a 1000 x 2000 mm stainless-steel tank with a water inlet at its head and an outlet drain at its foot. We constructed a barrier of medium sand 20 mm deep across the 1000 mm span of the tank. Barrier width varied 200–500 mm between trials. The barrier in each trial was topographically featureless, but in four of the six trials we introduced Lego "obstructions" to the back-barrier floodplain (**Fig. 1b**). The obstructed fraction of the floodplain (obstructed relative to total area proximal to the back-barrier edge) was approximately 0.2–0.3. Obstructions – gridded in two trials and arranged haphazardly in two others – were fit onto Lego base plates and the plates affixed to the tank with temporary adhesive. We surveyed the tank before and after each trial with a terrestrial laser scanner to create DEMs of the experimental topography. Students used the resulting DEMs to interpret and digitise deposit footprints in QGIS (v.3.36.2), from which they extracted measurements for deposit perimeter, area, and volume (**Fig. 2**).

I did not show the students what to digitize, yet their results reflect a notable degree of collective accuracy (**Fig. 3**). Their scaling relationships for washover perimeter and volume as a function of area, respectively, broadly take the pattern of a power law, qualitatively consistent with published results (Lazarus, 2016; Lazarus et al., 2021, 2022). Distributions of morphometric measurements by the students are effectively indistinguishable statistically from my own (**Fig. 4**).

The scaling relationship between washover volume and area (**Fig. 3b**) in this exercise is more scattered than the relationship between perimeter and area (**Fig. 3a**), likely because in many places deposition was visibly evident but only a few grains deep (~2–3 mm), commensurate with the lower limit of the vertical resolution of the terrestrial laser scanner and therefore challenging to discern in the DEM. The heavy-tailed distribution of the volume measurements (**Fig. 4c**) likewise points to volume as the most sensitive of the three morphometrics we measured. This suggests that students were able to reasonably identify washover shape, but subtle differences in the specific placement of their digitized washover footprints affected potentially large differences in volume.

Students had access to relevant articles (i.e., Lazarus, 2016; Lazarus et al., 2022), but received no mock examples or past exercises to which to compare their work. The 19 students whose results are reported here shared their data with me without having received any feedback on their coursework submission. During an in-class work session following the trials, students may have conferred and qualitatively compared their digitised footprints with each other in small groups of two or three, but all submitted their own data interpretations.

Discussion

Physical geography has a proud legacy of do-it-yourself stream tables (or table-top flumes) for teaching and experimentation (e.g., Payne and Fetherston, 1983; Wikle and Lightfoot, 1997; Smith, 1998), which now extends to recent innovations in "tangible landscape modelling systems" or "augmented reality sandboxes" (e.g., Woods et al., 2016; Hofierka et al., 2022). This exercise for producing washover in a box need not be complicated, nor reflect dynamic similarity, to be a useful way of teaching and learning about exploring and examining quantitative characteristics of physical landscapes. Paola et al. (2009) echo Hooke (1968) in their encouragement that there is valuable insight and inspiration to gain from "[treating] experiments not as models or miniatures, but simply as small systems in their own right."

Moreover, scaling relationships offer a conceptual gateway and tractable approach through which students may begin investigating an expansive variety of physical and social systems of their own choosing. Scaling relationships are a fundamental property of complex systems (Bak, 1996; Sornette, 2006; West, 2018); although complexity science is likely beyond the scope of most undergraduate geography curricula, signposting complex systems as a rich theoretical sphere might inspire geography students to pursue further research and continued study.

Supporting materials

Materials for replicating the data-analysis elements of this exercise are available from Lazarus (2024). These include: a post-trial DEM for a barrier with a "bare" back-barrier floodplain; step-by-step instructions for using the DEM to digitize and measure the washover deposits in QGIS; a Python script for plotting the data; and the dataset presented in Figs. 3 and 4. The DEM in these supporting materials differs sightly from the version used by the students whose data are reported here: to simplify the exercise for broader audiences (and obviate the need for additional files), this DEM has been vertically adjusted.

Acknowledgments

I am grateful to the students of module GGES2021 (Spring 2024) for their engagement with this exercise; to Peter Morgan, Luke Everett, Kamil Zahorski, Christopher Tomsett, and Julian Leyland for their technical support and provision of laboratory capacity for teaching and learning in the School of Geography and Environmental Science at the University of Southampton; and to Hannah Williams, Scott Armstrong, Evan Goldstein, and Alida Payson.

Disclosure statement

The author reports no conflicts of interest.

References

Bak, P. (1996). *How nature works: The science of self-organized criticality*. Springer New York.

Day, T. (2012). Undergraduate teaching and learning in physical geography. *Progress in Physical Geography*, 36(3), 305–332. https://doi.org/10.1177/0309133312442521

de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and virtual laboratories in science and engineering education. *Science*, 340(6130), 305–308. https://doi.org/10.1126/science.1230579

Dodds, P. S., & Rothman, D. H. (2000). Scaling, universality, and geomorphology. *Annual Review of Earth and Planetary Sciences*, 28(1), 571–610. https://doi.org/10.1146/annurev.earth.28.1.571

Donnelly, C., Kraus, N., & Larson, M. (2006). State of knowledge on measurement and modeling of coastal overwash. *Journal of Coastal Research*, 22(4), 965–991. https://doi.org/10.2112/04-0431.1

FitzGerald, D. M., Fenster, M. S., Argow, B. A., & Buynevich, I. V. (2008). Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences*, 36, 601–647. https://doi.org/10.1146/annurev.earth.35.031306.140139

Hack, J. T. (1957). Studies of longitudinal stream profiles in Virginia and Maryland. *U.S. Geological Survey Professional Paper*, 294-B, 1–97.

Harris, R., Fitzpatrick, K., Souch, C., Brunsdon, C., Jarvis, C., Keylock, C., Orford, S., Singleton, A. and Tate, N. (2013). *Quantitative methods in geography making the connections between schools, universities and employers*. London: Royal Geographical Society (with IBG). Retrieved July 2024, from https://orca.cardiff.ac.uk/id/eprint/59957/

Harris, R., Nicholas, T., Souch, C., Singleton, A., Orford, S., Keylock, C., Jarvis, C., & Brunsdon, C. (2014). Geographers count: a report on quantitative methods in geography. *Enhancing Learning in the Social Sciences*, 6(2), 43–58. https://doi.org/10.11120/elss.2014.00035

Hofierka, J., Gallay, M., Šupinský, J., & Gallayová, G. (2022). A tangible landscape modeling system for geography education. *Education and Information Technologies*, 27, 5417–5435. https://doi.org/10.1007/s10639-021-10847-y

Hooke, R. L. (1968). Model geology: prototype and laboratory streams: discussion. *Geological Society of America Bulletin*, 79(3), 391–394.

Keylock, C. J., & Dorling, D. (2004). What kind of quantitative methods for what kind of geography?. *Area*, 36(4), 358–366. https://doi.org/10.1111/j.0004-0894.2004.00237.x

Lazarus, E. D. (2016). Scaling laws for coastal overwash morphology. *Geophysical Research Letters*, 43(23), 12113-12119. https://doi.org/10.1002/2016GL071213

Lazarus, E. D. (2023). The role of storm-driven seaward sediment flux in coastal barrier dynamics is an enduring puzzle. *Journal of Geophysical Research: Earth Surface*, 128(7), e2023JF007168. https://doi.org/10.1029/2023JF007168

Lazarus, E. D. (2024). Supporting materials for 'Building quantitative skills with a simplified physical model of coastal storm deposition'. *Zenodo* [dataset]: https://doi.org/10.5281/zenodo.12635606

Lazarus, E. D., & Armstrong, S. (2015). Self-organized pattern formation in coastal barrier washover deposits. *Geology*, 43(4), 363–366. https://doi.org/10.1130/G36329.1

Lazarus, E. D., Davenport, K. L., & Matias, A. (2020). Dynamic allometry in coastal overwash morphology. *Earth Surface Dynamics*, 8(1), 37–50. https://doi.org/10.5194/esurf-8-37-2020

Lazarus, E. D., Goldstein, E. B., Taylor, L. A., & Williams, H. E. (2021). Comparing patterns of hurricane washover into built and unbuilt environments. *Earth's Future*, 9(3), e2020EF001818.

Lazarus, E. D., Williams, H. E., & Goldstein, E. B. (2022). Volume estimation from planform characteristics of washover morphology. *Geophysical Research Letters*, 49(22), e2022GL100098. https://doi.org/10.1029/2022GL100098

Nienhuis, J. H., & Lorenzo-Trueba, J. (2019). Can barrier islands survive sea-level rise? Quantifying the relative role of tidal inlets and overwash deposition. *Geophysical Research Letters*, 46(24), 14613–14621. https://doi.org/10.1029/2019GL085524

Paola, C., Straub, K., Mohrig, D., & Reinhardt, L. (2009). The "unreasonable effectiveness" of stratigraphic and geomorphic experiments. *Earth-Science Reviews*, 97(1-4), 1–43. https://doi.org/10.1016/j.earscirev.2009.05.003

Payne, C., & Fetherston, R. (1983). Fieldwork in the classroom: How to make and use a stream table. *Teaching Geography*, 8(4), 162–164. https://www.jstor.org/stable/23750561

Quality Assurance Agency (QAA) for Higher Education (2022). *Geography subject benchmark statement*. Retrieved July 2024, from https://www.qaa.ac.uk/the-quality-code/subject-benchmark-statements/geography

Sallenger Jr, A. H. (2000). Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3), 890–895. https://www.jstor.org/stable/4300099

Seel, N.M. (2017). Model-based learning: a synthesis of theory and research. *Educational Technology Research and Development*, 65, 931–966. https://doi.org/10.1007/s11423-016-9507-9

Sherwood, C. R., Ritchie, A. C., Over, J. S. R., Kranenburg, C. J., Warrick, J. A., Brown, J. A., Wright, C. W., Aretxabaleta, A. L., Zeigler, S. L., Wernette, P. A., Buscombe, D. D., & Hegermiller, C. A. (2023). Sound-side inundation and seaward erosion of a barrier island during hurricane landfall. *Journal of Geophysical Research: Earth Surface*, 128(1), e2022JF006934. https://doi.org/10.1029/2022JF006934

Sornette, D. (2006). *Critical phenomena in natural sciences: chaos, fractals, selforganization and disorder: concepts and tools*. Springer Science & Business Media.

Spronken-Smith, R., Bullard, J., Ray, W., Roberts, C., & Keiffer, A. (2008). Where might sand dunes be on Mars? Engaging students through inquiry-based learning in geography. *Journal of Geography in Higher Education*, 32(1), 71–86. https://doi.org/10.1080/03098260701731520

Smith, C. E. (1998). Modeling high sinuosity meanders in a small flume. *Geomorphology*, 25(1-2), 19–30. https://doi.org/10.1016/S0169-555X(98)00029-4

West, G. (2018). *Scale: The universal laws of life, growth, and death in organisms, cities, and companies*. Penguin.

Wigner, E. P. (1960). The unreasonable effectiveness of mathematics in the natural sciences. *Communications in Pure and Applied Mathematics*, 13 (I), 1–14.

Wikle, T. A., & Lightfoot, D. R. (1997). The stream table in physical geography instruction. *Journal of Geography*, 96(1), 23–30. https://doi.org/10.1080/00221349708978751

Williams, J. J., Buscombe, D., Masselink, G., Turner, I. L., & Swinkels, C. (2012). Barrier dynamics experiment (BARDEX): Aims, design and procedures. *Coastal Engineering*, 63, 3–12. https://doi.org/10.1016/j.coastaleng.2011.12.009

Woods, T. L., Reed, S., Hsi, S., Woods, J. A., & Woods, M. R. (2016). Pilot study using the augmented reality sandbox to teach topographic maps and surficial processes in introductory geology labs. Journal of Geoscience Education, 64(3), 199–214. https://doi.org/10.5408/15-135.1

Figures; figure captions (as a list)

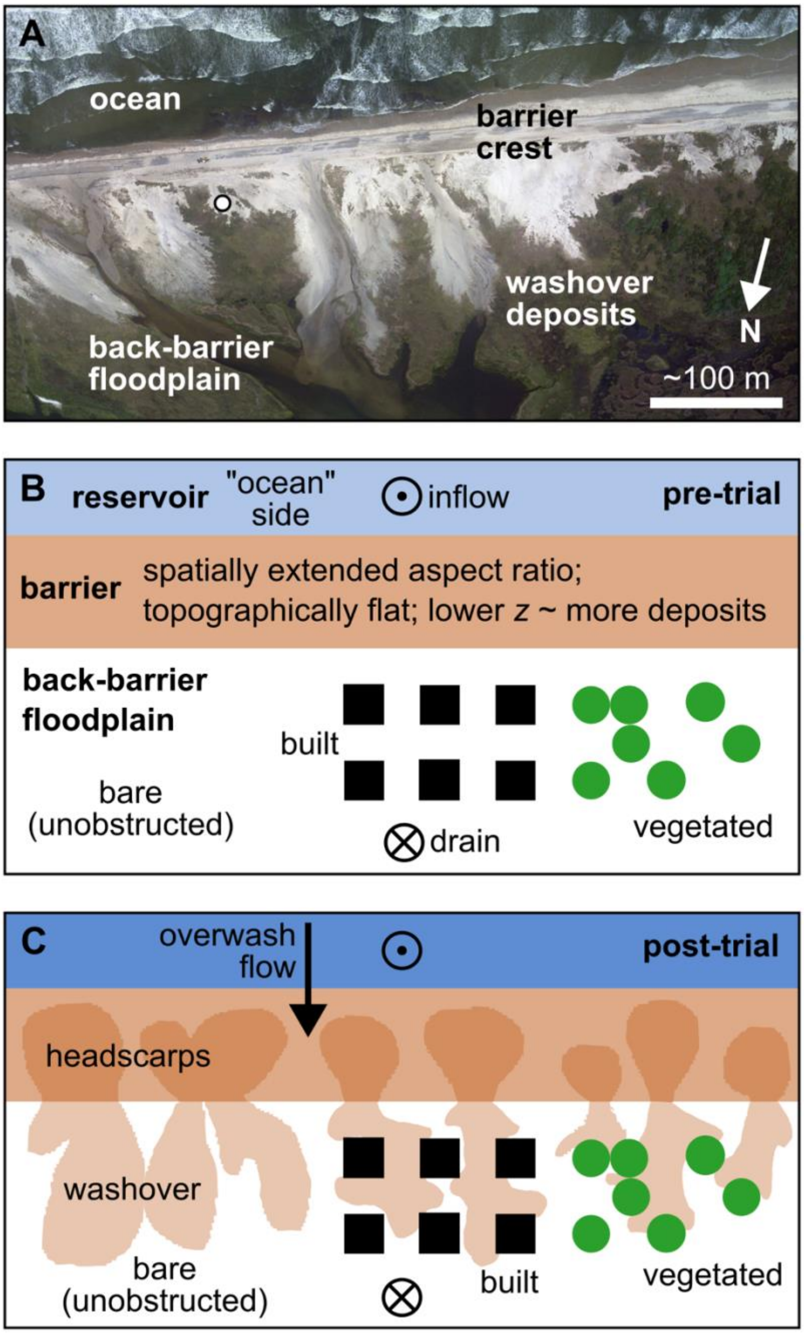

Figure 1 – (A) Example of washover on Ocracoke Island (North Carolina, USA) following Hurricane Florence in 2018. Aerial image (rotated and colour-corrected) from NOAA Emergency Response Imagery catalogue (https://storms.ngs.noaa.gov/storms/florence/index.html); filled circle marks lat/long 35.1687N, -75.8173E. (B) Illustrative schematic (not drawn to scale) of pre-trial set-up and (C) post-trial result of a deliberately simplified stream-table model of overwash morphology with different back-barrier floodplain conditions. An extended alongshore dimension relative to barrier height is essential to this design.

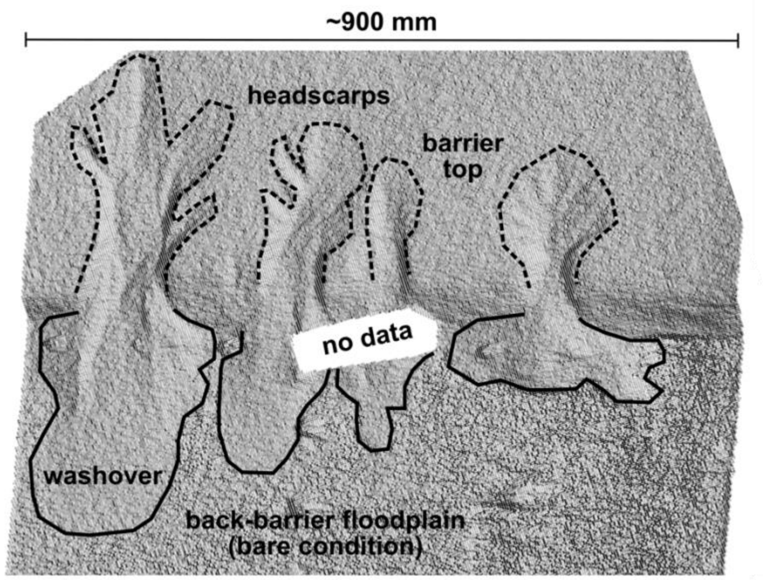

Figure 2 – Hillshaded digital elevation model (DEM) of a typical post-trial result for a bare back-barrier condition and a barrier height of 20 mm. A version of this DEM is included in the teaching materials supporting this article (Lazarus, 2024).

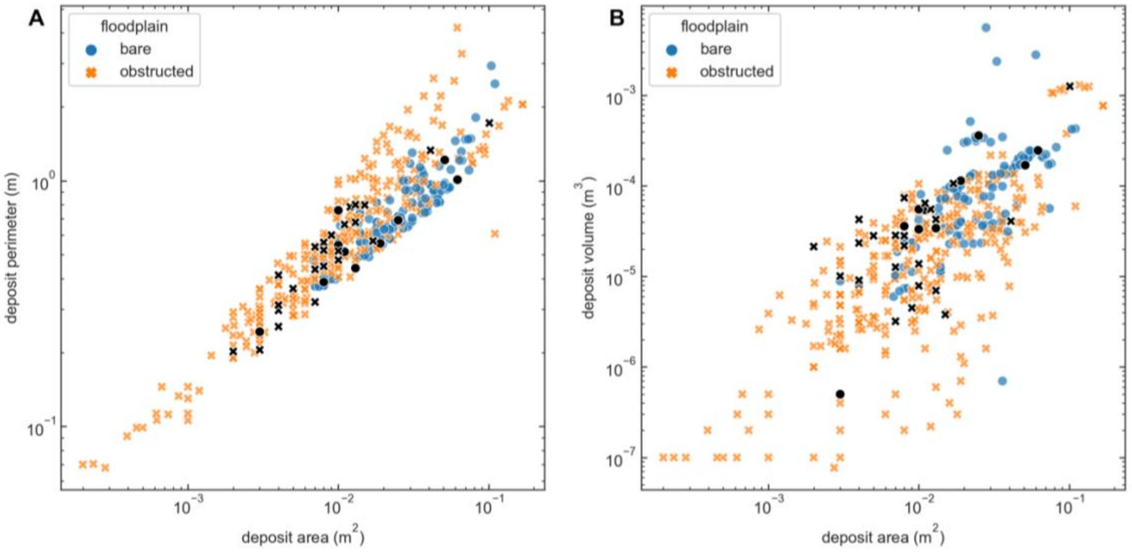

Figure 3 – Scaling relationships for washover (A) perimeter and area and (B) volume and area for bare (filled circles) and obstructed (x) floodplain conditions in six experimental trials (two bare; four obstructed). Student measurements are shown in blue and orange; instructor (EDL) measurements are shown in black.

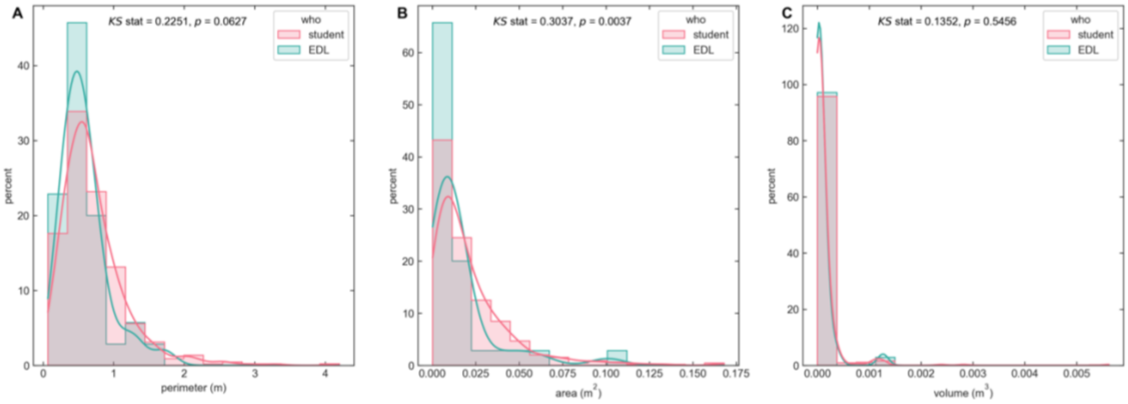

Figure 4 – Histograms and kernel density estimations of student (*n* = 19) and instructor (EDL) measurements of washover (A) perimeter, (B) area, and (C) volume from six experimental trials. For a threshold value $p = 0.001$, a two-sample Kolmogorov-Smirnov (KS) test confirms the null hypothesis that the student and instructor samples are drawn from the same probability distribution.